CFD Study On The Thermal Performance of Transformer Disc Windings Without Oil Guides

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Abstract

The hotspot temperature of disc windings has a close relation with the transformer age. In oil immersed transformers, oil guides are applied generally to enhance the cooling effects for disc windings. In some cases disc windings without oil guides are used. However, the lack of oil guides is expected to result in a more complicated thermal behavior of the windings, making it more difficult to predict the location and strength of the hotspot temperature (i.e. the hottest temperature in the winding). To get an improved understanding of the thermal behavior, a CFD study has been performed. This article describes the implementation of CFD simulation for 2D axisymmetry models without oil guides, and then analyzes the results of a series of parametric studies to see the sensitive factors influencing the cooling effects. These parameters include radial disc width, inlet mass flow rate, horizontal duct height, vertical duct width and the inlet/outlet configurations. Three main characteristics, the hotspot temperature, the location of the hotspot and the number of oil flow patterns are detected to describe the thermal performance.

Key words: Non-oil guided, disc windings, CFD, parametric study
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1 INTRODUCTION

1.1 Purpose

The main purpose of this report is to study the oil flow and temperature distributions in transformer disc windings without oil guides by using advanced CFD tools. By performing the parametric study on different design parameters, a good understanding of the sensitive factors that influence the thermal performance is obtained.

Different from study of disc windings with oil guides, this project mainly focuses on disc winding transformer without oil guides. The global cooling effect, hotspot temperature as well as its location and the oil distribution are unpredictable in such a large length scale transformer ducts model. This makes it necessary to do this investigation using advanced CFD tools. As a result, we want to see the cooling effects of the disc windings without oil guides comparing to the case with oil guides, the solution that is suitable for the study of non-oil guide model, the parameters that will affect the oil distribution and the temperature distribution, etc. Three indicators proposed for the cooling effects are the hotspot temperature which has a close relation to the age of transformer, the location of the hotspot which is important if it can be predicted in design and the oil flow distribution which will give a clear view about the heat transfer capability inside the disc winding. For most of large oil immersed transformer, oil guides are applied to enhance the cooling effects by guiding the oil flow in order to increase the heat transfer coefficient and make oil distribution stable. However, for some winding with a small radial dimension, it is difficult or not necessary to place guides, then, what will happen in the disc windings such as the oil flow distribution and temperature distribution, whether the solution for oil guided case is suitable for non-oil guided cases would be a new interest. At least, a good understanding about the oil distribution and temperature distribution could also help know more about the cooling effects of oil immersed disc winding and hopefully this result could contribute to other new cooling methods.
1.2 Scope and structures

This investigation gets experience from previous CFD studies by ABB, for example, (Kranenborg, 2008) on oil guided disc windings. Firstly, this report gives an introduction of transformers as well as their cooling methods and describes the problem without oil guides inside the disc winding generally. Then, the related theoretical analysis describes the physical models of the non-oil guided disc windings. The implemented process by using Ansys Fluent is given in the following part. The case study part consists of the base case study and parametric study, during which the comparison between oil guide and non-oil guide is also conducted. In the end, the final conclusion is given and the suggestions for future work is also proposed.

This investigation was performed mainly by doing CFD simulation using Ansys Fluent which is a program based on FVM (Finite Volume Method). In order to get an accurate result, a large number of nodes were generated for the full winding geometry model. The calculation time for each case was quite long, especially for time dependent simulation. Thus, the conclusion drawn in this investigation mainly gives a general description and estimation of the thermal performance. For a more detailed and exact result, more work should be done in the future.

This report has the following structure.

Section 1 is the introduction of the purpose and scope for this report as well as the nomenclature description; Section 2 gives a basic introduction of the oil-filled power transformer including the definition, classification, application and operating principles. The thermal cooling methods applied in power transformers are also described. Section 3 analyzes the physical winding model using heat and mass transfer theory. Describe the fluid model and the heat transfer model. Preparing for the numerical methods, the related governing equations and the bousiness approximation are introduced. Section 4 mainly describes the implementation process by applying Ansys Fluent including creating geometry model, generating grid models as well as its optimizing analysis and the Fluent settings. Section 5 performs the base case study which is close to real case. The solution and results are set as base case and reference for the following parametric studies. Section 6 is parametric study on sensitive parameters such as inlet mass flow rate, vertical duct width, horizontal duct height and the disc length. The comparison among different Inlet/Outlet configurations and the comparison between oil guided and non-oil guided models have also
been performed. Section 7 draws the general conclusion from all the studies above and gives a proposal about future work.

1.3 Review of previous experience

In this article, the investigated object is the model of disc windings in transformer without oil guides. By now, few studies, especially by using CFD tools, have been done on such kind of model. However, a lot of experience can be obtained from previous work on oil guided studies.

(Mufuta & Bulck, 1999) has performed a theoretical study of modeling the mixed convection to describe the flow behavior of transformer oil in the winding of a disc type transformer. In their following work (M.B. & Bulck, 2000), they focused on the phenomenon of mass flow distribution around rectangular cross-section of winding discs; (Xiu-chun, et al., 2001) analyzed the effects of the surface heat flow density of sections in the radial oil ducts on the heat exchange based on the test and researches. After then, (Xiu-chun & Jun-pu, 2008) did a research on temperature field on large forced directed oil cooling transformer; (Yan, et al., 2001) gave the analysis of the calculation and test on hotspot temperature rise in transformer windings; (Ying, et al., 2004) analyzed the heat transformer in forced-directed oil cooling transformers; (Yi-zhi, et al., 2004) proposed a calculation of transformer oil flow distribution by Newton-Raphson method; (Zhang & Li, 2006) established a coupled thermal model to investigate the thermal performance of a two-dimensional oil-filled transformer disc windings. Then, (Zhang & Li, 2006) proposed and investigated some certain designed parameters such as number of discs, horizontal and vertical ducts height, entrance oil temperature as well as the total mass flow rate which may influence the thermal performance; (Zhang, et al., 2007) conducted an experimental study to investigate oil and disc temperature in ON transformer windings for a variety of flow conditions, such as heat generation rates, and transformer winding geometries. Finally they proposed a two-dimensional axisymmetric model which is sufficiently accurate for the thermal simulation of the winding discs; (E.Rahimpour, et al., 2007) also created a model of disc windings based on experimental results. They investigated some factors, such as eddy losses, number of discs, model height, horizontal duct height and space number and width, which may affect the temperature distribution; (Kranenborg, et al., 2008) performed a numerical study on mixed convection and thermal streaking in transformer disc windings. It is found that the internal buoyancy and hot streak
formation play an important role in defining the oil flow and temperature distributions in a transformer disc winding. The hot streaks can impact the flow and temperature distributions in a disc winding; (R.Hosseini, et al., 2008) also applied the program FLUENT to describe the thermal performance of disc windings. They proposed some points for design and manufacturing of the transformers; (Taghikhani & A.Gholami, 2009) suggested a method to improve the accuracy of prediction of the hotspot temperature by solving the heat transfer partial differential equation (PDE) numerically; (Bo, et al., 2009) did a two dimensional analysis of thermal performance of disc winding by using FLUENT. (F.Torriano, et al., 2010) performed a CHT calculations by using a commercial CFD code to study the numerical model of disc windings, they also found that the hot streak plays an important role in the cooling of the windings; (W.Wu, et al., 2011) did some CFD calibration for network modeling of transformer cooling oil flows; (Tsili, et al., 2012) applied the finite element method and other numerical method to do a general thermal analysis of the power transformer; (Skillen, et al., 2011) gave a numerical prediction of local hotspot phenomenon in transformer disc windings. They descript the implementation process, explained the phenomenon and performed the sensitivity studies on mass flow rate.

Even though most of the analysis of thermal performance of transformer disc windings are based on oil guided disc windings, the methods and experience for conducting such studies of disc windings can also be gained and digested for non-oil guided cases.
1.4 Nomenclature

\( A_c \) Cross-sectional area (\( m^2 \))

\( C_p \) Specific heat at constant pressure (\( Jkg^{-1}K^{-1} \))

\( d \) Width of vertical duct (\( m \))

\( g \) Gravity (\( ms^{-2} \))

\( H \) Total height of disc windings (\( m \))

\( k \) Thermal conductivity (\( Wm^{-1}K^{-1} \))

\( L \) Characteristic Length (\( m \))

\( m \) Mass flow rate (\( kg/s \))

\( p \) Pressure (\( Pa \))

\( Q \) Heat Source (losses) (\( kW \))

\( r \) Inner diameter of cylindrical disc winding (\( m \))

\( S_E \) Heat source term (\( Wm^{-3} \))

\( \Delta T \) Temperature difference (\( K \))

\( u \) X component of the velocity (\( m/s \))

\( v \) Y component of the velocity (\( m/s \))

\( x, y, z \) Axis coordinate (\( m \))

\( \delta \) Step function (-)

\( \beta \) Thermal expansion (\( K^{-1} \))

\( \nu \) Kinematic viscosity (\( m^2s^{-1} \))

\( \tau \) Stress (\( Pa \))

\( \mu \) Dynamic viscosity (\( Pa \cdot s \))

\( Re \) Reynolds number

\( Nu \) Nusselt number

\( Pr \) Prandtl number

\( Gr \) Grasholt number

\( Ra \) Rayleigh number

\( LV \) Low voltage

\( HV \) High voltage

\( AC \) Alternating Currents
2 POWER TRANSFORMERS

2.1 Introduction of power transformers

A power transformer is the electrical device which is used to change the voltage of AC in power transmission system. The first transformer in the world was invented in 1840s. Modern large and medium power transformers consist of oil tank with oil filling in it, the cooling equipment on the tank wall and the active part inside the tank. As the key part of a transformer, the active part consists of 2 main components: the set of coils or windings (at least comprising a low voltage, high voltage and a regulating winding) and the iron core, as Figure 2.1 shows. For a step-up transformer, the primary coil is low voltage (LV) input and the secondary coil is high voltage (LV) output. The situation is opposite for a step-down transformer. The iron core is the part inducing the varying magnitude flux. Nowadays, transformers play key roles in long distance high-voltage power transmission.

![Figure 2.1 Structures of disc winding transformer](image1)

### 2.2 Operating principle of transformer

![Figure 2.2 Operating principle of transformer](image2)
A general operating process of a transformer is that a varying magnetic flux is created in the core due to the changing of the current of the primary coil. Then, a voltage at the secondary coil is induced by this varying magnetic flux. As Figure 2.2 shows, wires are wrapped around each side of the core frame which is made of materials with high magnetic permeability. The left winding is the primary winding and the right winding is the secondary winding. When an AC is connected to the left, the magnetic flux will be induced in the core. The magnetic flux will pass through the secondary winding in the right side and induces voltage. This principle is basing on the Faraday’s law of induction or the induction law shown in Eq. (2.1).

\[ V_{\text{secondary}} = N_{\text{secondary}} \frac{d\Phi}{dt} \]  \hspace{1cm} [2.1]

where \( \Phi \) is the magnetic flux through one turn of the coil, \( N_{\text{secondary}} \) is the number of the secondary coils and \( V_{\text{secondary}} \) is the voltage generated in the secondary winding.

In an ideal transformer, there is a relation between the voltages and the number of coils on both sides as shown in Eq. (2.2). This equation indicates that the ratio of output voltage to the input voltage is defined by the ratio of the primary coils number to the secondary coils number. By this law, within a certain power capacity, transformer can be selected according to the output voltage.

\[ \frac{V_{\text{primary}}}{V_{\text{secondary}}} = \frac{N_{\text{primary}}}{N_{\text{secondary}}} \]  \hspace{1cm} [2.2]

Transformers can be classified by many standards, such as structures, applications, number of phases, cooling types, etc. For example, according to the number of phases, there are single-phase transformers and poly-phase transformers; according to the cooling methods, there are dry type cooling transformers and oil immersed cooling transformers; according to the application purpose, there are constant voltage transformers, variable voltage transformers, current transformers and constant-current transformers. In this project, the model created is mainly basing on oil immersed cooling type of power transformers which are widely used in high voltage power transmission.
### 2.3 Energy losses and thermal cooling methods

As one kind of electrical components, an ideal transformer has no energy losses. However, in reality, a transformer cannot reach a 100% efficient. The main losses come from the winding resistance thermal loss, the eddy current loss and the hysteresis loss. (R.Hosseini, et al., 2008)

Windings consist of helix wires made of copper or other conductors. Even though the resistance is low, the current through the wire can still cause resistive heat. Especially under a condition with high frequencies and high temperature in a transformer, the resistance will be increased. Eddy currents are circulating through the core and windings and the coupling effects of the frequency and material thickness could also lead to resistive heat loss. The hysteresis loss is mainly happening in the core which is a coupling effect from frequency and material properties. (F.Torriano, et al., 2010). Besides, there still some other reasons contributing to the energy loss, such as mechanical loss, stray loss, magnetostriction loss, etc.

However, the transformer life is limited by the age of insulation materials inside the transformer, such as insulation paper wrapping around the windings. The insulation materials, such as cellulose, will be destroyed if the transformer keeps working in the environment with high temperature. It is said from experience that when the hotspot temperature is in the range 80-140°C, the transformer life will be halved for every 6 degree increase (M.B. & Bulck, 2000). Thus, measures must be taken to avoid high temperature inside the transformer by removing the heat generated in the core and windings effectively. As described above, according to the size and capacity of the transformer, different methods are applied to achieve the cooling targets.

For dry type cooling method, the windings and cores inside the transformer are exposed in the air. The cooling effects can be achieved by natural convection of the air around the windings and cores or the air blast from the blower. The radiation from other parts of the transformer also adds the cooling effects. Due to the relative low cooling efficiency, this cooling method is usually applied for small size and low capacity transformer.

For liquid immersed transformer, the active part including cores and windings is immersed in some insulating liquid, usually the transformer oil, filling in the transformer. The heat
generated by windings and cores will be transferred to the transformer wall by convection. Then, the heat will dissipate into the environment by radiation and convection. Usually, for some large transformers, fins and radiators are applied for improving the cooling capability. A typical example of the liquid immersed transformers is the large oil immersed transformer in which a blower is installed forcing the circulating air to enhance the cooling effects.

Another cooling method is gas-vapor cooling transformers. This method applies a vaporizable liquid as the coolant. The liquid coolant is pumped to the top of the windings and cores then vaporizes while absorbing the heat generated, the hot vapor gas with heavy density than normal air would go down to the bottom circulating tubes. The vapor would be cooled into liquid in the cooler and back to the pump for the next circulation. This cooling method is usually used for large transformer.

2.4 Oil immersed transformers

Oil immersed cooling methods have been applied in large capacity transformer for more than 50 years. Nowadays, the oil immersed transformer can be divided into different types according to the cooling modes.

There are three main cooling modes inside the oil tank: ON (Oil Natural), OF (Oil Forced) and OD (Oil Directed) as well as three main cooling modes for the outside radiator: AN (Air Natural), AF (Air Force) and WF (Water Force). Principle of the typical cooling mode ONAN is described below.

Figure 2.4.1 shows the ONAN cooling principle. Figure 2.4.1a is the cross-sectional image of a transformer construction. This transformer consists of oil tank, cores, windings, and radiator. Transformer oil is filling inside the oil tank and radiator. In a steady state, cold oil comes in the tank from radiator. Oil is heated inside the transformer and hot oil will go up to the top and then go out of tank into radiator. Oil inside radiator will be cooled by natural convection of the air and the radiation in the environment. Oil flow inside the entire oil tank is actually buoyancy driven flow. When passing through windings and core, it is being heated and the density would be changed as well. Then, a buoyancy force is generated to drive the flow up. As Figure 2.4.1a shows, the green line indicates the circulation direction of the oil. In this cooling circulation, the natural convection of the oil plays the key role for cooling the disc winding and the core. This cooling mode is called ON (Oil natural) cooling. If the oil inside the
radiator is cooled by natural convection of air in surroundings, this cooling mode can be called ONAN cooling mode.

Oil temperature in different parts along the circulation is always important for cooling design. As Figure 2.4.1b shows, points are marked in the critical area including the inlet/outlet of radiator, inlet/outlet of windings. In the line chart, points 1, 2, 3 and 4 are the temperatures in the oil, while points 1’and 2’ indicate the temperatures in the winding. The line chart shows the temperature variation in the circulation under the ideal condition. It can be seen that from point 1 to point 2, the temperature increases. This process is the cooling process of winding and core in which the cooled oil will be heated to a higher temperature. Point 2 is the outlet of winding and point 3 is the inlet of radiator. The position of point 3 is higher than point 2. This is because of the temperature gradient from downwards to upwards is positive in the oil tank, thus, the temperature of point 3 is higher than point 2. The process from point 3 to point 4 is the cooling process of the oil by radiator. Oil inside the radiator is cooled in the air and the temperature will decrease. The temperature decrease from point 4 to point 1 is also due to the geometry position of these 2 points inside the oil tank. For a steady state of the global cooling, temperature at these points are constant. One key indication of the cooling capacity is the average temperature between the top oil and the bottom oil, as shown in the line chart, the middle point between point 1 and point 2.

Figure 2.4.1 a ONAN cooling circulation

Figure 2.4.1 b Temperature variation
Other cooling modes for large transformer include ONAF, OFAF, OFWF, ODAF, ODWF, etc. Figure 2.4.2 (a) shows the construction of ONAF cooling transformer. The difference between ONAN and ONAF cooling mode is that a fan which helps increase the cooling capacity of the radiator is added. Figure 2.4.2 (b) shows the construction of OFAF cooling transformer. Oil is pumped into the oil tank to increase the convection capability. This oil flow is forced flow. OFWF cooling transformer applies water circulation for the radiator cooling, as Figure 2.4.2 (c) shows. Figure 2.4.2 (d) show the construction of an ODAF cooling transformer. Different from ON and OF cooling transformers, the guide ducts are added to make the cooled oil pass through the winding s and core directly. This construction can increase the cooling effects a lot. Figure 2.4.2 (d) shows the OD oil cooling type with an AF air cooling mode. For ODWF cooling transformer, the fan is replaced by water circulation cooling facilities.
2.5 Oil guided and non-oil guided disc windings

Oil guided and non-oil guided windings are proposed in disc windings transformers. In the active part, as shown in Figure 2.1, between winding and core, LV windings and HV windings, and windings and outer casing, there are insulation board layers. Then, a closed space can be formed for each layer of windings. Figure 2.5 shows the 2D cross sectional area of one layer of disc windings. As Figure 2.5 (a) shows, the guides are set in vertical ducts every 6 discs are oil guides. The purpose of setting oil guides is to improve the natural convection capability of the oil flow by avoiding the stagnation of the oil inside ducts. It can be seen from Figure 2.4.2, cold oil come in the windings from the bottom and the go through the vertical and horizontal ducts, the oil guides would change the oil flow direction and make the global oil distribution even. This enhances the global heat transfer coefficient.

In reality and the real manufacturing process, considering some situation with quite small windings radius as well as cost effective consideration, the non-guided disc windings may be applied. Figure 2.5 (b) shows the 2D cross-sectional image of non-oil guided winding. It can be seen that the construction of non-oil guide winding looks like a longer section of winding with oil guides. For non-oil guided model, due to its large scale in the vertical length, the oil flow distribution as well as the temperature distribution are expected to become complex.
2.6 Transformer oil

Oil inside the transformer is incompressible fluid and acting as both the insulation material and the coolant for inner parts of transformer. Thus, requirement for transformer oil is that it is good insulator and has good property for transferring heat from active parts to the cooling parts. However, as a kind of oil, it usually has high viscosity and high Prantl number, which may decrease natural convection capability. At present, the most widely used transformer oil is mineral oil. During operation, measures are always taken to avoid deterioration caused by oxidation and moisture.
3 ANALYSIS OF THEORETICAL MODEL

3.1 Physical models of disc windings

The problem of cooling disc windings is a combined heat and mass transfer problem. Inside the disc windings, both conduction heat transfer and convection heat transfer exist. Convection by the oil is the dominant heat transfer mode and the high global heat transfer coefficient would contribute to improve the cooling effects. Conduction happens in the inner disc windings, from the inner strands which are the conductors of the windings, to the insulation layers around the disc windings. The oil flow passes through the spaces between each adjacent discs and spaces between one layer of disc windings and cylindrical insulation cardboard around the windings. This forms the hydraulic model in which the fluid is a high Prandtl number fluid and the regime is laminar. In 2D model, this laminar flow can be regard as passing through a duct. Figure 3.1.1 shows this hydraulic model.

![Figure 3.1.1 Oil flow in spaces](image1)

Figure 3.1.1 Oil flow in spaces

![Figure 3.1.2 Temperature gradient](image2)

Figure 3.1.2 Temperature gradient

The thermal model is shown in Figure 3.1.2. Strands inside the disc are made of conductive materials, usually copper, and is to be regard as heat losses source when the transformer is operating. Temperature inside the windings is higher than the oil flow around it. Heat is transferred by conductivity from copper strands to insulation layers around it. The oil flow outside the windings will take away the heat by natural convection. In a steady state, the energy balance will be achieved, under which the oil flow distribution and the temperature distribution will be stable. In Figure 3.1.2, temperature of the strands is assumed as an uniform value, the total temperature gradient from stands to the steady-state oil flow is $\Delta T_v$, the temperature gradient from the strands to insulation layers due to heat conductivity is $\Delta T_\lambda$. 

\[ \Delta T_v = \Delta T_\lambda + T \]
and the gradient from insulation layers to the oil flow due to the natural convection is \( \Delta T_a \), then the relation can be expressed by Eq. (3.1.1).

\[
\Delta T = \Delta T_X + \Delta T_a
\]

Thus, the physical model of this disc winding cooling field is coupling of a hydraulic model and a thermal model. The related dimensionless numbers are applied to characterize these models and the coupling relations. (Zhang & Li, 2006)

**• Reynolds number**

Reynolds number, Re, is used to identify the regime of the flow, laminar, transition, or turbulent. It indicates the ratio of inertial forces to viscous forces. When Re is very high, usually higher than 2000, the inertial force is much higher than the viscous force, then, the inertial force becomes the dominant force, which usually leads to turbulent flow; when Re is low, the viscous force would be the dominant force, which would lead to laminar flow. Re can be expressed by Eq. (3.1.2).

\[
Re = \frac{\rho v L}{\mu}
\]

where \( L \) is the characteristic length, \( v \) is the characteristic velocity and in this case, \( L \) is defined by Eq. (3.1.3).

\[
L = \frac{4A_c}{P}
\]

where \( A_c \) is the cross-sectional area and can be calculated by \( A_c = w \cdot l_c \) and \( P \) is the wetted perimeter which can be calculated by \( P = 2 \cdot (w + l_c) \). \( w \) is the width of the vertical duct and \( l_c \) is the mean circumference of the disc windings. According to the properties of transformer oil and the dimension of the disc winding geometry, the range of Re can be estimated smaller than 2000 which determines the oil flow is laminar flow.

**• Nusselt Number**

Nusselt Number, Nu, is defined as the ratio of convective heat transfer to conductive heat transfer at the boundary in a fluid close to a wall. Usually, for a laminar flow, the value of Nu is close to 1, while a higher Nu means more active convection, such as turbulent heat transfer. The Nusselt Number can be expressed as Eq. (3.1.4) below.
\[ Nu = \frac{hL}{k} \]  

where \( h \) is the convective heat transfer coefficient, \( L \) is the characteristic length and \( k \) is the conductive heat transfer coefficient.

The Nu of a natural convection can be expressed as: \( Nu = f(Ra, Pr) \) and the Nu of a forced convection is usually expressed as: \( Nu = f(Rc, Pr) \).

**Grashof Number**

Grashof Number, \( Gr \), in this case is mainly used to indicate the behavior of the transformer oil under a certain temperature. It can be expressed as the ratio of buoyancy to the viscous force. Thus, it is applied to describe this natural convection of the oil. Oil flow is driven by the buoyancy generated due to the density variation as a function of the temperature. In this case, transformer oil is one kind of fluid with high viscosity, the coupling effects of gravity and viscous force of the fluid become resistance to the buoyancy. Usually, a high Grashof Number of fluid indicates a high capability of natural convection while a small Grashof Number shows the low capability of natural convection.

The oil flow between different disc windings can be regarded as the oil flow passing through the plates, then, the empirical calculation method of the local Grashof Number can be expressed by the Eq. (3.1.5) below:

\[ Gr = \frac{g \cdot \beta \cdot \Delta T \cdot L^3}{v^2} \]  

where \( \beta \) the volumetric thermal expansion coefficient, \( \Delta T \) is the temperature between surface temperature and the bulb temperature (K).

Usually, when \( Gr < 10^8 \), the boundary layer of the convection is laminar, when \( 10^8 < Gr < 10^9 \), it is usually the transition from laminar to turbulent, when \( Gr > 10^9 \), the boundary layer is turbulent. In this case, according to the properties of the transformer oil and the geometry dimensions, the Grashof Number can be estimated as:

\[ Gr = \frac{g \cdot \beta \cdot \Delta T \cdot D^3}{v^2} = \frac{g \cdot \beta \cdot \Delta T \cdot L^3 \cdot \mu^2}{\rho^2} = 5 \times 10^5 < 10^8 \]

Thus, the boundary layers of this convection can be regarded as laminar flow.
• Prandtl Number

Prandtl Number, Pr, is the ratio of fluid viscosity and thermal diffusivity. It shows the relation between the hydraulic property and the thermal property of the fluid. Transformer oil is high Prandtl Number fluid. That means the viscosity of the oil will impacts a lot on the thermal diffusivity. The Pr number can be estimated as Eq. (3.1.6) below.

\[ Pr = \frac{C_p \cdot \mu}{k} \]  

where \( C_p \) is specific heat (J/(kg.k)), \( k \) is thermal conductivity (w/mk).

The Prandtl Number of the transformer oil is generally larger than 50.

• Rayleigh Number

Rayleigh number shows the relation between the Grashof Number and the Prandtl Number and it is used as an indication of the heat transfer mode. For one certain buoyancy driven flow, there is a critical value, when the local Rayleigh Number is below this value, the conduction is dominant, and when the local Rayleigh Number is higher than this value the convection heat transformer is dominant.

In most situations, the value of Rayleigh is around \( 10^6 \) to \( 10^8 \). The equation can be used to estimate the value of Rayleigh Number as shown in Eq. (3.1.7):

\[ Ra = Gr \cdot Pr = \frac{g \beta \cdot \Delta T \cdot L^3}{\nu \cdot \alpha} \]  

[3.1.7]

3.2 Governing equations

By applying numerical methods, the Governing equations for the physical models are proposed. In this case, the governing equations are the Navier-Stokes Equations which are conservation equations of mass, momentum and energy.

3.2.1 Navier-Stokes equations

Navier-Stokes Equations are the governing equations playing roles in the numerical calculation for this case. In analysis, the Eulerian frame is applied for describing the
conservation of mass. While, for describing the momentum and energy conservations, the Lagrangian frame is applied.

3.2.1.1 Mass balance analysis

A fluid element is built in the oil flow field, the conservation of mass can be described as that the rate of increase of oil in this element equals to the net rate of the oil flow into the element. Figure 3.2.1 shows this conservation process.

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} = 0$$  \[3.2.2\]
The term $\frac{\partial \rho}{\partial t}$ is change in density. In this physical model, transformer oil can be regard as incompressible fluid and this term is actually 0. The equation describing the conservation of the mass can be written as Eq. (3.2.3) as below.

$$\frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} = 0$$

[3.2.3]

### 3.2.1.2 Momentum analysis

For a certain oil particle, Newton’s second law is applied to describe the momentum equation as that the change of momentum equals to sum of forces. Forces on fluid particles are usually including surface forces such as pressure and viscous forces and body forces such as gravity, centrifugal, coriolis and electromagnetic forces. For this 2D oil flow, there are momentum equations in 2 directions, x-momentum equation and y-momentum equation.

$$\left( r_{yx} + \frac{\partial r_{yx}}{\partial y} \cdot \frac{1}{2} \delta y \right) \delta y - \left( r_{xx} - \frac{\partial r_{xx}}{\partial x} \cdot \frac{1}{2} \delta x \right) \delta x - \left( r_{yy} - \frac{\partial r_{yy}}{\partial y} \cdot \frac{1}{2} \delta y \right) \delta y - \left( r_{yx} + \frac{\partial r_{yx}}{\partial x} \cdot \frac{1}{2} \delta x \right) \delta x =$$

$$\left( p + \frac{\partial p}{\partial x} \cdot \frac{1}{2} \delta x \right) \delta y - \left( p + \frac{\partial p}{\partial x} \cdot \frac{1}{2} \delta x \right) \delta y - \left( p - \frac{\partial p}{\partial x} \cdot \frac{1}{2} \delta x \right) \delta y$$

[3.2.4]

Figure 3.2.2 Momentum balance on 1 fluid element

Forces are analyzed in x-direction as shown in Figure 3.2.2. The balance can be expressed as Eq. (3.2.4) shown.
The rate of change of the x-momentum is \( \rho \frac{Du}{Dt} \) and the sum of the body forces is assumed as momentum source, \( S_{Mx} \). There is no momentum source in x direction, thus \( S_{Mx} = 0 \). Then, the x-momentum equation can be written as Eq. (4.2.5) shows.

\[
\rho \frac{Du}{Dt} = \frac{\partial (-p + \tau_{xx})}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} \tag{3.2.5}
\]

The left term consists of change as a function of time and change as a function of the location, which can be expressed as Eq. (3.2.6) shows.

\[
\rho \frac{Du}{Dt} = \rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) \tag{3.2.6}
\]

By introducing the dynamic viscosity \( \mu \) of the fluid, the terms \( \tau_{xx} \) and \( \tau_{yx} \) can be expressed as \( \mu \frac{\partial u}{\partial x} \) and \( v \frac{\partial u}{\partial y} \). Substitute these terms as well as the Eq. (3.2.6) to above Eq.(3.2.5), the momentum balance can be expressed as Eq. (3.2.7).

\[
\rho \left( \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( \mu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu \frac{\partial u}{\partial y} \right) \tag{3.2.7}
\]

Similarly for y direction, the y-momentum balance can be written as Eq. (3.2.8) below. The momentum source in y direction is the gravity, g. (Mufuta & Bulck, 1999)

\[
\rho \left( \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left( \mu \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu \frac{\partial v}{\partial y} \right) + \rho g \beta \Delta T \tag{3.2.8}
\]

**3.2.1.3 Energy balance analysis**

The conservation of energy is described by the first law of thermodynamics: rate of change of energy of a fluid particle is equal to the rate of heat addition plus the rate of work done. Here, the conservation equation will be derived by regarding the change in energy is the result of work done by viscous stresses and the net heat conduction.
An analysis of the work done by surface stresses in x direction is shown in Figure 3.2.3. The similar analysis is also performed in y direction. Sum all the terms and divide by $\delta x \delta y$, the total work done by surface stresses can be expressed by Eq. (3.2.9).

$$w_x = -p \frac{\partial u}{\partial x} - p \frac{\partial v}{\partial y} + \frac{\partial (u \tau_{xx})}{\partial x} + \frac{\partial (u \tau_{xy})}{\partial y} + \frac{\partial (v \tau_{xy})}{\partial x} + \frac{\partial (v \tau_{yy})}{\partial y} \tag{3.2.9}$$

Then, an analysis of energy flux due to heat conduction is done as shown in Figure 3.2.4. In this 2D model, the heat flux vector $q$ has two components, $q_x$ and $q_y$. Sum all terms and divide by $\delta x \delta y$, the net rate of heat transfer per unit volume can be derived as:

$$q = -\frac{\partial q_x}{\partial x} - \frac{\partial q_y}{\partial y} \tag{3.2.10}$$
According to Fourier’s law of heat conduction, the relation between the heat flux to the local temperature can be describes as:

\[ q_x = -k \frac{\partial T}{\partial x} \quad q_y = -k \frac{\partial T}{\partial y} \]

Then, the net rate of heat transfer can be expressed as:

\[ q = k \left[ \left( \frac{\partial T}{\partial x} \right)^2 + \left( \frac{\partial T}{\partial y} \right)^2 \right] \tag{3.2.11} \]

The rate of change of energy can be expressed as the polynomial:

\[ \rho \frac{DE}{Dt} = \rho \left( \frac{\partial E}{\partial t} + \frac{\partial E}{\partial x} \cdot u + \frac{\partial E}{\partial y} \cdot v \right) \]

The energy source is assumed as \( S_E \). Sum all terms above and the energy balance equation can be written as:

\[ \rho \frac{DE}{Dt} = w_t + q^+ s_E \tag{3.2.12} \]

Substitute all the expressions of the terms in above the equations, a full expression can be derived.
\[
\rho \left( \frac{\partial E}{\partial t} + \frac{\partial E}{\partial x} \cdot u + \frac{\partial E}{\partial y} \cdot v \right) = -p \frac{\partial u}{\partial x} - p \frac{\partial v}{\partial y} + \frac{\partial (u \tau_{xx})}{\partial x} + \frac{\partial (u \tau_{yy})}{\partial y} + \frac{\partial (v \tau_{xx})}{\partial x} + \frac{\partial (v \tau_{yy})}{\partial y} + k \left[ \left( \frac{\partial T}{\partial x} \right)^2 + \left( \frac{\partial T}{\partial y} \right)^2 \right] + s_E
\]

[3.2.13]

For the thermal model of disc wingdings, the source term \( s_E \) can be replaced by heat density of the losses \( \dot{Q} \), while there is no work done by surface stress.

### 3.2.2 The Boussinesq approximation

To get a fast convergence in calculation, the Boussinesq model is applied. The fluid density will be treated as a function of temperature. The buoyancy term caused by density variation is only taken into account in the momentum equation but not in other solved equations. In fluid field, the buoyancy can be derived by the Eq. (3.2.1).

\[
g' = \left( \frac{\rho - \rho_0}{\rho} \right) \cdot g
\]

[3.2.14]

where, \( g' \) is the new local acceleration and \( \rho - \rho_0 \) is density difference.

The Boussinesq approximation is established by applying the equation below.

\[
\rho = \rho_0 (1 - \beta \Delta T)
\]

[3.2.15]

From Eq. (3.2.14) and Eq. (3.2.15), the effects of the buoyancy term on the momentum equation can be expressed by Eq. (4.2.16) below.

\[
(\rho - \rho_0)g = -\rho_0 \beta (T - T_0)g
\]

[3.2.16]

Usually speaking, the Boussinesq approximation is valid when \( \beta (T - T_0) << 1 \), in this case \( \beta (T - T_0) \approx 0.03 << 1 \) thus, this approximation can be applied.
3.3 Simplification and assumption

Simplification and assumption have been done in order to simplify the model and make it easier to be implemented and calculated. In addition to the fluid model of oil and the solid model of discs in this case as shown in Figure 3.3.1, a completed geometry model of disc windings includes more structures and details, such as the collar structure, solid insulation layers and the disc internal structures (copper strands). In reality, there are actually some other geometrical characteristics, such as roughness of the internal surface, the rounded angle as well as some other irregular configurations are. However, in this study, the attention should be paid to the domain part of the disc windings and the oil circulating around them, the conditions which may be caused by the factors above can be defined by assumption from experience. For instance, the collar parts were neglected in this study while to define the oil inlet and the oil outlet condition. Other assumption and simplification have also been made listed below to solve this problem.

(a). No solid insulation layers. In order to decrease the complexity and guarantee the grid quality, the solid insulation layers are not created in geometry model. Instead, the insulation property is defined on the interior surface between discs and oil;
(b). Materials inside discs are all assumed as copper material. The detailed internal structures are neglected, instead, all the solid inside are regard as copper. Considering the strands structure which will affect the thermal conductivity distribution, the orthotropic function is applied to describe the equivalent affects;

(c). Oil flow is assumed as laminar flow which is also regard as fully developed. According to previous theoretical analysis, the maximum Reynolds’ number of the oil is far less than 2000, which satisfies the laminar flow requirement. The mineral oil used is the fluid with high Prandtl number which is around 70. Therefore the flow can be considered as fully developed flow. (R.Hosseini, et al., 2008);

(d). For models simulating ON cooling type, the operating temperature is defined as the average temperature of the top oil and the bottom oil of the disc windings. The operating temperature is assumed as the average temperature of the environmental temperature which is assumed to have a linear distribution in outer cooling process;

(e). Mass flow at the inlet is defined as uniform distributed. In reality, considering the boundary layers and the local mass distribution, there should be a profile of the velocity, however, as an initial condition, velocity at the inlet is defined as constant in this model;

(f). Heat loss density is defined as constant. All kinds of heat losses are combined and simplified as constant total heat losses which will be distributed evenly on discs;

(g). Walls except for the walls of the discs are defined as adiabatic walls. This assumption is made to achieve an ideal state without heat dissipation.
4 WINDING MODEL IMPLEMENTATION

4.1 Winding geometry model

The three-dimensional structure of the transformer winding can be approximated by axisymmetry 2D model of the cross-sectional area which can be defined in Fluent. According from the data of a real case, the 2D model was created as shown in Figure 3.3.1, there are 128 disc in the first coil, H is the total height from the bottom disc to the top disc; h is the height of the space between two adjacent discs, d is the width of the vertical duct, l is the disc length in radius direction and r is the inner radius of this layer of windings. The collar structures are not considered in this project and the oil inlet and outlet are defined in the vertical direction. The inlet/outlet configuration, inner side or outer side, are also considered as one of the investigated design parameters, while for a base case the inlet is defined in the inner side and the outlet is defined at the outer side. Other investigated design parameters in geometry include the radial disc width l, the horizontal space height h, the vertical duct width d and the inlet/outlet configuration. Related geometry dimensions investigated in this project are listed in Table 4.1 [ABB internal].
4.2 Grid model

Mesh is one of the most important steps in a CFD calculation. High quality grids could improve the solution. For this case, due to the large scale of the total height and relative small scale in radius dimension, thus, an optimization is needed to get an alternative solution for meshing. There should be a balance between the quantity and the calculation time.

4.2.1 Mesh solution

In this investigation, grids were generated by Ansys mesh tool which is a mesh tool package in Ansys. By defining the number of divisions of edges of the 2D model combing with the mapped type mesh, as Figure 4.2.1 and Table 4.2.1 [ABB Internal] below show, the mesh solution was created. To do a further grid quality sensitivity check, a reference mesh solution was also created.

![Figure 4.2.1 Mesh setting by sizing edges of the 2D model](image)

Even though the high resolution grids can give a precise calculation result, as shown in following part, however, the large quantity of grids increase the computer cost and time cost, which is not applicable in CFD calculation. A compromise between the grids resolution and the cost should be made. An alternative way is to reduce the number of grids in non-sensitive area, such as the solid disc winding, where a low density quad grids can be used instead of high resolution grids. For the fluid field, due to the oil has a high viscosity, the boundary layer near the solid wall should be paid much attention to. The inter-surface between disc windings and oil is actually the heat exchanging surface and the boundary layer generated here has great influence on the heat transfer capacity. Thus, a more refined grids are needed there to be able to capture the fluid phenomenon. (Skillen, et al., 2011) Thus, the bias setting on splitting edges was done. As we can see from Table 4.2.1 above, side B and side E
formed a square frames, which are actually the insulation layers between disc windings and oil flow. On the oil side, the inflation was applied to define the oil grids. That means in the vertical as well as horizontal ducts, near the solid boundary, the grids were defined by bias. As Figure 4.2.2 (b) below shows, the inflation setting in the flow reduced the grids quality sensitivity influence.

The grids generated by these two solutions are shown in Figure 4.2.2 (a) and Figure 4.2.2 (b).

![Figure 4.2.2 Grid models generated](image)

**4.2.2 Grid quality analysis**

A general view of the grid quality has been done by using Ansys Package - Elements Metrics. Before analyzing the result, some key parameters indicating the elements quality are listed below:

- **Element quality**, the ratio of the element volume to the edge length with its value range [0, 1], 0 means the worst quality while 1 means the best quality;
- **Aspect ratio**, set quad grid as example, there are two group of opposite sides, create 2 straight lines connecting the opposite middle point of the sides separately, the aspect ratio is actually the ratio of the longer connected lines to the shorter connected lines. For a normal square grid, the aspect ratio is 1, then, the higher the value, the lower the quality;
- **Jacobian ratio**, the ratio of the maximum to the minimum sampled value of the Jacobian matrix with the best value of 1 and the higher the value, the lower the quality;
- Warping factor, a value shows the height difference between the edge and its projection, 0 means the grid is in one surface and the higher the value, the lower the quality;

- Parallel deviation, in a quadrilateral, an angle can be calculated from the acos function of the dot product of two opposite edges, the highest value is regard as the parallel deviation with a best value of 0;

- Maximum corner angle, the maximum angle of the grid, the best value for triangle is 60 degree, and for the quilateral the best value is 90 degree;

- Skewness, two solutions to calculate the skewness value, Equilateral-Volume-Based Skewness and Normalized Equiangular Skewness. The value range is [0, 1], and the lower the better.

Table 4.2.2 shows the quality statistical results of the element quality, Figure 4.2.3 (a) and Figure 4.2.3 (b) show the quality distribution in column charts. Distributions of other indicators in column are shown in Appendix I [].

Table 4.2.2 Results of quality analysis by Elements Metrics

<table>
<thead>
<tr>
<th>Mesh Solution</th>
<th>Total elements</th>
<th>Elements type</th>
<th>Element quality</th>
<th>Jacobian ratio</th>
<th>Aspect ratio</th>
<th>Warping ratio</th>
<th>Parallel ratio</th>
<th>Maximum corner angle</th>
<th>Skewness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>4168070</td>
<td>Linear Quadrilateral</td>
<td>[1, 1]</td>
<td>[1, 1]</td>
<td>[1, 1]</td>
<td>[0, 0]</td>
<td>[0, 0]</td>
<td>[90, 90]</td>
<td>[0, 0]</td>
</tr>
<tr>
<td>Optimized</td>
<td>1486470</td>
<td>Linear Quadrilateral</td>
<td>[0.151, 0.9995]</td>
<td>[1, 1.054]</td>
<td>[1.001, 13.079]</td>
<td>[0, 0]</td>
<td>[0, 1.2069]</td>
<td>[90, 93.12]</td>
<td>[1.31e-10, 3.46e-02]</td>
</tr>
</tbody>
</table>

![Figure 4.2.3 (a) Quality Distribution in Column Charts](chart.png)
From the statistics of the grids quality, it can be seen that the reference grids model can be regard as a base model with all of its quality in perfect condition. However, due to some bias applied in the optimized grid model, the general quality was decreased, especially for the aspect ratio. That means the bias setting in the grids has caused some irregular quadrilateral grids. However, the elements number of optimized grids is only $\frac{1}{3}$ of the elements number of reference grids. Considering the balance between the time cost and accuracy, the optimized grids was preferred.

A grids sensitivity investigation has been done to prove the feasibility of the optimized grids. And the critical parameters are the hotspot temperature, hotspot location and the number of alternating flow patterns. The results are shown in the following form. From the Table 4.2.3 below, it can be seen that the temperature of these two cases are almost the same, as well as the hotspot location and the number of flow patterns which can indicate the flow situation to some extent. That comparison of the results show that the optimized grids can be regard as equivalent to the refined reference grids for calculation, and are qualified enough to get rid of the influence of the grids. (W.Wu, et al., 2011)

<table>
<thead>
<tr>
<th>Grids Cases</th>
<th>Hotspot temperature (K)</th>
<th>Hotspot location (Disc No.)</th>
<th>Number of flow patterns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>366.3542</td>
<td>124</td>
<td>12</td>
</tr>
<tr>
<td>Optimized</td>
<td>366.3538</td>
<td>124</td>
<td>12</td>
</tr>
</tbody>
</table>
4.3 FLUENT Setting

In Fluent, the material properties, boundary conditions, solver types, solution methods and monitors are defined. Settings can be seen in Appendix II [ABB Internal]. In General settings the axisymmetry model is selected in order to consider the 3D characteristics in real case. The axis of this model is X axis, thus, the gravity is defined in the opposite X direction. To define materials of the model, materials of oil, strands and insulation-layers are defined. In order to approximate the ON cooling type, the operating temperature is defined as the average temperature of the top oil and bottom temperature.

Boundary conditions are defined in zones of the model. For base case study and mass flow rate sensitivity investigation, the oil inlet is defined as mass flow inlet and the oil outlet is defined as pressure outlet. The insulation layers around the discs are defined by giving the thickness and the thermal conductivity with the material of insulation layers.
5 BASE CASE STUDY

The base case study was conducted in order to get a general view of the non-guide winding which is close to real case. A primary understanding of the physical models and the process can be gained. In addition, the result of the base case can be applied for the reference of other parametric studies.

5.1 Base case setup

Data from a real case can be seen in Table 5.1 [ABB Internal]. According to these data, calculations are performed to get the initial condition and the boundary condition.

5.1.1 Estimation of initial condition

![Figure 5.1.1 Configuration of disc windings](image)

- **Oil inlet mass flow rate**

In a steady state, the heat losses generated in discs is taken away by oil flow. An energy balance can be achieved as shown in Eq. (5.1).

\[ Q = m \times C_p \times \Delta T \]  

[5.1]
where \( Q \) is the heat losses; \( \Delta T \) is the temperature difference between bottom oil inlet and top oil outlet; \( m \) is the average mass flow rate; \( C_p \) is the specific heat of transformer oil.

Then, the inlet mass flow rate can be calculated as:

\[
m = \frac{Q}{C_p \cdot \Delta T} = \frac{155784}{2055 \times 32} = 1.237065 \text{ kg/s}
\]

**Heat density of strands**

In this case, the heat loss density of the strands in the discs is assumed as constant (Taghikhani & A.Gholami, 2009). Number of the discs is 128. Without considering the spiral profile of winding, the volume of the disc winding can be calculated as below:

Volume per disc winding:

\[
V_{each} = \pi \cdot (R_2^2 - R_1^2) \cdot h = 2368373.902 \text{ mm}^3
\]

Volume of total disc winding:

\[
V_{total} = 128 \cdot \pi \cdot (R_2^2 - R_1^2) \cdot h = 303151859.4 \text{ mm}^3 = 0.30315186 \text{ m}^3
\]

Thus, the heat density should be revised as:

\[
Q = \frac{63300}{0.303152} = 208806.1435 \text{ W/m}^3
\]

**5.1.2 Base case setting**

The base case simulation was set up with the inlet mass flow rate of 1.237 kg/s and uniform distribution in the inlet. The heat density of the inner strands in disc windings is defined as 208806.1435 W/m³ with uniform distribution in windings as well. In order to approximate the ON cooling type, the operating temperature is set as 334.7 K which is the average temperature of the bottom oil temperature and the top oil temperature. The outlet of the oil duct is defined as pressure outlet. Firstly, a steady state calculation was done to see the general scenario and phenomenon. Then, due to the unstable solution, a time dependent calculation was performed.
5.2 Base case analysis

5.2.1 Steady state solution

In the real calculation process for steady state, the solution did not converge well by monitoring the residual plot. A monitor of hotspot was set up to be another indicator of the convergence. That means, when the temperature of hotspot did not change by iterations, this solution can be regard as converged to some extent.

During the calculation process, after about 50000 iterations, the temperature of hotspot approach a steady state value but with a small fluctuation added (per iteration step) with small amplitude. By estimation, the variation of hotspot temperature is [365.7 K, 366.9 K], as shown in Figure 5.2.1.

![Figure 5.2.1 Hotspot as a function of iterations](image)

![Figure 5.2.2 Velocity and temperature distribution in disc windings](image)
The velocity distribution of the oil and temperature distribution on disc windings are shown in Figure 5.2.2. Here, the color of contour on discs stands for the temperature level while the color in ducts shows the velocity magnitude.

From the temperature distribution on the disc windings in Figure 5.2.2, it is clear that the temperature increases from bottom to the top of the total winding. This is caused by the fact that the thermal losses in the discs the oil heats up while travelling from the bottom to the top. The highest temperature appeared in the top area, but not the very top disc. The alternating flow patterns appeared in the ducts around windings. The oil goes into the ducts from the bottom inlet and up in the inner vertical ducts. After a certain distance, the oil passes through the horizontal ducts from inner side of the vertical duct to the outer side and continues to go up in the outer vertical duct. Then, after another distance, the oil flow comes back by pass through the horizontal ducts. These movements repeat until the oil reaches the top outlet. The number of flow patterns is 12 and divides the total height into 12 sections. Between each section, there are critical horizontal ducts in which the flow changes its direction. Figure 5.2.3 shows a scope of one of the critical horizontal ducts between disc 29th and disc 30th. The color of the contour shows the temperature distribution and the vectors show the velocity distribution.

![Figure 5.2.3 oil flow and temperature distribution near adjacent sections](image)

In Figure 5.2.3, the vector shows the velocity in y direction. It can be seen that the flow from both inner duct and outer duct encounter in the horizontal duct between disc 29th and disc 30th. Due to the collapse, the velocity of the flow in y direction becomes low. However, in the
adjacent left and right ducts, the velocity in y direction is higher. And from the left adjacent ducts, it can be seen that the farther the ducts away from the critical duct, the higher the velocity. A higher oil flow velocity yields higher local heat transfer coefficient and better cooling to the discs.

Generally speaking, the maximum temperature of each disc increases from bottom to the top. However, the global distribution of temperature may be affected by the oil flow distribution which may be not evenly in each section. Thus, an investigation of the maximum temperature on each disc was done with the results shown in Figure 5.2.4.

![Figure 5.2.4 Maximum temperature of disc from bottom to top](image)

The red points stand for the highest temperature of each disc and the blue points stand for the average temperature of each disc. It can be seen that the temperature goes up from bottom to the top not linearly but wave-like. Especially for the beginning, there is a large wave peak, and the wave becomes more even. The highest temperature of all the discs appeared on the 124th disc, but not the top disc. The temperature distribution is actually caused by the oil flow distribution in the windings. As seen from Figure 5.2.2, the wave-like distribution of the temperature has a close relation with the velocity distribution of the oil. In the top section, the velocity near the outlet is high, which will lead to high local horizontal velocities and enhance the local heat transfer coefficient to lead to a good cooling effect. That is why the hotspot does not lay on the 128th disc.
However, the temperature seems not stable when the calculation was finished. In addition to the value of hotspot, the location was also captured as a function of iterations. An effective prediction of the location of the hotspot can help engineers modify the design.

When the hotspot temperature becomes oscillating, 20 hotspot points were detected every 300 iterations in the solution. The locations of these points are shown in Figure 5.2.5.

![Figure 5.2.5 Locations of hotspot as a function of iterations](image)

As Figure 5.2.5 shows, among these 20 points, 18 points were located on disc 124 and only 2 points were located on disc 125. The oil distribution corresponding to these two cases also
investigated in as Figure 5.2.6 shows. The top figure is oil velocity distribution and the bottom figure is the temperature distribution.

### 5.2.2 Time dependent solution

See from the results of steady state solution simulation, it is clear that the solution is close but not exactly at a steady state. Thus, a time dependent solution is appropriate to be performed. Adaptive time step size is adopt to assure a suitable Courant number and the total calculation time is 1500 s. Monitor of the hotspot temperature is set up. The variation of the winding hotspot temperature as a function of time is shown in Figure 5.2.7.

![Figure 5.2.7 Temperature of hotspot as a function of time](image)

Figure 5.2.7 shows that the hotspot temperature has a fluctuation with a range of \([364.9 \text{ K}, 365.5]\) which is a very small fluctuation. Time for 1 fluctuation period is about 120s. To see more details, the first period of the variation is taken out and analyzed. Figure 5.2.8 shows the variation of temperature in 1 period and 12 points in this period are marked. Data of these 12 points detected are listed in Table 5.2.

#### Table 5.2 Data of 12 points in 1 fluctuation period

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (K)</td>
<td>365.946</td>
<td>365.781</td>
<td>365.603</td>
<td>365.517</td>
<td>365.53</td>
<td>365.421</td>
</tr>
<tr>
<td>X (mm)</td>
<td>17.7</td>
<td>17.7</td>
<td>17.7</td>
<td>16.49</td>
<td>16.49</td>
<td>16.49</td>
</tr>
<tr>
<td>Y (mm)</td>
<td>6.57</td>
<td>7.3</td>
<td>7.79</td>
<td>8.03</td>
<td>6.57</td>
<td></td>
</tr>
<tr>
<td>Time (s)</td>
<td>70</td>
<td>80</td>
<td>90</td>
<td>100</td>
<td>110</td>
<td>120</td>
</tr>
<tr>
<td>Temperature (K)</td>
<td>365.551</td>
<td>365.727</td>
<td>365.769</td>
<td>365.913</td>
<td>365.912</td>
<td>365.756</td>
</tr>
<tr>
<td>X (mm)</td>
<td>17.7</td>
<td>17.7</td>
<td>17.7</td>
<td>16.49</td>
<td>18.99</td>
<td>17.7</td>
</tr>
<tr>
<td>Y (mm)</td>
<td>6.81</td>
<td>6.81</td>
<td>2.64</td>
<td>2.69</td>
<td>6.57</td>
<td>7.3</td>
</tr>
</tbody>
</table>
By marking the location of these points on winding disc according to the data in Table 5.2, all of these points stay on disc 125. To see the phenomenon of the unstable oil flow and temperature variation, the related animations about the hotspot area were done. The animation shows that the oil flow is oscillating in ducts on the top of the disc winding. The time for 1 period is about 120 s. The temperature on the disc winding changes only marginally. It can be seen from above result that the time dependent solution is close to a steady state. The hotspot temperature fluctuation at the top of windings are caused by the oscillatory oil flow rate, however, this fluctuation has small effects on hotspot position and strength. Thus, it can be concluded that the steady state gives a reasonable approximation on the thermal behavior in this case.
6 PARAMETRIC STUDIES

6.1 Radial disc width sensitivity investigation

Disc width is the radial length of the disc windings as shown in Figure 6.1.1. Assume heat
density of the strands inside the windings as well as other parameters are constant, as
calculated before, the disc width will determine the total heat loss which is proportional to the
volume of the disc windings. That means the change of disc width is the only reason leads to
the change of corresponding geometry while other initial conditions and boundary conditions
are kept constant. 8 cases with the disc length from 15 mm to 50 mm with the interval of 5
mm are studied.

Figure 6.1.1 Disc length in radial direction

To get a general view of the influence with different disc length, the steady state simulations
were performed firstly. Then, some points were calculated by transient solver to see more
details of the oil velocity distribution and the temperature distribution. It is assumed that the
heat density of the strands is constant, which means the winding loss increases with radial
width. In this case, in order to see effects caused by the change of total heat loss, the inlet
mass flow rate should be defined as pressure based instead of a fixed value. Thus, the
boundary condition of the oil inlet here is defined as pressure inlet. The operating
temperature is defined with the average temperature of the top oil temperature and the
bottom oil temperature to approximate the ON cooling type.

Table 6.1 shows the results of steady state simulation. The temperature of hotspot as well as
the mass flow rate of the oil increase when the disc length increases. The number of oil flow
patterns decreased while the hotspot location varied with a little decrease trend. Figure 6.1.2 shows the increase of the hotspot temperature.

Table 6.1 Results of disc length sensitivity study

<table>
<thead>
<tr>
<th>Disc Length L (mm)</th>
<th>Hotspot Temperature (K)</th>
<th>Hotspot Location (Disc No.)</th>
<th>Number of Flow Patterns</th>
<th>Mass Flow Inlet (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>360.9</td>
<td>127</td>
<td>18</td>
<td>0.42</td>
</tr>
<tr>
<td>20</td>
<td>362.9</td>
<td>126</td>
<td>16</td>
<td>0.55</td>
</tr>
<tr>
<td>25</td>
<td>364.4</td>
<td>125</td>
<td>16</td>
<td>0.69</td>
</tr>
<tr>
<td>30</td>
<td>366.3</td>
<td>126</td>
<td>14</td>
<td>0.82</td>
</tr>
<tr>
<td>35</td>
<td>368.5</td>
<td>124</td>
<td>14</td>
<td>0.93</td>
</tr>
<tr>
<td>41</td>
<td>370.4</td>
<td>124</td>
<td>12</td>
<td>1.03</td>
</tr>
<tr>
<td>45</td>
<td>371.9</td>
<td>125</td>
<td>12</td>
<td>1.16</td>
</tr>
<tr>
<td>50</td>
<td>372.3</td>
<td>125</td>
<td>10</td>
<td>1.29</td>
</tr>
</tbody>
</table>

Figure 6.1.2 Temperature of hotspot under different disc length

Detailed results of the Case with the disc length of 15 mm are analyzed. Figure 6.1.3 and Figure 6.1.4 show the velocity distribution of the oil flow and the temperature distribution on disc windings. Figure 6.1.3 shows that the alternating flow patterns appeared in the oil ducts. The vertical oil ducts can be divided into many sections. The stagnation of the oil in the ducts seems some oil guides in oil guide situation. According to the temperature distribution on the disc windings, the hotspot temperature appeared on the top sections but not the top disc, on
disc 127 instead. The final temperature of hotspot is 360.9k. However, the steady-state calculation result is not stable with a fluctuation in the end, as shown in Figure 6.1.5, which makes it necessary to do a time dependent simulation to see more details.

Figure 6.1.3 Velocity distribution of oil flow

Figure 6.1.4 Distribution of Temperature on disc winding
The transient solver was applied to run the time dependent simulation for the case with the disc length of 15 mm and a total time of 500s was defined. The initial condition is from the steady state calculation result. The hotspot variation as function of time is shown in Figure 6.1.5. It can be seen that when the solution converged, the hotspot fluctuation become periodical. The hotspot range can be estimated as $[360.0 \text{ K}, 360.4 \text{ K}]$ consequently the hotspot variation due to the time-dependent effects is only minor. The fluctuating period is about 80 s.

To see the variation of the oil flow, 2 probe points were set up to monitor the velocity in the vertical ducts near hotspot disc 127. The velocity variations of these 2 points as a function of time are shown in Figure 6.1.6.
time are shown in Figure 6.1.7 and Figure 6.1.8. The variation process of the velocity in outer ducts is opposite to the variation in inner vertical duct. From the animation of the oil flow, it can be seen that the oil flow is an alternating oil flow and the time of 1 period is about 80 s.

The variation process of the velocity in outer vertical duct is opposite to the variation in inner vertical duct. From the animation of the oil flow, it can be seen that the oil flow is an alternating oil flow and the time of 1 period is about 80 s.

The above simulation results prove that in this time dependent case, oil flow would oscillate in the ducts with a circulating period of 80s. The temperature of the hotspot can be expressed as [360.0 K, 360.4 K]. The location of hotspot in the time dependent case was also studied. However, the calculated error of the temperature in time dependent case is less than 5%, which can be regard as approximation to the steady state calculation results.
By similar way, another 3 time dependent investigations were performed with the disc length of 25 mm, 35 mm and 45 mm. The comparison between steady state and time dependent are shown in Table 6.2. The variation of hotspot temperature with in cases with disc length of 15mm, 25mm, 35mm and 45mm are shown in Figure 6.1.9.

Table 6.2 Comparison of results of steady state and transient simulation

<table>
<thead>
<tr>
<th>Disc Width ( l ) (mm)</th>
<th>Hotspot of Steady State ((K))</th>
<th>Location of Steady State (Disc. No)</th>
<th>Hotspot of Transient ((K))</th>
<th>Location of Transient (Disc. No)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>360.9</td>
<td>127</td>
<td>[360.0, 360.4]</td>
<td>[126,127]</td>
</tr>
<tr>
<td>25</td>
<td>364.4</td>
<td>125</td>
<td>[363.8, 364.4]</td>
<td>[125,127]</td>
</tr>
<tr>
<td>35</td>
<td>368.5</td>
<td>124</td>
<td>[368.4, 369.8]</td>
<td>[125,127]</td>
</tr>
<tr>
<td>45</td>
<td>371.9</td>
<td>125</td>
<td>[370.1, 371.0]</td>
<td>[124,127]</td>
</tr>
</tbody>
</table>

Figure 6.1.9 Comparison of hotspot temperature of steady state and transient solution

The blue bars indicate the temperature range of hotspot as a function of time in transient simulation. The red points are the hotspot temperature from steady state simulation. It can be seen that in cases with the disc length of 15 mm, 25 mm, 35 mm and 45 mm, the temperature of hotspot from steady state calculation are higher than the temperature range from time dependent simulation. When disc length increases, the range of hotspot temperature will be increases at the same time.
From these phenomenon above, a primary conclusion can be made that the when the initial inlet/outlet condition, the uniform heat density of the disc windings and the operating condition are fixed, the increase of the radial disc width will also increase the hotspot temperature. In this ON cooling type, the oil mass flow will be increased, while the number of flow patterns will decrease. In addition, seen from the result of steady state solution and time dependent solution, the steady state model can give a conservative estimate of the hotspot temperature.

6.2 Mass flow rate sensitivity investigation

In this investigation, the mass flow rate is considered as an independent variable, while other parameters are maintained. Different mass flow rate may cause different oil flow distributions which have a close relation with the global and local heat transfer coefficient. The critical indicators, temperature of hotspot and location of hotspot would be detected. A general effect will be described.

The results of a series of design points with different inlet mass flow rate were listed in Table 6.2. 26 points with inlet mass flow rate from 0.5 kg/s to 3 kg/s were studied.

According to data in Table 6.2, the relation between hotspot temperature and mass flow rate in this investigation are shown in Figure 6.2.1. It can be seen that when the inlet mass flow rate is increased from 0.5 kg/s to 0.7 kg/s, the hotspot temperature increases. However, when the inlet mass flow rate continues increase from 0.7 m/s to 2 kg/s, the hotspot temperature decreases. After that when the inlet mass flow rate is increased from 2 kg/s to 3 kg/s, the hotspot temperature fluctuated with a rise trend. From the hotspot temperature distribution in Figure 6.2.1, it seems there is an optimal inlet mass flow rate at which the hotspot temperature can be the lowest and this value is around 2 kg/s.

When the inlet mass flow rate is changed, most of the hotspot location varies from the 124th disc to the 127th disc. With the inlet mass flow rate is 0.5 and 0.6 kg/s, the location of the hotspot stays on the 119th disc and the 117th disc separately. Especially for the case with the inlet mass rate of 2 kg/s, the hotspot location moves to the 17th disc. By now, the variation of the hotspot cannot be predicted exactly. The study of the case with the mass flow rate of 2 kg/s is studied in following part.
An obvious phenomenon can be seen that when the inlet mass flow rate increases, the number of flow patterns will decrease. By analyzing the base case, it is clear that the mass flow will pass through the horizontal ducts to the other vertical duct due to the pressure difference between the two sides. This phenomenon happens when the oil flow has zero velocity in vertical direction. The higher inlet mass flow rate would lead to a higher inlet velocity, according to Newton’s second law, the distance from the initial velocity to zero velocity in vertical ducts will be longer. That makes the distance of 1 alternating flow is longer than the case with low inlet mass flow rate.

![Figure 6.2.1 Hotspot temperature as a function of inlet mass flow rate](image1)

![Figure 6.2.2 Hotspot temperature in time dependent solution](image2)
Table 6.3 Results of mass flow rate sensitivity investigations

<table>
<thead>
<tr>
<th>Mass Flow Inlet (kg/s)</th>
<th>Hotspot Temperature (K)</th>
<th>Hotspot Location (Disc No.)</th>
<th>Number of Flow patterns</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>372.5</td>
<td>119</td>
<td>21</td>
</tr>
<tr>
<td>0.6</td>
<td>377.7</td>
<td>117</td>
<td>20</td>
</tr>
<tr>
<td>0.7</td>
<td>383.1</td>
<td>126</td>
<td>16</td>
</tr>
<tr>
<td>0.8</td>
<td>378.9</td>
<td>125</td>
<td>14</td>
</tr>
<tr>
<td>0.9</td>
<td>375.3</td>
<td>126</td>
<td>13</td>
</tr>
<tr>
<td>1</td>
<td>371.9</td>
<td>124</td>
<td>12</td>
</tr>
<tr>
<td>1.1</td>
<td>369.4</td>
<td>125</td>
<td>12</td>
</tr>
<tr>
<td>1.25</td>
<td>367.7</td>
<td>124</td>
<td>12</td>
</tr>
<tr>
<td>1.3</td>
<td>366.5</td>
<td>126</td>
<td>11</td>
</tr>
<tr>
<td>1.4</td>
<td>363.1</td>
<td>125</td>
<td>10</td>
</tr>
<tr>
<td>1.5</td>
<td>363.8</td>
<td>126</td>
<td>11</td>
</tr>
<tr>
<td>1.6</td>
<td>360.4</td>
<td>124</td>
<td>10</td>
</tr>
<tr>
<td>1.7</td>
<td>363.4</td>
<td>127</td>
<td>10</td>
</tr>
<tr>
<td>1.8</td>
<td>360.7</td>
<td>124</td>
<td>10</td>
</tr>
<tr>
<td>1.9</td>
<td>360.4</td>
<td>127</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>358.3</td>
<td>17</td>
<td>8</td>
</tr>
<tr>
<td>2.1</td>
<td>361.2</td>
<td>124</td>
<td>8</td>
</tr>
<tr>
<td>2.2</td>
<td>360.1</td>
<td>125</td>
<td>8</td>
</tr>
<tr>
<td>2.3</td>
<td>362</td>
<td>125</td>
<td>8</td>
</tr>
<tr>
<td>2.4</td>
<td>360.3</td>
<td>21</td>
<td>8</td>
</tr>
<tr>
<td>2.5</td>
<td>364.6</td>
<td>116</td>
<td>8</td>
</tr>
<tr>
<td>2.6</td>
<td>367.3</td>
<td>120</td>
<td>6</td>
</tr>
<tr>
<td>2.7</td>
<td>362.4</td>
<td>25</td>
<td>6</td>
</tr>
<tr>
<td>2.8</td>
<td>366.9</td>
<td>122</td>
<td>5</td>
</tr>
<tr>
<td>2.9</td>
<td>366</td>
<td>123</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>363.4</td>
<td>28</td>
<td>5</td>
</tr>
</tbody>
</table>
Table 6.4 Results of time dependent solution with different mass flow rate

<table>
<thead>
<tr>
<th>Mass flow rate (kg/s)</th>
<th>Hotspot of Steady State (k)</th>
<th>Location of Steady State (Disc. No)</th>
<th>Hotspot of Transient (k)</th>
<th>Location of Transient (Disc. No)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>371.9</td>
<td>124</td>
<td>[371.1, 372.0]</td>
<td>[124,126]</td>
</tr>
<tr>
<td>1.5</td>
<td>363.8</td>
<td>126</td>
<td>[360.5, 364.0]</td>
<td>[123,126]</td>
</tr>
<tr>
<td>2</td>
<td>358.3</td>
<td>17</td>
<td>[356.8, 358.4]</td>
<td>17 &amp; [123, 127]</td>
</tr>
<tr>
<td>2.5</td>
<td>364.6</td>
<td>116</td>
<td>[359.0, 364.6]</td>
<td>[22,24]</td>
</tr>
</tbody>
</table>

Preliminary investigation is based on steady state solution, which, even though can give a general view of the thermal performance, however, cannot describe the flow exactly. Thus, time dependent solution was applied for 4 cases with different mass flow rate, 1 kg/s, 1.5 kg/s, 2 kg/s and 2.5 kg/s. Table 6.4 shows the results of time dependent solution and Figure 6.2.2 shows the hotspot temperature as a function of mass flow rate. The blue bars stand for the hotspot range in time dependent solution and the red points stand for the steady state solution. It can be seen that the hotspot range are different with different mass flow rate, while follows the steady state results. As seen from Figure 6.2.4 to Figure 6.2.7, the location of hotspot moved to the bottom sections of the disc windings with the mass flow rate of 2 kg/s and 2.5 kg/s. This affects can be seen more clearly in Figure 6.2.3 which shows the temperature distributed along a middle line crossing the discs from the bottom to the top vertically. It can be seen that along the middle line, the temperature shows a wave-like increase tendency. Each temperature wave peak on the line is corresponding to a hot area and the highest peak can generally describe the hotspot. When the mass flow rate is 2 kg/s, the bottom temperature wave peak may increase to be higher than the top wave peaks. When the mass flow rate is 2.5 kg/s, the bottom temperature wave peaks will be totally higher than the top wave peaks. At the same time, when the mass flow rate increase, the number of the waves (alternating flow patterns) would also decrease.
The conclusion can be drawn that the hotspot temperature does not decrease with mass flow rate, instead, with the mass flow rate from 0.5 kg/s to 3 kg/s, the hotspot temperature will decrease first and then increase; the steady-state model can give a conservative estimate of hotspot. Generally speaking, the hotspot temperature as well as the location of both steady-state model and time dependent model has close value and similar varied tendency; In these four cases, with the mass flow rate increases from 1 kg/s to 2.5 kg/s, the position of the hotspot is highly variable, there are many local hotspots that are approximately equally strong.
Figure 6.2.4 Location of hotspot with the mass flow rate inlet of 1 kg/s
(Cut off temperature is 371.1 K)

Figure 6.2.5 Location of hotspot with the mass flow rate inlet of 1.5 kg/s
(Cut off temperature is 360.25 K)
Figure 6.2.6 Location of hotspot with the mass flow rate inlet of 2 kg/s
(Cut off temperature is 356.7 K)

Figure 6.2.7 Location of hotspot with the mass flow rate inlet of 2.5 kg/s
(Cut off temperature is 358.5 K)
6.3 Horizontal space height sensitivity investigation

Horizontal duct height is the space height between every 2 disc windings. In this 2D geometry, as shown in Figure 6.3.1, it is the channel between 2 adjacent discs. According to previous study by others, this parameter will affect the final result as well. In this investigation, 6 design points of the space height were studied from 2mm to 7 mm with an interval of 1 mm.

![Horizontal height in 2D cross-sectional model of disc winding](image)

Table 6.5 shows the hotspot temperature, the hotspot location and the number of flow patterns in cases with different horizontal duct height. It can be seen that when we increase the horizontal duct height from 3 mm to 7 mm, the hotspot will not change much as well as the hotspot location and the number of flow patterns. The points of the temperature are shown in Figure 6.3.2. In these 5 points, when the horizontal ducts height is 4 mm, the temperature of the hotspot is the lowest one in these five. However, when the horizontal height is set to 2 mm, the result seems quite different from other cases, the solution is quite unstable. A detailed study will be shown in following parts.

<table>
<thead>
<tr>
<th>Horizontal duct height (mm)</th>
<th>Hotspot temperature (K)</th>
<th>Hotspot location (Disc No.)</th>
<th>Number of Flow Patterns</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>359.5</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>3</td>
<td>367.3</td>
<td>120</td>
<td>12</td>
</tr>
<tr>
<td>4</td>
<td>364.7</td>
<td>123</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td>365.6</td>
<td>125</td>
<td>12</td>
</tr>
<tr>
<td>6</td>
<td>366.3</td>
<td>124</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>367.2</td>
<td>124</td>
<td>12</td>
</tr>
</tbody>
</table>
For the case with the horizontal duct height of 2mm, the time dependent solution was applied. Due to the time limitation, combined with estimation, the primary time step size was set 1s at first. Thus, this solution can only give a general view hotspot variation. Figure 6.3.3 shows the variation of the hotspot temperature in 1000s. 10 points every 100s were marked on the variation line. The temperature and hotspot location are captured and listed in Table 6.6. The locations of these 10 points are shown in Figure 6.3.4 in which the red area stands for the hotspot area. It can be seen that from the beginning to the end, the hotspot temperature has a wave-like fluctuation. The amplitude becomes smaller and smaller while the wave length decrease at the same time. The hotspot location varied between disc 110 and disc 124, as Figure 6.3.4 shows. From Figure 6.3.3, the first wave length is about 600s with the amplitude of about 5°C, the last wave length is only about 200 s with the amplitude of 1°C. However, this line cannot show a clear discipline. Thus, another two solutions with smaller time step size were applied to do new simulations for time between point 0 to 3 and point 4 to 5.

Table 6.6 Temperature and hotspot location of 10 points in 1000 s

<table>
<thead>
<tr>
<th>Point No.</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disc No.</td>
<td>123</td>
<td>124</td>
<td>123</td>
<td>123</td>
<td>105</td>
<td>110</td>
<td>107</td>
<td>106</td>
<td>116</td>
<td>120</td>
<td>119</td>
</tr>
<tr>
<td>Hotspot (K)</td>
<td>356.3</td>
<td>354.9</td>
<td>354.4</td>
<td>353.8</td>
<td>354.1</td>
<td>357.1</td>
<td>358.1</td>
<td>356.2</td>
<td>357.4</td>
<td>357.2</td>
<td>356.9</td>
</tr>
</tbody>
</table>
Figure 6.3.3 Variation of hotspot temperature in 1000 s

Figure 6.3.4 Locations of hotspot in 1000 s

The section between point 0 and point 3 in previous was studied with smaller time steps of 0.1 s. The total time is 200 s.

Table 6.7 Temperature and hotspot location of 10 points in 200 s

<table>
<thead>
<tr>
<th>Point No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disc No.</td>
<td>123</td>
<td>124</td>
<td>123</td>
<td>125</td>
<td>125</td>
<td>123</td>
<td>124</td>
<td>124</td>
<td>123</td>
<td>122</td>
</tr>
<tr>
<td>Hotspot (K)</td>
<td>356.6</td>
<td>356.3</td>
<td>355.9</td>
<td>355.2</td>
<td>354.8</td>
<td>354.3</td>
<td>353.9</td>
<td>353.7</td>
<td>353.6</td>
<td>353.6</td>
</tr>
</tbody>
</table>
During this time, the hot spot temperature decreases from 356.6 k to 353.6 k. 10 points on this line are investigated and the related data including hotspot value as well as its location are listed in Table 6.7. It is clear that in this period, hotspot temperature has a trend of decrease. However, from point 3 to 4, the temperature has a peak value. From Table 6.7, it is can be seen that the hotspot of the points stay around disc 122 to 125. By animating the process in 200s, it is clear that the oil flow inside the ducts oscillates while the temperature distribution on disc varied as well.

From point 4 to point 5 in Figure 6.3.5, the temperature of hotspot increases in following 100s. Another solution with smaller time step size of 0.008s was performed in this time period to see more details and validate the increase trend. Table 6.8 shows the temperature and the location of hotspot of 7 points distributed evenly in this time period. Figure 6.3.6 shows the variation of the temperature.

Table 6.8 Temperature and hotspot location of 10 points in 50 s

<table>
<thead>
<tr>
<th>Point No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disc No.</td>
<td>109</td>
<td>113</td>
<td>108</td>
<td>112</td>
<td>107</td>
<td>107</td>
<td>108</td>
</tr>
<tr>
<td>Hotspot (K)</td>
<td>354.3</td>
<td>354.5</td>
<td>354.8</td>
<td>355.4</td>
<td>355.8</td>
<td>356.1</td>
<td>356.2</td>
</tr>
</tbody>
</table>
A conclusion can be drawn that the case with the horizontal height of 2 mm has a very unstable solution. The oil flow inside the ducts has a strong oscillation which will change the temperature distribution on discs. This phenomenon may make it difficult to predict the hotspot in real case. By analyzing current results, it is difficult to get a clear variation about the hotspot temperature and its location, however, it can be estimated that the oscillating period is larger than 1000 s according to the variation of the hotspot location. Thus, a solution with longer time and more suitable time step size is needed to do to validate the estimation.

Figure 6.3.6 Variation of hotspot temperature from 400 s to 450 s
6.4 Vertical duct width sensitivity investigation

Vertical duct width is the width between the vertical surfaces of discs to the isolating wall. In this 2D model it is the vertical duct as shown in Figure 6.4.1. This geometry parameter will affect the oil flow distribution. In this investigation, for simplification, both the inner vertical duct width and the outer vertical duct width as assumed as equal. Other boundary conditions, such as mass flow rate inlet, heat density of the strands as well as other geometry parameters are all assumed the same. 5 design points with the width from 4mm to 12 mm were studied.

![Vertical duct width in 2D disc winding](image)

The temperature of the hotspot and related location are listed in Table 6.9. The width of the vertical increase from 4 mm to 12 mm, while the temperature of the hotspot increase from 382.6 K to 365.9 K. As Figure 6.4.2 shows, from the case with 4 mm width to the case with 6 mm width, the temperature of hotspot decrease dramatically while from the case with 6 mm width to the case with 12 mm width, the temperature of the hotspot decrease tardily. The locations of hotspot are all in the top sections except for the case with width of 6 mm, which has the location of the hotspot far away from the top. When the width of the vertical duct increases from 4 mm to 12 mm, the number of flow patterns increase from 5 to 12. That gives us a primary conclusion that in addition to the mass flow rate sensitivity, the vertical duct width also has positive affect to the number of flow patterns.
Table 6.9 Results of the investigation on the sensitivity of the vertical duct width

<table>
<thead>
<tr>
<th>Width of vertical duct (mm)</th>
<th>Hotspot Temperature (K)</th>
<th>Hotspot Location (Disc No.)</th>
<th>Number of Flow patterns</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>382.6</td>
<td>126</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>369.6</td>
<td>107</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>368.7</td>
<td>123</td>
<td>10</td>
</tr>
<tr>
<td>10</td>
<td>366.3</td>
<td>124</td>
<td>12</td>
</tr>
<tr>
<td>12</td>
<td>365.9</td>
<td>125</td>
<td>12</td>
</tr>
</tbody>
</table>

Figure 6.4.2 Temperature of hotspot in cases with different vertical duct width
6.5 Inlet/Outlet configuration sensitivity investigation

The 2D model applied in this investigation is axis-symmetry model, which means that the initial inlet velocity in inner vertical duct and outer vertical duct are different. In this case, the oil inlet configuration, such as inlet in inner side or outer side, may affect the oil flow distribution and the cooling effects (Zhang & Li, 2006). This makes sense to do an investigation on sensitivity of inlet/outlet configuration.

![Figure 6.5.1 Four types of Inlet/Outlet configurations](image)

There are 4 types of configurations of inlet/outlet, shown in Figure 6.5.1 (a), (b), (c) and (d), inlet in inner side with outlet in outer side, inlet in inner side with outlet in inner side, inlet in outer side with outlet in inner side and inlet in outer side with outlet in inner side. The inlet mass flow rate and other boundary conditions are all assumed the same. The results of the solution are shown in Table 6.10.

<table>
<thead>
<tr>
<th>Inlet/Outlet Type</th>
<th>Hotspot Temperature (K)</th>
<th>Hotspot Location (Disc No.)</th>
<th>Number of Flow patterns</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>366.6</td>
<td>124</td>
<td>12</td>
</tr>
<tr>
<td>(b)</td>
<td>368.2</td>
<td>126</td>
<td>12</td>
</tr>
<tr>
<td>(c)</td>
<td>366.9</td>
<td>127</td>
<td>12</td>
</tr>
<tr>
<td>(d)</td>
<td>366.2</td>
<td>127</td>
<td>12</td>
</tr>
</tbody>
</table>

It can be seen that type (a), (c) and (d) have similar hotspot temperature, the difference is that in type a, the hotspot appeared on disc 124, while in type c and d, the hotspot appeared
on disc 127. For type (b), the hotspot temperature is higher than other types with the hotspot location on disc 126. The variation of the hotspot location of these 4 cases is not very clear. The reason may be that the solution applied is as stable as assumed, thus, the results would fluctuate. However, it is clear that all of the results from these 4 types have the same number of flow patterns. That means that inlet/outlet configuration of inlet/outlet types does not have sensitivity to the number of flow patterns.
6.6 Oil guided case investigation

Oil guided disc windings have blocks (guides) placed between discs. To get an optimal cooling effect, the number of oil guides cannot be too few or too many. Too few guides cannot play the role in improving the oil flow distribution while too many guides will increase the pressure drop which will counteract the inlet mass flow. Thus, there should be an optimal number of guides for an optimal cooling effect.

In the base case study of non-oil guide model, 12 alternating flow patterns appeared, in order to conduct a comparison of the performance between oil guided case and non-oil guided case, the guides are created in vertical ducts in the 2D model at places where the stagnation oil appeared in the simulation without oil guides. The number of oil guides is not optimized. The number of blocks is 12 and the material properties of oil guides are shown in Table 6.11. Except for adding solid blocks, all other parameters and settings are maintained with non-oil guide case. Solution of steady state is applied for oil guide case according to empirical method. The pressure drop of the disc windings should be considered, thus, instead of mass flow inlet, the boundary condition is defined as pressure inlet with the temperature of 322.25 K, while the boundary condition of outlet is maintained as pressure outlet with the temperature of 347.15 K. To approximate the ON cooling mode, the operating temperature is estimated as the average temperature of the top oil and the bottom oil, which is 334.7 K.

Table 6.11 Properties of guide materials

<table>
<thead>
<tr>
<th>Property</th>
<th>Method</th>
<th>Values</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>constant</td>
<td>1000</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Cp (Specific Heat)</td>
<td>constant</td>
<td>1000</td>
<td>J/kg-k</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>constant</td>
<td>0.3</td>
<td>W/m-k</td>
</tr>
</tbody>
</table>

The steady state solution converged well. As shown in Figure 6.6.1, the maximum temperature of the discs, which can be regard as the hotspot temperature, reaches the value of 365.76 K and becomes stable. The oil velocity distribution and temperature distribution of the top three sections are shown in Figure 6.6.2 and 6.6.3.
Figure 6.6.1 Hotspot temperature monitored in solution

Figure 6.6.2 Oil velocity distribution of the top 3 sections

Figure 6.6.3 Temperature distribution of the top 3 sections
Figure 6.6.2 shows the velocity distribution of the oil and Figure 6.6.3 shows the temperature distribution in disc windings. The highest temperature on discs is 365.76 K. By cutting off color contour lower than 365 K, the location of the hotspot can be seen, as Figure 6.6.4 shown. The hotspot appeared on disc 127. The mass flow rate detected is 1.08223 kg/s at the inlet. The pressure distribution can be seen in Figure 6.6.5.

![Figure 6.6.4 Location of hotspot on discs](image)

For non-oil guided case, to compare the hotspot temperature with oil guided case, the solution is still kept as steady state. The inlet here is defined as pressure inlet with the oil temperature of 322.25 K. The outlet is defined as pressure outlet with the oil temperature of 347.15 K. The operating temperature is defined as the average temperature of the top oil and bottom oil to approximate the ON cooling mode. Figure 6.6.6 shows the hotspot temperature as a function of iterations. The hotspot temperature shown is fluctuating, while the average temperature read from the chart is about 371.1 K. It is clear that the steady state solution does not work well for this case.
Figure 6.6.6 Hotspot temperature as a function of iterations of non-oil guided case

A comparison of the results between oil guided disc windings and non-oil guided disc windings is conducted. A general view of the velocity distribution of the oil and the temperature distribution on discs is shown in Figure 6.6.7.

Figure 6.6.7 Results Comparison of Guide case and Non-Guide case

Figure 6.6.7a shows the velocity distribution in guided windings and non-guided windings. It can be seen that, in guided winding, the total height is divided into 12 sections by guides (blocks) evenly. Oil flow is guided by the guides and changes its direction in horizontal ducts from one section to the next section. In non-guided winding, the oil flow also shows
alternating flow patterns and divides the total height into 12 flow sections as well. However, the length of each section is not equal and there exists some stagnation parts in flow ducts.

Figure 6.6.7b shows the temperature distribution in windings with and without oil guides. In guided windings, the relative high temperature area is distributed to the last 4 or 5 sections. While in non-guide winding, the high temperature area are more concentrate in the last section.

By comparing the results of the model with without oil guides, a conclusion can be drawn that when the heat losses (heat source) and the environment condition (temperature of top oil & bottom oil) are maintained, the application of oil guides can decrease the hotspot temperature, from 365.76 K to 371.1 K. The oil flow field is stable, which could lead to the stable temperature distribution on disc. This is good for prediction of the hotspot. Secondly, the hotspot temperature is much lower by applying oil guides, more than 5K than non-oil guide case in this comparison. While for the case without oil guides, the oil flow is unstable.
7 CONCLUSION

For the model of a non-guided disc winding, the flow behavior is complex. It is clear that the alternating flow patterns appear and the temperature distribution on discs is affected by this alternating flow. There is not an enforced flow direction in the horizontal ducts, instead, the alternating oil flow changes its vertical way by passing through the horizontal ducts from one vertical duct to the other one automatically. The global oil flow is characterized by such kind of alternating flow directions by creating “cells” in both steady state and time dependent simulations. This phenomenon happens because of the pressure drops on inner vertical duct and the outer duct due to uneven mass distribution of oil. The actual flow patterns appear to vary greatly, depending on the model parameter changed. This means in practice that it is very difficult to predict the position and strength of hotspot in this type of winding.

The results of steady state model and time dependent models differ only marginally. It can be seen that the hotspot temperature of time dependent model is close to a steady state model. Even though, the hotspot temperature fluctuation at the top of winding appeared caused by the oscillatory oil flow rate, it has small effects on hotspot position and strength. Thus, based on current results, the steady state can give a reasonable approximation on the thermal behavior.

When the designed parameters are changed, the thermal performance of disc windings are changed as well. This can be seen indicated by hotspot temperature as well as its location.

i) It can be anticipated that once the cooling requirements and conditions are maintained, there should be an optimal mass flow rate that could lead to the best cooling performance, however, when the mass flow rate is quite high, the position of hotspot is highly variable, there are many local hotspots that are approximately equally strong. Consequently, for this type of winding, it is very difficult to predict (and measure) the strength and position of the global winding hotspot;

ii) Keeping the radial disc width as an independent variable, the tendency shows that the longer the radial disc width, the higher of the hotspot temperature and the more complex of the oil flow distribution
iii) When other design parameters are fixed, small horizontal duct height would decrease the hotspot temperature, however, the oil flow distribution as well as the temperature distribution may become unstable based on the results of current simulation.

iv) The steady-state models with different vertical ducts width give a preliminary overview. When the vertical duct increase, the hotspot temperature will decrease based on current results;

v) Different position of inlet/outlet would affect the thermal cooling performance. The case with inner inlet and inner outlet has a relatively high hotspot temperature due to the radial effects on the inlet oil velocity.

vi) Based on the comparison between guided and non-guided disc winding models, it can be seen that the oil guided disc winding have a more predictable thermal performance.

Overall, based on the current simulation results it can be concluded that the thermal performance of non-guided disc winding is more complex and unpredictable than guided disc winding. Even though the general view can show a preliminary impression and a rough tendency of thermal performance due to the change of some designed parameters, the mass field as well as the thermal field is unstable to some extent for such a large case model.

Due to limitation of time, some of the time dependent cases have not been finished. Thus, a more precise solution should be established in the future to get a more clear view and better understanding of such type of winding.
8 FUTURE WORK

1. Continue to finish running uncompleted cases. By now, due to the time limitation, the time dependent simulations have only been performed for certain cases or certain designed parameter points. In order to see more details and get more exact results, it is necessary to continue to finish running the uncompleted cases and perform more time dependent simulations covering all the designed cases. However, this work will be very time-consuming therefore the demand for the computer should be high;

2. Perform investigations on more designed parameters. Current simulations are based on some assumptions and simplifications in order to see the independent influence of a certain designed parameter. However, there are more other parameters which would also affect the thermal performance in disc winding, such as the inlet velocity profile, operating conditions, material properties, etc. To get a broader scenario of the sensitive parameters on the thermal performance, more investigation should be performed on more designed parameters;

3. Further study on a full model and three dimensional model considering more geometry details and characteristics. The model of disc winding used in this article is mainly the model of disc winding. In the future, it is necessary to investigate other detailed geometrical characteristics like the impacts of rounded angle and roughness. The three dimensional model should also be established in the future, in which, the effects of spacers among discs and other structures can be considered;

5. Compare the simulation results with experimental results. The conclusion here in based on the numerical results and need to be verified by experimental result. By comparing simulation results with the results of experiments, the solution can be verified.
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APPENDICES

Appendix I. Grid Quality Statistics [ABB Internal]

Appendix 2 Fluent settings [ABB Internal]