Prediction of static pressure drop, velocity and flow rate of higher viscous nature of ester oil in power transformers under oil directed cooling conditions

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Abstract*—The study on oil flow rate, pressure drop (pressure losses) behaviour of ester oil group (both natural and synthetic ester oil) due to its higher viscous nature is important for thermal designer during thermal design stage, since oil flow distribution within the winding has a direct impact on thermal performance of the transformer. During oil directed (OD) cooling modes, the static pressure drop over the continuous disc type of winding determines the ester oil split among low voltage windings (LV) and high voltage windings (HV) which is connected hydraulically in parallel. In addition, the oil flow distribution in disc type of transformer windings in conjunction with power loss (noload and load loss) of transformer will decide the location and magnitude of the hot-spot temperature in transformer. Hence, there is still a technical challenge with ester oil for transformer manufacturers and utilities to use in large rating power transformers mainly in OD cooling modes. In this paper, the effects of mineral oil and ester oil on frictional pressure, gravitational pressure, oil flow rate, velocity in cooling duct, temperature distributions in top and bottom insulation, main winding zones, core, radiators and coolers are investigated under OD cooling conditions. The typical transformer rating of 60/75/90MVA, 220/33kV is considered for thermal analysis. Since, natural ester oil and synthetic ester oil are potentially different in thermal properties, the thermal analysis results are compared with mineral oil. The thermal hydraulic network model (THNM model) are used for fast calculations of thermal parameters in typical large power transformer. The power losses distributions are calculated from FEM based simulations as an input for thermal analysis.

***Keywords*—Transformer winding, Ester oil, Thermal performance of transformer, THNM model, Winding insulation, Temperature rise test.**

I. INTRODUCTION

Significant experience has been gained by transformer manufacturers and utilities to understand the behavior of commonly used petroleum based mineral oil [1-7]. In recent years, transformers are filled with ester oil due to its advantageous of biodegradability, low maintenance and fire safety for green and fire safe substations [8,9]. Ester oil has higher temperature stability to provide the higher continuous overloading capabilities and greater solubility of water than mineral oil. If the transformer manufacturer and utilities are decided to go with ester oil, then it is not possible to expect same thermal parameters (top oil rise, winding rise and hot-spot temperature) of mineral oil filled transformer due to differences in thermal properties of the mineral oil and ester oils since the chemical composition of ester oil are changes from mineral oil [8,9]. It is important for the transformer manufacturers to ensure that ester oil has adequate thermal properties to use in large power transformer application.

To analyze the temperature distribution within the transformer windings, viscosity of the oil (mm^2/s) plays a major rule other than thermal conductivity (W/m°C), specific heat (J/kg°C) and density (kg/dm^3). The ester oil is more viscous in nature due to higher carbon molecules which tends to move slowly compared to mineral oil which is a lower viscous oil. For a given geometry of transformer and inlet velocity of winding model (m/s), the higher viscous nature of ester oil in a power transformer will lead to higher pressure drop in the winding and lesser oil flow rate under OD cooling modes than oil natural (ON) and oil forced (OF) cooling modes [8,9]. Since, the oil flow and heat transfer are weakly interconnected in OD cooling modes, thermal analysis parameters calculations are necessary for different types of ester oil group of natural ester oil and synthetic ester oil [8-10]. Hence, the understanding and prediction of oil flow distribution across the oil cooling ducts (horizontal and vertical cooling duct) inside the transformer windings is necessary for the thermal designer to avoid localized oil starvations and hot-spot temperature in OD cooling modes and to meet the guarantee limit of temperature as per given in ester oil transformer technical specifications of utilities due to different thermal properties of ester oil [8-12]. It is therefore important and necessary for thermal designer at the stage of thermal design to utilize the adequate horizontal and vertical cooling ducts that take into account the thermal properties of oil. THNM model is used in this study to provide a solution for predicting pressure drops in each component in the typical transformer and thereby support for transformer designer to select a proper oil pump. Hence, objective of this paper is to compare the two different ester oil groups of natural ester oil and synthetic ester oil with the comparison of mineral oil results under ODAF cooling modes using a same winding geometry of 60/75/90MVA 220/33kV transformer.

II. THERMAL MODELLING OF TRANSFORMER

The thermal modelling techniques are very useful to meet the customer guarantee values of oil temperature rise, winding temperature rise and hot-spot temperature at the stage of thermal design. In addition, it is more essential if hot-spot temperature prediction becomes necessary for utilization of any alternate oil for transformer applications or for new operational loading scenarios. Different models of thermal analysis are developed to predict oil flow distribution during design phase to meet the technical specification requirement of transformer. The commonly used lumped network models (THNM) and computational fluid dynamics (CFD) models can be used to predict the top oil, bottom oil, flow rate of oil, pressure drop over the disc windings since both the thermal models will follow the basic principle of mass conservation, momentum conservation and energy conservation [8-14]. CFD models will provide more thermal information to designer about thermal distribution of complete transformer geometry due to distributed parameter model compared to THNM. Due to complex nature of CFD analysis, the computation time for complete transformer geometry will be more hours or days and even sometimes it is very difficult to solve the different discretization level. THNM model will provide solution between calculation speed and approximation detail on thermal parameters than CFD models [8-17].

THNM is effectively utilized to find the pressure drop across each component in typical transformer and the oil temperature at the points where the oil exists. Due to thermal driving force and oil pump, the sum of pressure drops across each closed oil loop in the transformer is equal to calculated produced pressure and these components are based on oil flow through all parts of the transformer. The oil flow is generally estimated by iterative calculation [18,19]. The end criteria of iterative calculation of oil loops should be sum of produced pressure is in equilibrium and pressure drop across each of the oil loops. The oil temperature at the exit of last component in the loop should be equal to assumed oil temperature at inlet to first component in the closed loop [18]. The main objective of the iterative calculation loops is to estimate the oil flow in each component in the transformer with its distribution in the oil channels inside the components and oil and conductor temperatures in order to estimate the position of the hot-spot temperature and its temperature using THNM model [18,19].

III. TRANSFORMER OIL UNDER CONSIDERATION

The transformer oil should fulfill the higher demands on dielectric properties besides serve as coolant and diagnostic tools. Traditionally, mineral oils are being used in all types of transformer and special transformers. The viscosity characteristics of mineral oil are generally changed through proper selection of the proportions of aromatic contents and aliphatic hydrocarbons. In recent years, ester oil is utilized for transformer applications to meet the requirements of reduced fire, eco friendly substations and better benefit-to-cost ratios. The dielectric, chemical and thermal properties of natural ester oil and synthetic ester oil are different from mineral oil [8]. Though, the thermal conductivity of ester oil is higher than mineral oil it will not give the sufficient compensation due to higher viscous nature of ester oil for heat dissipation. Hence, higher viscous nature of ester oil will lead to influence (or worsen) the cooling performance of transformer mainly in OD cooling conditions. Hence, thermal design guidelines for cooling of transformer that have been established from heat run tests and thermal modeling using mineral oil might not be applicable for ester oil filled transformer. In addition, the higher viscous nature of ester oil may be useful to suppress the reverse flow of oil in OD cooling modes and flow distribution will be more uniform at the cost of a higher pressure drop [8,9].

IV. TRANSFORMER COOLING MODES UNDER CONSIDERATIONS

The internal and external cooling design of transformer are mainly designed to dissipate the generated heat due to power losses in the transformer based on loading of transformer. Based on oil circulation as a closed loop system, oil absorbs the generated heat from winding conductors across insulating paper (kraft paper/ thermally upgraded kraft paper/ hybrid insulation), cores and other heating parts and it transfer and dissipates the heat out to atmospheric temperature by equipped external radiator facilities. Hence, thermal performance of transformer is generally based on continuous circulation of oil through different cooling modes between internal and external cooling modes and how external and internal cooling modes are working together. In power transformer rating, the oil is either circulated naturally in air or forced to circulate with external pumps based on power losses of the transformer windings. Hence, the different types of cooling methods of oil natural air natural (ONAN/KNAN), oil natural air forced (ONAF/KNAF), oil directed air forced (ODAF/KDAF) for transformer are generally developed to meet the thermal criteria specified by the customers based on quantity of heat to be handled with a suitable external cooling modes [8-14].

The oil flow in ONAN/ KNAN cooling modes is mainly driven by buoyancy forces and hot-streak dynamics and it plays a major role in determining oil flow and temperature distributions in the transformer. In ONAF /KNAF cooling modes, external cooling fans are facilitated on the radiators to improve the cooling efficiency in order to enhance the thermal driving force. Under OD cooling modes, oil is forced to circulate within the winding using a suitable pump (centrifugal pump or positive displacement pump). During the selection of pump, hydraulic loss within the loop needs to be estimated properly and it should be known by the thermal designer of transformer at the stage of design. Generally, static pressure drop will decide the selection of oil pump for OF and OD cooling modes [8,9]. In OF conditions, the better thermal performances can be achieved on the account of maintenance of oil pump, risk of failure of oil pump and running cost of pump.

In OD and cooled disc type of power transformer, oil is forced to flow through the winding in a zig-zag fashion using oil guiding washer (oil restriction washers). Hence, the oil flow is not free to distribute between the different routes within the winding geometry. The direction of oil flow facilitated by oil guiding washer is mainly used to circulate the oil in the source of heating such as windings and core in a zig-zag fashion [9]. The zig-zag nature of oil flow direction through OD cooled disc type transformer windings adds to the complexity of estimating oil flow distribution in winding cooling ducts. Hence, OD cooling modes are considered in this paper with zig-zag nature of oil flow to provide the proper guidelines to transformer manufacturer and utilities to select the proper pump.

V. TRANSFORMER DETAILS UNDER CONSIDERATIONS FOR THERMAL ANALYSIS

A. Internal cooling modes of transformer

The three phase, 3 limb, star connected (YNyn0), transformer power rating of 60/75/90MVA with operating voltage of 220/33kV, ±15% HV tap on HV variation for the steps of 1.25% are considered. The thermally upgraded paper covered conductors are used in both 220kV and 33kV windings. It has higher tensile strength and bursting strength than commonly used kraft paper for conductor insulations and it provides support to ester oil under continuous overloading conditions. In this study, the effect of bulging is also considered to decide the radial depth of the windings. There are 66 discs in low voltage (LV) windings of 33kV and 82 discs in high voltage (HV) windings of 220kV. The oil cooling ducts windings are axial symmetric in nature and which are as follows

- horizontal cooling ducts formed by gap between stacked parallel discs of winding conductors
- vertical cooling ducts formed at inner and outer pressboard cylinders after radial stick on both side of any windings

Generally, if width of vertical cooling duct is higher or lower then horizontal duct height will provide more uniform oil flow distributions and it will provide the lower winding temperature with the cost of increased pressure drop. If the horizontal cooling duct height increases, then it will cause more distorted oil flow distribution and less pressure drop over the winding structure [8]. If number of discs in a pass between two diverting washers is lower, then flow of oil will be more in each horizontal cooling duct uniformly and there will not be reverse oil flow in its directions. In the transformer winding geometry, the majority of heat transfer will happen in the horizontal oil cooling ducts between the discs than vertical cooling duct. Since, vertical cooling ducts are shorter width and it has single contact surface with the sources of heat [9]. Hence, horizontal cooling ducts will act as a main source/ path to transfer the heat from winding discs to oil. The width of the horizontal cooling ducts for both LV and HV windings and the inner and outer vertical ducts are properly designed to match with the power losses of the transformers. To avoid the reverse oil flow in the cooling duct, the number of discs per passes is carefully selected in this transformer.

B. Oil guiding washer for zig zag cooling of windings

The oil flow in LV and HV winding are directed into a zig-zag fashion using oil guiding washers or oil seal. The 1.5mm thickness of oil guiding washer and oil seal are used at inner diameter and outer diameter of each winding respectively to cool the windings effectively at the entrance and exit of each oil circulation pass. The oil guiding washer blocks a vertical duct from inner side of the winding and it will allow the oil to flow into or out of a pass from opposite side. In this transformer, LV and HV winding has 6 and 9 number of zig-zag passes respectively. Due to lower losses in the coarse and fine winding of tap, zig-zag cooling passes are not considered.

Generally, oil seal should be properly placed during manufacturing of winding in order to avoid the leakages of oil out from the active parts. The oil sealing in the winding is a typical manufacturing concern and a quality issue [18,19]. Hence, it will be very difficult to predict or model the oil leakage. In THNM model, the perfect sealing is generally assumed for thermal analysis, but it is possible to mention the number and diameter of the opening on the oil distribution channel [18]. The appearance of oil openings causes the appearance of oil bypass. The oil bypass changes mainly based on number and diameter of the opening on the oil distribution channel [18,19]. In this study, 15 number of opening for oil leakages and 20mm diameter of holes are considered to model the nonperfect sealing of the oil channel (oil seal) supplying the oil to the windings. The oil flow bypass is estimated by subtraction of oil flows through the windings (calculated) and from the oil flow through the cooler bank [18]. In addition, if the oil flow in non-OD cooling components / elements of the oil directed cooling transformer is required, then opening in the oil distributions should be designed to achieve the oil flow through non-OD cooling components.

C. External cooling modes of transformer

In this transformer, 16 numbers of radiators with each radiator having 30 fins. The center to center height of each fin has an 3100 mm. The width of the each radiator is 520mm and each radiators are separated by 100mm. The horizontal mounted external cooling fan of 500watts, 900 RPM, 415V, 3 phase, 50Hz with volumetric air flow rate of 22100 m3/hr is used.

For OD cooling transformer, a suitable pump at different desired flow rates should be equipped for driving oil flow into the transformer with the specification of hydraulic head versus the flow rate. The hydraulic head reflects the total hydraulic resistance that oil pump must overcome in the flow system. The hydraulic resistance will come from frictional pressure drop along the oil channels inside the transformer core, windings, fitting of pipe, radiator, local pressure drop due to pipe bend and connections at every junction [8]. Hence, the calculation of friction pressure in the transformer under OD cooling condition is necessary. Since, the oil circulation in the transformer will act as a closed loop system, the static head which indicates the effect of gravity does not need to be resisted by the oil pump [8.9]. In this transformer, 6 inch, 1800LPM, 1.2kW, 415V, 3phase 50Hz, BC-30/1 is considered for the analysis.

In this transformer, the distance between tank bottom to cold oil entry and distance between top tank to inlet of radiator are 400mm and 1.32m respectively. The two parallel internal piping has 100mm diameter and length of 210mm. The hot oil pipes between cooler and tanks consists of 150mm diameter of two parallel pipes with length of 8.25m. The rectangular shape of the hot oil collecting pipe and cold oil collecting pipe has the dimensions of 300mm width and 300mm height. The cold pipe between radiator and tank has two number of parallel pipe with dimeter of 150mm and length of 8.46m. The hot pipes between cooler and tank and cold pipe between radiator and tank consists of two numbers of flexible tube of 150mm diameter and 450mm length.

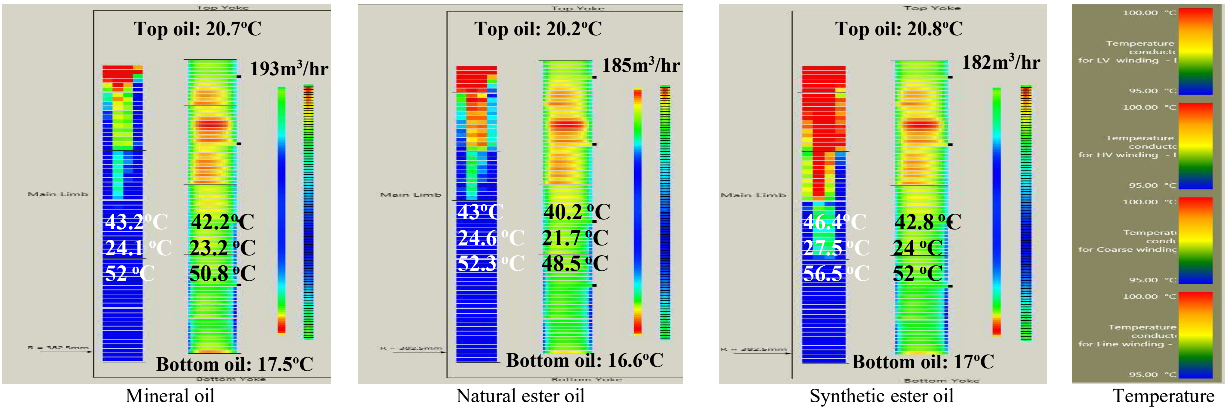


Fig.1. Temperature distribution (top oil, bottom oil, winding gradient, winding temperature) and oil flow of mineral oil and ester oil filled transformer under ODAF cooling conditions

The oil guiding systems for distribution of oil consists of 4.45m length of channel, inner width and height of 178mm and it has 15 numbers of oil leakage opening with the dimeter of 20mm. The pressure drop on the above mentioned part of the oil loop is calculated from hydraulic network. The localized pressure drops on the pipes (curves, valves, etc.) are also considered in the hydraulic network.

D. Transformer power loss estimation

The first preparation procedure prior to conduct THNM model comprises the calculation of magnitude and distribution of power loss. The heat generation in the transformer is generally based on core loss and load loss (resistive losses, winding eddy loss and stray loss) once the transformer is energized. Therefore, accurate prediction of power losses is main input for thermal performance of transformer since the losses behave as heat source. While the resistive losses of the winding are generally uniformly distributed, winding eddy losses are non-uniformly distributed. Hence, the total power loss distribution of the transformer will not be uniform over the winding. Therefore, empirical methods are not always feasible to calculate the winding eddy losses and stray losses accurately. Hence, FEM based techniques are used to estimate the winding eddy loss and stray losses. The effect of losses due to solar radiation on the tank, irradiated walls and the radiators bank are not considered in this paper.

VI. THERMAL ANALYSIS RESULTS OF TRANSFORMER

The main objective of thermal design is to pass the temperature rise test at factory, in which top oil temperature rise of 60ºC, winding temperature rise of 65ºC. In order to guarantee the temperature rises, the sufficient oil flow rate is mandatory for ester oil filled transformer with respect to existing mineral oil filled transformer design.

A. Oil flow rate and temperature distributions within the windings

Generally, the temperature distribution and oil flow rate in cooling ducts are based on horizontal cooling duct, vertical cooling duct, number of disc per pass, inlet oil velocity, inlet oil temperature, power losses in the winding disc and thermal properties of the oil. In this study, the thermal performance of a given transformer geometry with OD cooling modes, how oil flows within the winding and how temperature is distributed due to different types of ester oil with respect to mineral oil. Fig.1 shows the temperature distribution, volumetric oil flow (m3/hr), top and bottom oil temperature, gradient of winding, winding temperature rise and hot-spot temperature of mineral oil and ester oil filled transformer of 90 MVA. Fig.2 shows the frictional pressure, gravitational pressure, oil flow rate, velocity in cooling duct, temperature distributions in various places of transformer.

During temperature rise test, the branch of core (parallel to branch of oil bypass) are omitted since, the oil flow through the core is equal to zero due to non-OD cooled type of core. For the case of ONAN/KNAN and ONAF/KNAF cooling modes, there will not be a pressure produced by oil pump. In addition, thermal conductivity of copper conductor (approximately $380Wm^{-1}K^{-1}$) is higher than conductor insulation of thermally upgraded kraft paper (approximately $0.2Wm^{-1}K^{-1}$) [9]. Hence, temperature gradient inside the copper conductor is negligible. Since conductor insulation thickness is thin (mm), temperature variations across the conductor insulation of paper are ignored. To express the heat transfer principle of heat conduction across conductor insulating paper, the conductive heat transfer equation Fourier's law of thermal conduction is described as [14,15]

$$Q_{conduction} = \frac{k}{d_p}\left(t_{conductor} - t_{wall}\right) \tag{1}$$

Where, dp–Thickness of conductor insulation paper
k–Thermal conductivity of oil
$t_{conductor}$–Temperature of winding conductor
t_{wall}–Wall temperature of duct

In oil filled transformers, convection heat transfer mode plays an important role than conduction which is mainly governed by conservation laws of mass, momentum and energy. To express the convection mode from the duct walls to the flow bulk, the convective mode equation along the horizontal cooling ducts are described as

$$Q_{convection} = \frac{N_u \cdot k}{D}\left(t_{wall} - t_{duct}\right) \tag{2}$$

Where, N_u– Nusselt number
k– Thermal conductivity of transformer oil
D– Equivalent hydraulic diameter of oil duct
t_{duct}– Bulk temperature of oil duct

The oil flow rate, temperature distribution within the windings and hot-spot temperature are based on the fundamental principles of Reynolds number (P_r), Prandtl number (P_p) and ratio of Grashof number (P_g) and Reynolds number (G_r/R_e^2). The Richardson number ($R_i=G_r/R_e^2$) represents whether the flow of oil is driven by ON or OD. If $R_i>>1$, then the ON cooling is dominated. If $R_i<<1$, the OD cooling modes is dominated [8,9]. From the equation P_r, V_{in} and kinematic viscosity of the oil affect the P_r for a fixed given winding geometry. The dynamic viscosity, N.S/m^2 (ratio between the shear stress to the velocity gradient) and kinematic viscosity (which is related to dynamic viscosity by oil density) are related to each other. The higher values of kinematic viscosity of the oil, lower the P_r resulting more uniform oil flow within the given horizontal cooling ducts. The kinematic viscosity of the oil is temperature dependent parameter which is also based on oil type used.

$$P_r = \frac{V_{in} \times D_{\text{horizontal duct}}}{\nu} \tag{3}$$

$$P_g = \frac{9.81 \times \beta_{thermal\,\text{expanision}} \times D^3{}_{vertical\,\text{duct}}}{\nu^2} \times \left(T_{winding} - T_{oil}\right) \tag{4}$$

Where,

$D_{\text{vertical duct}}$– Vertical cooling duct -hydraulic diameter in m

$B_{\text{thermal expansion}}$–Oil volumetric thermal expansion coefficient

T_{winding}– Mean winding temperature in Deg.c

T_{oil} – Mean oil temperature in Deg.C

υ – Kinematic viscosity of oil-m^3/s

From Fig.1, synthetic ester oil causes more uniform flow distribution due to higher kinematic viscosity than natural ester oil and mineral oil and it will offers more resistance to oil reverse flow phenomenon. If mineral oil is replaced with ester oil in transformer then the oil flow rate is decreased due to higher viscous nature of ester oil.

B. *Frictional pressure drop*

Generally, if the higher viscous oil flows through straight oil cooling duct, then viscous force acts at the duct wall to resist the oil flow movement, which incurs frictional pressure drop along the ducts [8]. The frictional pressure drop along the ducts based on Reynolds numbers (=UL/υ) of flow however, it is applicable for sufficiently low Reynolds numbers and it implies a laminar flow. It is denoted by Darcy-Weisbach Equation as [8,9]

$$\Delta P = \frac{4fL}{D}\frac{\rho U^2}{2} \tag{5}$$

Where,

ΔP– Pressure drop between inlet and outlet of duct

D–Equivalent hydraulic diameter of fluid duct

$f = 24/R_e$ - Average dimensionless friction coefficient of oil duct

ρ – Density of oil

U– Average flow velocity of oil duct

L– Length of oil duct

From the Fig.2, additional structures and dimensions of windings should be considered as a primary step to minimize pressure drop due to higher viscous of ester oil for transformers in design stage. Generally, the wider vertical oil cooling ducts will give the more uniform oil flow distributions and lower pressure drop over the windings. In addition, other than frictional pressure losses occurring at horizontal ducts, there will be pressure losses in windings due to different oil flow directions if these oil flows combine or divide at a junction based on winding geometry and it is called as junction pressure loss. The oil flow distribution is mainly based to hydraulic network of winding cooling ducts where flow of the oil is combining or dividing at duct junctions and it is unavoidable [8,9]. In this study, the junction pressure loss is not considered since it is very low.

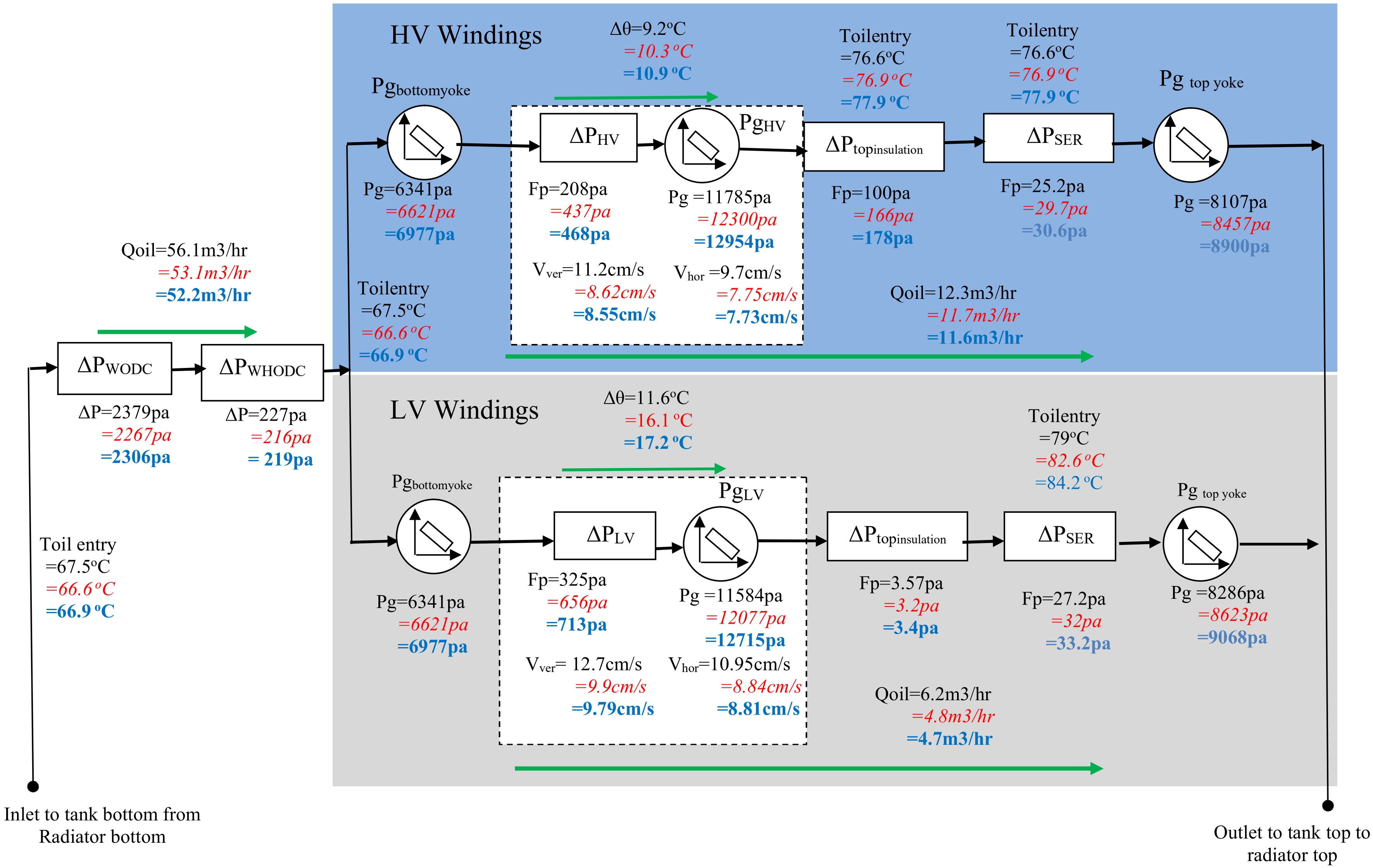
C. *Estimation of total pressure drop and oil velocity*

The total pressure drop in LV and HV windings with tap windings are calculated from the sum of pressure drop in top insulation, pressure drop in bottom insulation and frictional pressure drop in the windings and its results are given in Fig.3. The horizontal cooling ducts and thicknesses of vertical cooling ducts will decide the oil velocity within the transformer winding and the percentage rate of heat dissipation from each winding [8,9]. For example, the horizontal and vertical velocity of HV windings are given in Fig.4. In this study, for a given winding geometry with given radiator configurations and a given power loss, the total pressure drop and oil velocity is calculated to study the effect of ester oil.

The following points are observed in total pressure drop calculations

- The magnitude of frictional drop in the winding is a dominant factor in total pressure drop in the windings
- The magnitude of pressure drop in the bottom end insulation of LV and HV is negligible.
- In both mineral and ester oil, magnitude LV winding pressure drop in top end insulation is less than 1% of frictional drop in the winding in all cooling modes.
- The magnitude of HV winding pressure drop in top end insulation has varied from 25% to 50% for both mineral and ester oil in cooling modes.
- The magnitude of HV winding pressure drop in top end insulation filled with ester oil is lowered by 20% of mineral oil.

From Fig.3&4, total drop pressure drop of all the winding and maximum axial and radial velocity of HV windings are low in ONAN/KNAN and ONAF/ONAF cooling modes than ODAF/KDAF modes. The total oil flow rate in ON transformer arising from thermosiphon is usually of very low magnitude compared to OD cooling mode transformer and it is reflected in the pressure drop (Fig.3 & 4). The total pressure drop over the windings in ON conditions is lower compared to OD [8,9]. Hence, static pressure drop over the winding in an ON cooling mode is not important to determine the oil split among windings due to its low magnitude. A relatively uniform oil split in hydraulically in parallel will establish naturally in ON transformer due to lower oil flow rate and significant effect of buoyancy forces. It indicates that, the hydraulic system and thermal system are fully coupled with each other to analysis of oil flow rate and temperature distribution analysis in ON cooling modes.


HV Windings
Δθ=9.2°C
=10.3 °C
=10.9 °C
Toilentry
=76.6°C
=76.9 °C
=77.9 °C
Toilentry
=76.6°C
=76.9 °C
=77.9 °C
Pgbottomyoke
Pg top yoke
ΔPHV
PgHV
ΔPtopinsulation
ΔPSER
Pg=6341pa
=6621pa
=6977pa
Fp=208pa
=437pa
=468pa
Pg =11785pa
=12300pa
=12954pa
Fp=100pa
=166pa
=178pa
Fp=25.2pa
=29.7pa
=30.6pa
Pg =8107pa
=8457pa
=8900pa
Qoil=56.1m3/hr
=53.1m3/hr
=52.2m3/hr
Toilentry
=67.5°C
=66.6 °C
=66.9 °C
Vver=11.2cm/s
=8.62cm/s
=8.55cm/s
Vhor =9.7cm/s
=7.75cm/s
=7.73cm/s
Qoil=12.3m3/hr
=11.7m3/hr
=11.6m3/hr
ΔPWODC
ΔPWHODC
ΔP=2379pa
=2267pa
=2306pa
ΔP=227pa
=216pa
= 219pa
LV Windings
Δθ=11.6°C
=16.1 °C
=17.2 °C
Toilentry
=79°C
=82.6 °C
=84.2 °C
Pgbottomyoke
PgLV
Pg top yoke
ΔPLV
ΔPtopinsulation
ΔPSER
Toil entry
=67.5°C
=66.6°C
=66.9 °C
Pg=6341pa
=6621pa
=6977pa
Fp=325pa
=656pa
=713pa
Pg =11584pa
=12077pa
=12715pa
Fp=3.57pa
=3.2pa
=3.4pa
Fp=27.2pa
=32pa
=33.2pa
Pg =8286pa
=8623pa
=9068pa
Vver= 12.7cm/s
=9.9cm/s
=9.79cm/s
Vhor=10.95cm/s
=8.84cm/s
=8.81cm/s
Qoil=6.2m3/hr
=4.8m3/hr
=4.7m3/hr
Inlet to tank bottom from Radiator bottom
Outlet to tank top to radiator top

Fp – Frictional pressure of component, Pg– Gravitational pressure of component, Pc– Total pressure, Δθ – oil temperature gradient, V_{hor} – maximum horizontal velocity, V_{ver} – maximum vertical velocity, ΔP– Component of pressure drop (frictional and local), Toilentry – Oil temperature, Qoil– Oil flow rate, ΔP_{WODC} – From ODC to entrance to entrance holes of winding support bracks, ΔP_{WHODC} – Winding holes (for OD windings), $Pg_{bottomyoke}$–From bottom to top of lower yoke, $\Delta P_{topinsulation}$ – Insulation structure above the windings, ΔP_{SER} – Under pressure rings, $Pg_{top\ yoke}$– From the top of the winding to top of the core, $\Delta P_{ODTank\ entrance}$–From tank entrance to bottom of the core for OD elements, $\Delta P_{NONODTank\ entrance}$ –from tank entrance to bottom of the core for non-OD elements, $\Delta P_{channel}$–On opening on oil distribution channel for cooling of non-OD elements, ΔP_{core} – Core, $\Delta P_{core\ top}$– From top of the core to oil entrance to cooler, ΔP_{cooler}– From oil exit from tank to top of the cooler (OD branch), ΔP_{pipe}–Complete piping with cooler (OD branch), $\Delta P_{cooler\ to\ tank}$–From bottom of the cooler to oil entrance to tank (OD branch)

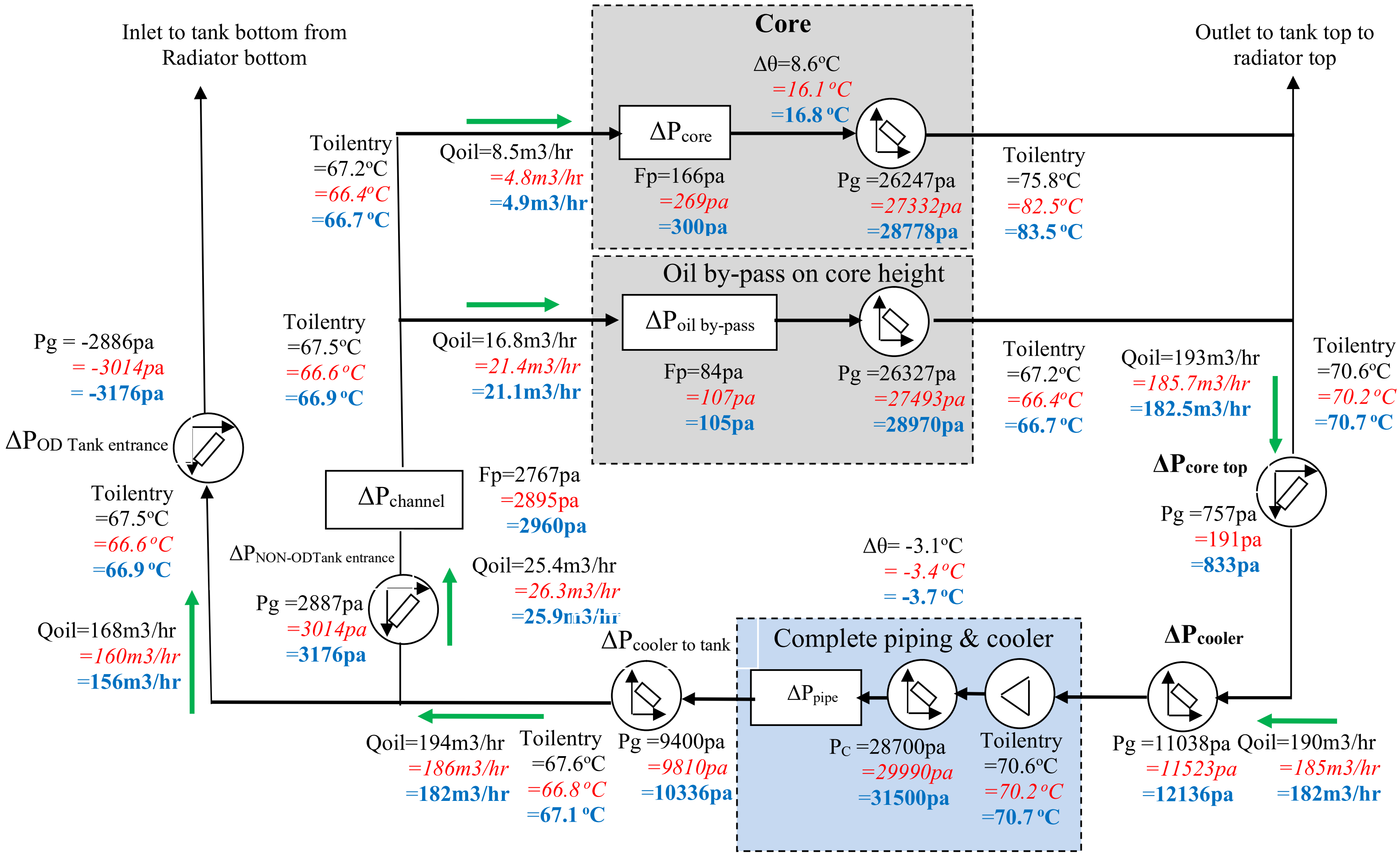


Fig.2. Frictional pressure, gravitational pressure, oil flow rate, velocity in cooling duct, temperature distributions in various places in transformer

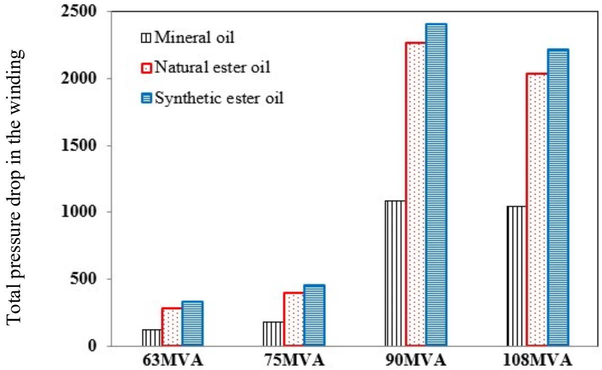


Fig. 3. Total pressure drop of the transformer

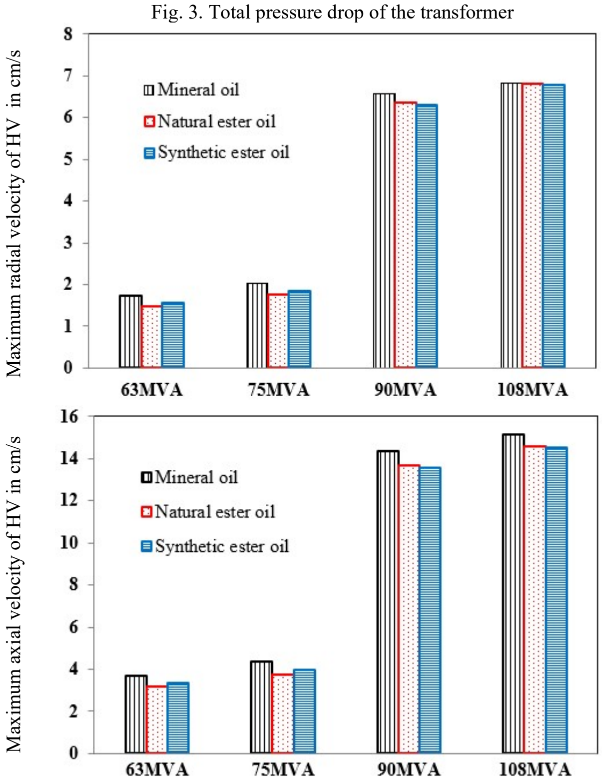


Fig.4. Maximum radial and axial velocity of HV windings

VII. CONCLUSIONS

The main objective of thermal design of any oil filled transformer is to guarantee that the transformer can able to pass the temperature rise test at factory. It is very important for the ester oil transformer manufacturer and utilities to know about how the generated heat due to power loss is conducted and dissipated in the internal and external cooling modes of transformer [22]. The viscosity of the ester oil affects the pressure drop with the windings geometry mainly in OD cooling conditions and it will influence the pass inlet velocity. To investigate the influence of different types of ester oil on oil flow and temperature distributions, 60/75/90MVA, 220/33kV transformer under cooling modes of ODAF are considered. If a transformer is retro-filled with ester oil, the reduction of pass inlet velocity should be estimated beforehand in order to compare the performance of ester oil with respect to mineral oil. In addition, mineral oil with kraft paper in winding conductor cannot be replaced by ester oil in an old power transformer during retro-filling stage in order to get the benefits of continuous overloading capabilities of ester oil, since top oil temperature rise, winding the temperature rise, gradient of the winding and hot-spot temperature will be higher due to higher viscosity nature of ester oil.

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