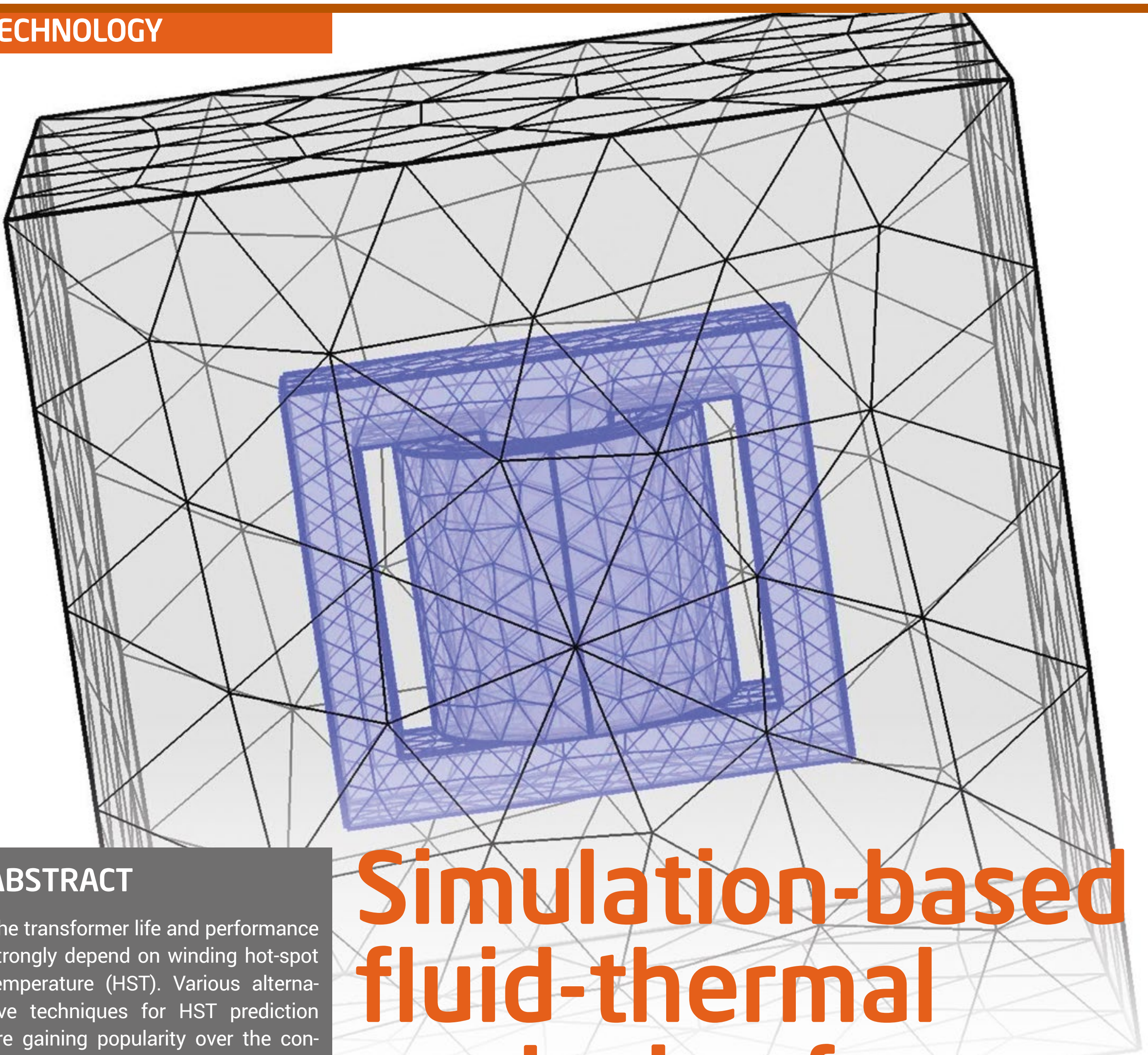


Simulation-based fluid-thermal analysis of power transformers

Critical reviews on advanced thermal assessment

ABSTRACT

The transformer life and performance strongly depend on winding hot-spot temperature (HST). Various alternative techniques for HST prediction are gaining popularity over the conventional direct-measurement methods. In this context, the application of Computational Fluid Dynamics (CFD) based thermal models is particularly interesting because of their accurate assessment, higher precision and low cost. Besides, it can remarkably evaluate and improve the design efficiency of transformer without overshooting the capital cost. In the present work, a comprehensive understanding of CFD-based fluid-thermal assessment is attempted to encourage the readers to review transformer thermal models. It is also expected that these attempts will progressively assist in correlating various economical and operational parameters of transformer manufacturing and asset management.

KEYWORDS

oil-filled transformers, cooling, hot-spot, thermal assessment, Computational Fluid Dynamics

1. Introduction

The economic reliability of power transformer changes dramatically with its thermal performance. Renewed interests in improving the heat-induced failure models have steered the manufacturers and researchers towards application of advanced thermal modelling techniques that use highly efficient numerical approximation and visually-aided simulation-based solution approach. Two widely acclaimed methods for transformer thermal assessment are Thermal-Hydraulic Network Modelling (THNM) and Computational Fluid Dynamics (CFD). Their sole objective is to predict the oil-winding temperature rise and improve the winding-HST displacement predictions without compromising the capital cost.

These methods are realistic, cost-effective, scientifically accurate, and efficient in improving transformer performance through real-time simulations of multiple interdependent physical phenomena,

> **Thermal simulations are a step forward in comprehensive understanding of temperature rise phenomena within transformers with respect to localized heating and buoyancy-driven flows**

which ultimately affects the temperature rise and HST evaluation. The attractive aspects of such methods include reliable estimation of the magnitude of internal heat, effect of coolant oil pattern and transformer configuration, and most significantly, its solution technique. Figure 1 is a representation of key aspects in CFD-based thermal modelling of any transformer.

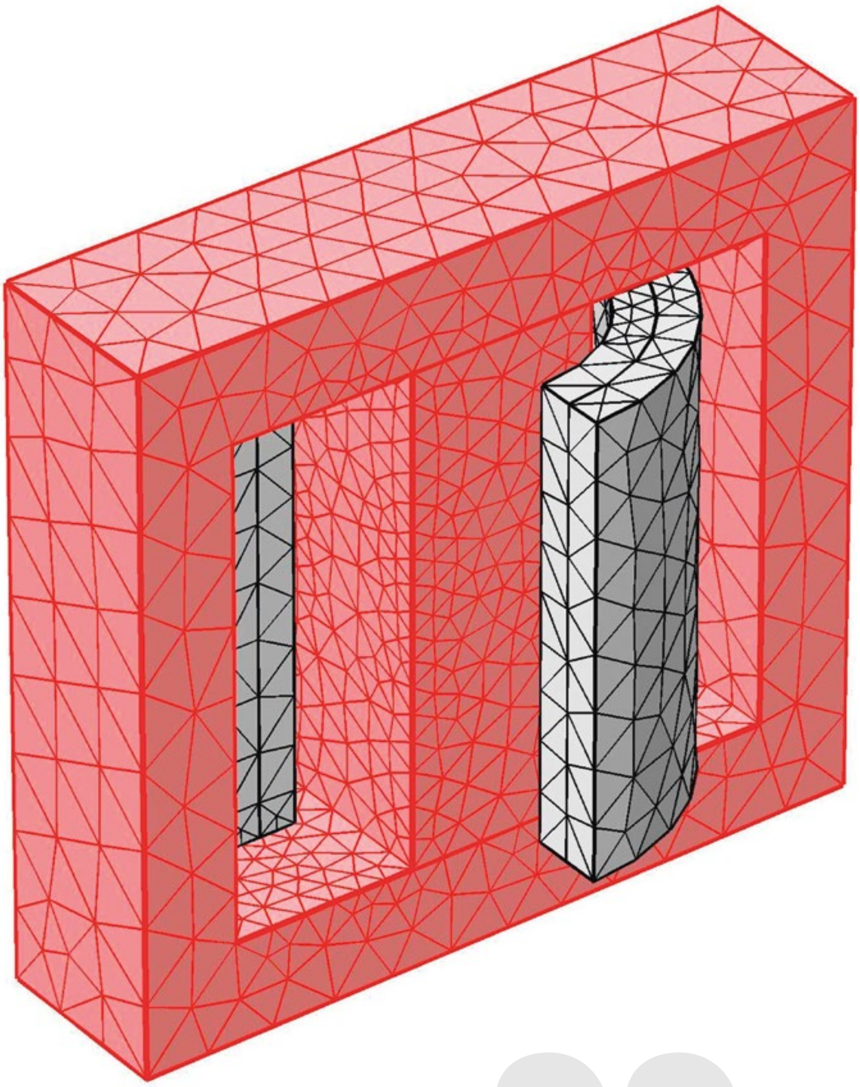
The upcoming sections of this article will assist the reader to gain a comprehensive understanding about CFD-based thermal modelling of an oil-filled transformer through an in-depth analysis of the concomitant multiphysics, application and limitations.

2. CFD-based thermal modelling: Key aspects

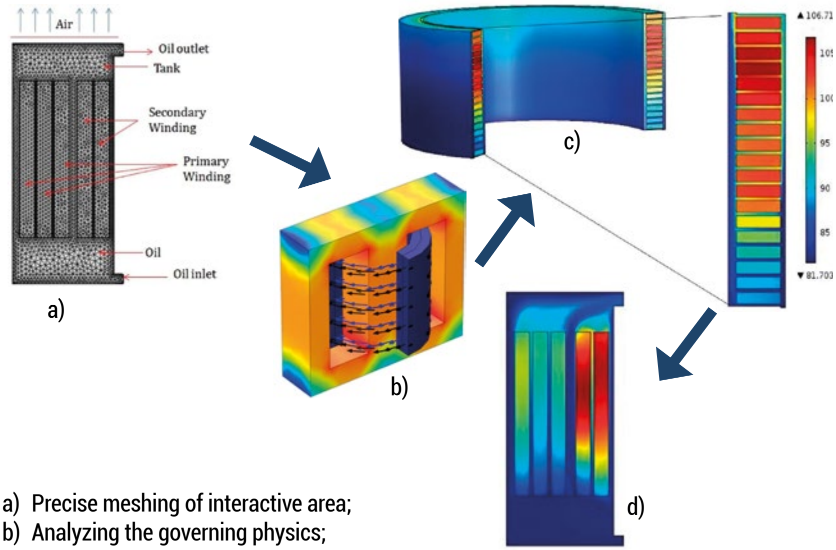
The accuracy of any CFD-based assessment improves inherently with proper understanding of governing physics and a potential solution technique. Therefore, pertinent information about the key aspects propelling a CFD-based assessment includes: calculation domain, governing physics and meshing scheme [1]. As we move forward, we will understand the physical significance of each of these aspects in detail.

2.1 Calculation domain

A 3D investigation of the equipment's thermal behaviour is undoubtedly the best incentive to assess, optimize and improve its functionality and in-service life. However, such an assessment not only requires pertinent information about

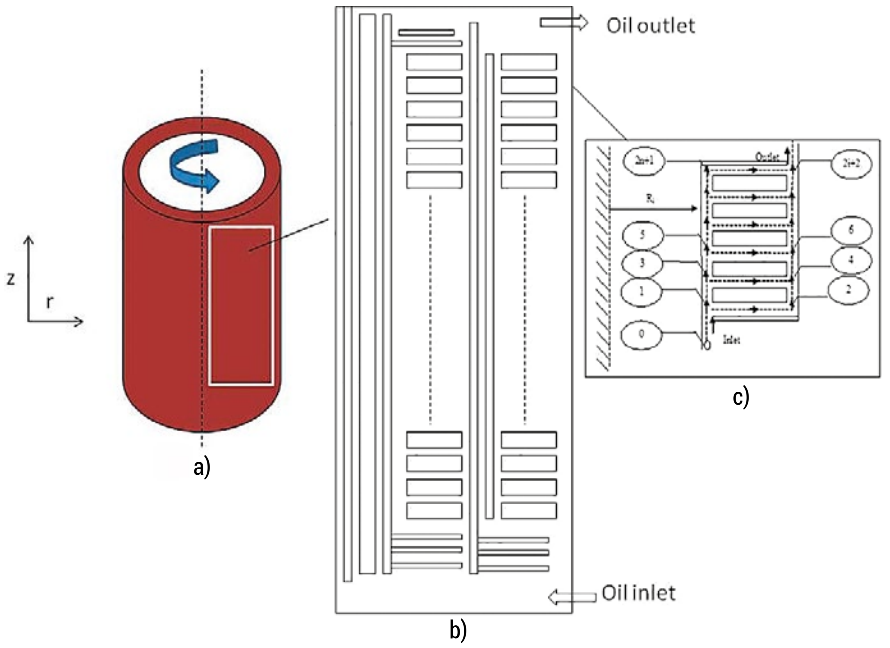


> **The transformer life and performance strongly depend on winding hot-spot temperature**



a) Precise meshing of interactive area;
b) Analyzing the governing physics;
c) Evaluating the effect of winding configuration;
d) Proposing the temperature in 2D or 3D design

Figure 1. Representation of key aspects of CFD-based thermal modelling of transformers



a) 3D winding;
b) 2D axisymmetric model;
c) 2D slice model

Figure 2. Simplification of the winding domain for CFD applications by schematic representation of 3D winding, 2D axisymmetric model, and 2D slice model

> **Apart from the transformer construction and operating conditions, interactive winding geometry strongly influences the transformer thermal behaviour**

transformer construction, but also becomes tiresome if one is solely interested in examining the winding thermal performance as shown in Figure 2.

In the present work, exclusive discussions are presented on the CFD applications in improving the design of core-type transformers containing disc windings. Previous CFD-based attempts on estimating the impact of winding geometry on flow distribution reveals that the complex labyrinth of radial and axial channels in disc windings is responsible for mixed convection, thermal streaking and HST disposition with respect to buoyancy changes [1, 2, 5, 6, 8, 9]. This clearly indicates that apart from the transformer construction and operating conditions, interactive winding geometry strongly influences the transformer thermal behaviour.

2.2 Governing equations and boundary conditions

Classical combination of Navier-Stokes with energy conservation equations governs the fluid-thermal assessment of transformers by conservation of mass, momentum and energy, as shown below:

$$[\partial\rho/\partial t+((u.\nabla).\rho)]+\rho.(\nabla.u)=0 \tag{1}$$

$$\rho.[\partial u/\partial t+((u.\nabla).u)]-\nabla.\sigma=F_v \tag{2}$$

$$\rho.[\partial E/\partial t+((u.\nabla E)]-\nabla.(k_s.\Delta T_s)+p.\nabla u-Q_s=0^* \tag{3}$$

Since oil is weakly-compressible, despite an infinitesimally small density variation ($\beta\cdot\Delta T_f \ll 1$), the viscous flow will become strong enough to allow desired fluid-thermal interactions. This is known as the Boussinesq approximation and expressed mathematically as follows [4]:

$$F_v=\rho(T)\cdot g \tag{4}$$

$$\rho(T)=\rho_0\cdot[1-\beta\cdot\Delta T_f] \tag{5}$$

These governing equations require an inlet flow rate and hydrostatic pressure of oil as primary boundary conditions. In this context, oil inlet velocity can be obtained from an energy balance equation, whereas the inlet pressure of oil can be obtained by evaluating the hydrostatic pressure difference between the top and bottom of windings as shown below [7]:

$$u_0=Q_s/(A_c\cdot C_p\cdot\rho\cdot\Delta T_f) \tag{6}$$

$$p_0=\rho(T)\cdot g\cdot H\cdot\Delta T_f \tag{7}$$

Where:
$\partial\rho/\partial t$ = rate of mass change (kg/m^3·s)
$\partial u/\partial t$ = rate of momentum change (m/s^2)
$\partial E/\partial t$ = rate of energy change (W/s)
u = vector representing velocity (m/s)
ρ = temperature dependent oil density (kg/m^3)
ρ_0 = temperature dependent oil density at average ambient (kg/m^3)
σ = viscosity tensor (Pa·s)
F_v = viscous body force (N/m^3)
E = internal energy (W)
k_s = thermal conductivity of winding material (W/m·K)
T_s = winding thermal gradient (K)
Q_s = volumetric heat source (W/m^3)
p = hydrostatic pressure (Pa)
T_f = oil temperature (K)
g = gravitational acceleration (m/s^2)
u_0 = inlet oil velocity (m/s)
p_0 = inlet pressure (Pa)
A_c = cross sectional area of inlet channel (m^2)
H = height of winding (m)

2.3 Meshing and grid analysis

The accuracy of any CFD-based assessment depends on its meshing precision. Meshing is the spatial discretization of the investigated domain into smaller blocks or cells of definite shapes (e.g. triangular or quadrilateral for 2D geometries, and tetrahedral, hexahedral, pyramids, or prisms for 3D geometries). Figure 3 shows a meshing scheme using 2D triangular elements of the investigated winding domain.

Previously, Finite Difference Method (FDM) based assessment produces false-time stepping over structured meshes, whereas FDM-based iterative approaches

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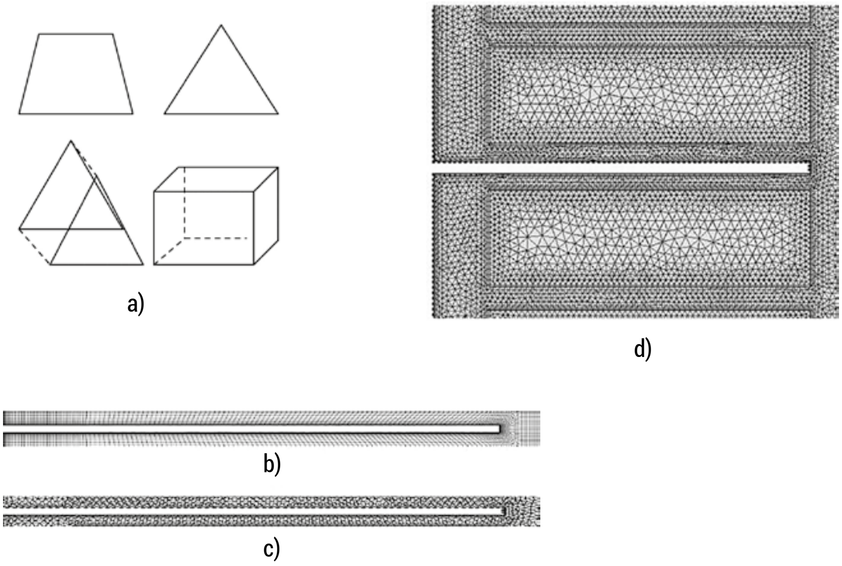
**The equations are in vector representation, where the dot "." represents multiplication of a scalar with a vector having spatially changing values.*

show divergent patterns while analyzing buoyancy-driven flows. Unlike such loose and oversimplified grids, Finite Volume Method (FVM) not only incorporates a tighter grid, but also refines it continuously to ascertain the independence of physical properties over mesh complexities thereby increasing the solution accuracy, otherwise known as grid analysis [1]. Similar approaches exist within the Finite Element Method (FEM) based CFD environments, namely, COMSOL Multiphysics, Code_ Saturne, etc. Both FVM and FEM apply various iterative solvers with suitable algorithms to analyze the proposed problems. Therefore, the solver continues to operate until the solution converges and the truncation error minimizes. The relative tolerance and convergence of FDM and FVM/FEM is approximately 10^{-3} and 10^{-6}, respectively, thus suggesting relatively tightly-controlled grid.

> **The application of CFD-based thermal models is particularly interesting because of their accurate assessment, higher precision and low cost**


a)
d)
b)
c)

a) 2D and 3D mesh elements in FVM and FEM packages;
b) Structured meshing near washer;
c) Unstructured meshing near washer;
d) Free meshing of solid-fluid domain in FEM

Figure 3. Various meshing aspects of simulation-based fluid-thermal assessment of windings

3. CFD analysis: Parametric investigations

The CFD-based fluid-thermal assessment of transformers, especially windings, depends on winding configuration and flow parameters besides the obvious transformer operating conditions. In this context, we investigate the effects of various parameters on oil-winding temperature rise and HST disposition on a 2D slice model of disc windings. Torriano et al. [9] provide the configuration details for a potential case-study on disc windings with various boundary conditions.

3.1 Effect of inflow: Location, magnitude, and pattern

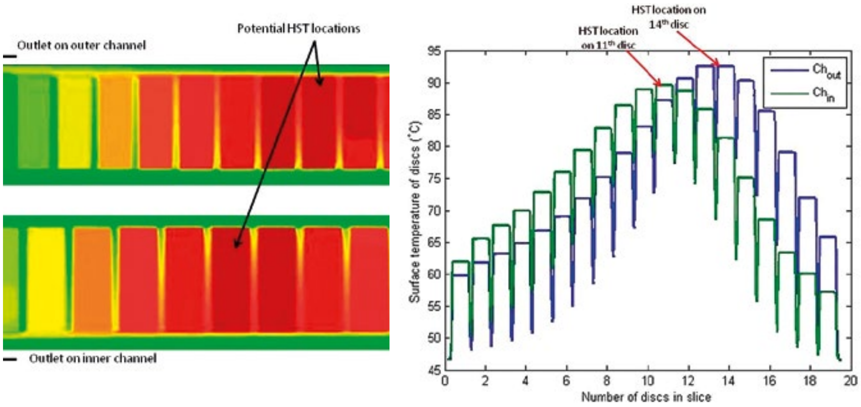
Winding thermal performance strongly depends on flow distribution behaviour within the immediate vicinity of conducting discs. In fact, IEC 60076-2 (1993) suggests that the temperature rise limits and HST can be significantly improved through suitable analysis of oil-flow patterns [10]. In this context, analysis of oil inlet location, width of inlet, inflow velocity and flow pattern are prominent.

Figure 4(a) shows that upon changing the inlet location, the temperature rise limits can vary significantly. The effect of location is proposed by observing the inlet at inner (Ch_{in}) and outer (Ch_{out}) channels respectively, such that oil enters from bottom and exits from top of the winding. If the inlet channel width is small, then there is a homogeneous mixing of oil near the entrance of winding which decays with increasing entry length, thereby accumulating excess heat near the centre of the winding. This is also why HST exists somewhere in the middle or near the top, if not on the top most disc on the winding.

Figure 4(b) shows a sort of a parabolic temperature profile over a finite number of conducting discs, which is due to the parabolic velocity profile and fully developed hydrodynamic boundary layers near the conducting surfaces. The blue line depicts the surface temperature behaviour of conductors when the oil inlet is positioned at the outer channel given by the bottom contour of Figure 4(a). Similarly, the green curve depicts the surface temperature rise behaviour when inlet is located within the inner channel of winding as given by top contour of Figure 4(a). Hence, a complete "bath-tub" temperature curve can be expected from such simulations.

Moreover, while a wider inlet channel (Ch_{in} = 8.9 mm) allows lower temperature rise limits (HST at 89.92 °C) unlike narrow channels (Ch_{in} = 6.4 mm, HST at 92.702 °C), its application is also dominated by the flow calculations. In this particular case, the inner channel is 1.4 times the width of the outer channel as reported elsewhere [9]. At this point, one can easily observe that suitability of the inlet channel width and location depends entirely on the inflow conditions.

It is understood that if upstream oil circulation is extremely slow, then buoyancy decreases due to the overwhelming conduction. The resultant low oil velocities are rendered useless and winding heat dissipation fails. Hence, minimum oil velocity must be known to optimize and improve the transformer thermal design. The parametric investigation shown in Figure 5(a) reveals that average oil temperature rises rapidly beyond a certain value. Similar results can be expected to portray average conductor temperature.



a)

b)

a) 2D plots depicting the effect of inlet location;
b) 1D plots depicting the effect of inlet location

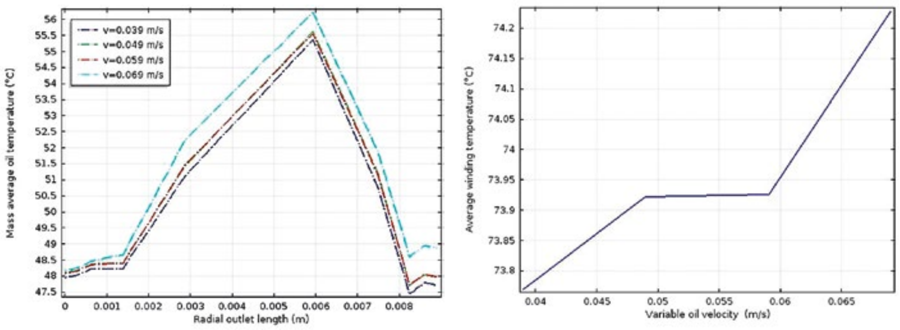
Figure 4. Effect of inlet location and inlet channel width on temperature rise limits and HST

> **If upstream oil circulation is extremely slow, then buoyancy decreases due to the overwhelming conduction**

It is evident from Figure 5 that without attaining the desired minimum velocity, efficient heat dissipation cannot be achieved. For example, if we apply very high velocity (u >0.059 m/s) to a relatively thinner inlet channel, the average surface temperature will increase due to non-uniform mixing throughout the entry length. Maintaining uniform oil velocity across the winding height is equally significant, without which local heat accumulation and "heat-pool" formation can occur. To overcome this, pressboard washers (in the form of sticks and blocks) are strategically placed within the axial and radial channels of windings. Washer assisted oil flow is referred to as directed cooling, where washer location depends largely on radial duct height, number of discs, oil inlet velocity and transformer cooling pattern.

Figure 6(a) shows the application of various blocks and stick washers for improving transformer thermal design. Figure 6(b) shows the effect of stick spacers on winding thermal behaviour using 2D contour plots.

The strategic placement of these washers can dramatically reduce the HST magnitude. For example, when three passes are created within the single slice of winding by introducing washers near the 6th and 12th disc from the bottom, the magnitude of HST decreases by almost 5.8 °C when compared to two-pass structure. Washers alter the oil interaction pattern, thereby causing sudden change in temperature of conductor and the oil surrounding it. It is also obvious that despite better cooling efficiency, application of directed cooling is restricted by winding configuration and thus requires further improvement during the thermal assessment.



a)

b)

a) Rise in average oil temperature over outlet length;
b) Rise in average winding surface temperature

Figure 5. Effect of variable oil velocity on temperature rise behaviour

3.2 Effect of winding design: disc and layer

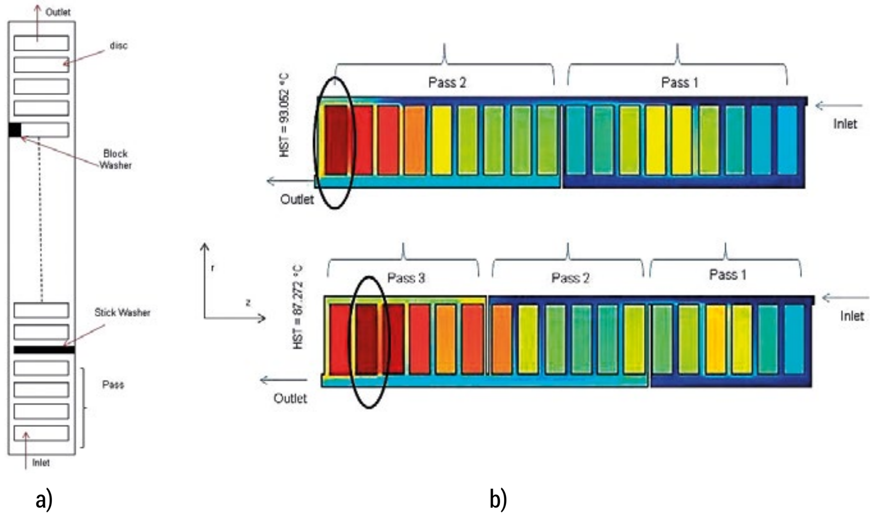
Figure 6 suggests that the transformers are not only distinguished on the basis of core configuration, but also by winding construction. Therefore, accurate information pertaining to winding configuration can influence the accuracy of any simulated assessment. Although a comparison between the disc and layer winding thermal profile is not possible because of obvious reasons, we still will try to objectify some of the critical outcomes that may support our hypothesis.

The thermal conductivity of copper and insulates is highly anisotropic [9], which varies for disc and layer arrangement even within the same transformer. This not only affects the heat source and resultant temperature calculations, but also affects the magnitude and location of HST formation on the assembly. Specific simulations reveal that while a hot-spot is expected somewhere near the top in case of disc windings, it is always encountered at the top in case of layer windings [12, 13]. However, the accuracy of this observation is yet to be established by further investigations using CFD-based techniques.

Although the scientific literature is abundant with various aspects of simulation-based thermal assessment of disc and layer type windings, suitable CFD calibrations to improve such models using modern day FVM and FEM solvers remain to be seen.

3.3 Effect of approximation approach

Any discussion on CFD-based assessment will remain incomplete without analysing the competency of the nume-



a) Type of washers in disc windings;
b) Effect of stick washer on winding temperature rise

Figure 6. Effect of washers on winding temperature rise and HST behaviour

Minimum oil velocity must be known to optimize and improve the transformer thermal design

rical approximation technique. A CFD software package comprises three components: pre-processor, post-processor and solver. Basically, this solver acts as the brain of applied software package and hence one can navigate between packages based on solver operation. There are two basic solvers commercially available on the market: direct solvers and iterative solvers for analysing stationary, non-linear partial differential equations. As the name suggests, direct solvers apply matrix solution techniques such as Lower-Upper (LU) decomposition or Gauss elimination method, whereas iterative solvers apply numerical iteration techniques until the solution converges and the truncation error is minimized. This is also known as the convergence of applied solver as discussed earlier.

Since solvers apply a wide variety of algorithms to analyse and solve the posed problem, robustness and accuracy becomes intertwined. Over the years, FVM-based packages have acquired more than three quarters of the CFD market due to their easy implementation and wide range of applicability. Various researchers have implemented popular FVM packages such as ANSYS Fluent, Gambit, etc. to analyse the thermal behaviour of transformers. However, structured meshing and need for an alternate meshing interface adds to the overall computation cost of such packages.

On the other hand, FEM-based software packages are slowly gaining popularity among CFD users due to the high precision and ease of handling complex problems [12]. It is true that both FVM and FEM provide more-or-less the same geometric flexibility, unlike FDM packages which are strictly restricted to structured girds despite any curvature. However, FEM packages are exceptional due to their peculiar use of continuous Galerkin methods to generate weighed residual functions within the partial differential equations. Such an approach not only helps in reducing the domain complexity, but also simplifies the applied boundary conditions, thereby increasing the accuracy of solutions. This particular feature makes FEM superior to FVM despite its somewhat disadvantageous feature – domain dependence. Currently researchers are feverishly trying to improve such pitfalls of FEM-based packages and improved versions; namely, COMSOL Multiphysics, Code_Saturne, etc. are beginning to float in the commercial market.

4. Result verification

One of the persistent questions with simulation-based assessments is verification of the CFD results. Currently, the simulated results are either compared against on-site heat-run tests, verified by gas analysis or applying continuously evolving standards such as IEC60354, IEC60076-2, etc. [10, 11]. At this point, one has to understand that the essence of simulation-based assessments is to inform the researcher/manufacturer about several manifolds of coupled multiphysics that ultimately govern the fluid-thermal behaviour of transformer under variable conditions. We hope to reach a point in the future where more advanced technologies could assist the researcher in analysing and verifying the CFD analysis without overshooting the recurring experimental costs.

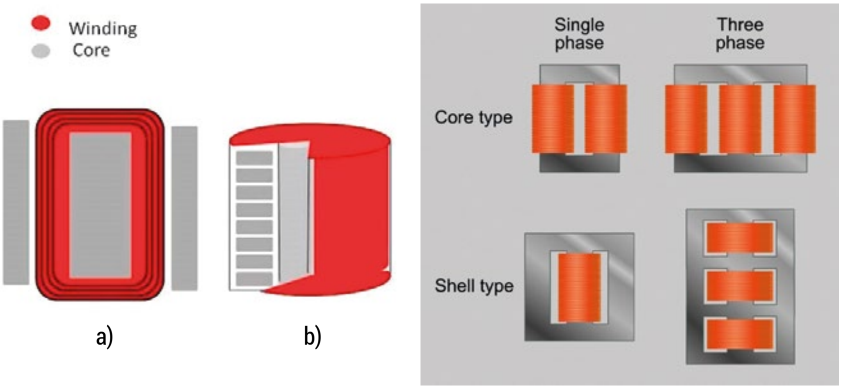


Figure 7. Various core and winding constructions in transformers: a) layer winding; b) disc winding

> **The accuracy of any CFD-based transformer thermal assessment depends on the accurate information on winding design, operational parameters, loading behaviour and its meshing precision**

Conclusion

The accuracy of any CFD-based transformer thermal assessment depends on accurate information on winding design, operational parameters and loading behaviour. It is a unique step forward towards comprehensive understanding of temperature rise phenomena within transformers with respect to localized heating and buoyancy driven flows. Such methods are immensely popular for determining design efficiency of transformers regardless of their operational stage. However, the sole limitation of this alternative is its accuracy restriction on oversimplified 2D models. In case of 3D systems, the computational time significantly increases, thereby increasing the cost of assessment. This suggests future scope of method improvement whether by software upgrading or mathematical simplification.

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