Renewable Energy, Environment, and Power Quality Journal (REE&PQJ)
ISSN:3020-531X
Volume 26, July 2026

# Porosity Strategies to Optimize Temperature Distribution in Oil-Directed Power Transformers

P.Quintanilla[1,2], E.Sanchez[1], T.Laneryd[1], A.Ortiz[2]

[1] R&D Department, Hitachi Energy
Escritor Conde Zamora s/n, Cordoba (Spain)
+34 622443196, pedro.quintanilla@hitachienergy.com

[2] Department of Electrical Engineering,
E.T.S.I.I.T., University of Cantabria (Spain)

**Abstract.** Power transformers rely on efficient oil circulation to ensure adequate cooling of their active parts and to prevent excessive thermal stresses that may compromise insulation life. In forced oil-directed (OD) cooling regimes, the flow distribution through winding ducts and oil guides plays a critical role in controlling local temperatures. However, conventional oil guide designs may promote flow stagnation and recirculation zones, particularly in the regions immediately above the oil guides, leading to the formation of localized hot spots on upper winding discs. In the cases where these effects happen, the cooling design is not optimum and affect to the lifecycle of the electrical machine.

This work presents a numerical investigation of oil guides modeled as porous media to mitigate these adverse flow phenomena. The porous approach is employed to replicate the hydraulic behavior of perforated oil guides, where discrete holes allow partial oil penetration through the guide cross-section. Given the two-dimensional nature of the computational domain as a practical compromise between accuracy and computational cost, the porous media formulation provides an effective and physically consistent approximation of the three-dimensional perforation effects.

Computational fluid dynamics (CFD) simulations are conducted to evaluate the impact of the porous guide representation on oil velocity fields and temperature distributions within the winding region. The results demonstrate a significant reduction in stagnation zones and recirculating flow structures, accompanied by a more uniform oil distribution and lower local temperatures in critical areas. The proposed methodology offers a practical and computationally efficient framework for improving thermal performance in OD-cooled power transformers.

**Key words.** Hot-Spot, Mineral Oil, Porosity, Power Transformer.

## 1. Introduction

As offshore wind farms grow in scale, the weight and footprint of conventional substation transformers significantly increase structural complexity and overall grid-connection costs. Compact transformers, with reduced mass and improved thermal and mechanical performance, offer a viable alternative to ease platform constraints while ensuring operational reliability as exposed Kazmi et al. (2021) [1]. The use of compact transformers with high temperature insulation or transformer with overloading capability can be a useful instrument to achieve optimal solutions even it means higher losses as concluded Reyes et al. (2014) in [2].

Temperature is widely recognized as a dominant factor governing transformer insulation aging. According to international standards such as IEC 60076 and IEEE C57.91, the thermal aging of cellulose-based insulation follows an exponential relationship with temperature, where local hot-spot temperatures (HST) largely determine the loss of life of the transformer. Excessive temperatures accelerate insulation degradation, reducing mechanical strength and dielectric integrity, and significantly increasing the probability of failure.

Field experience consistently confirms the strong link between thermal stress and transformer failures. The CIGRÉ Reliability Survey published in 2015 [3] reports that winding-related failures, together with tap changers and bushings, are among the most frequent causes of major transformer outages. This conclusion is further supported by the standardized reliability survey conducted by CIGRÉ Working Group A2.37, presented by Tenbohlen et al. in 2017 [4], which analyzed 964 major failures collected from 58 utilities worldwide. The study highlights that dielectric and thermal failure modes are dominant contributors, particularly in generator step-up and heavily loaded transformers, while windings remain the most critical failure location across voltage classes.

To cope with increasing power ratings and stricter thermal limits, forced OD cooling has become a common solution in medium and high-power transformers. In OD cooling systems, oil is actively driven by pumps and directed through specific paths in the winding assembly to enhance heat removal. Compared to natural oil (ON) cooling, OD regimes enable higher heat transfer coefficients and improved global thermal performance, as discussed by Santisteban et al. in 2019 [5]. However, the higher mass flow rates imposed in OD cooling may also introduce complex flow interactions. In particular, elevated oil velocities in radial channels can lead to an uneven flow distribution, limiting oil penetration into axial ducts and promoting stagnation or recirculation zones. These effects are especially critical in disc-type windings and are known precursors to localized hot-spot formation.

CFD has become a powerful and widely adopted tool for analyzing thermofluid behavior in power transformers. Two-dimensional axisymmetric models offer a practical compromise between physical fidelity and computational cost. Several studies have successfully employed these models to investigate oil flow and temperature distributions in transformer windings. Campelo et al. (2016) in [6] demonstrated the capability of CFD to capture detailed thermofluid behavior in disc-type windings, while Altay et al. (2020) in [7] applied similar methodologies to layer-type windings and alternative insulating fluids.

Within this context, the porous media approach has emerged as an effective modeling strategy to represent complex geometrical features that are impractical to resolve explicitly. This methodology has been successfully applied to the thermal modeling of transformer radiators, enabling accurate prediction of pressure losses and heat transfer behavior with reduced computational effort (Fdhila et al., 2011 in [8]). More recently, porous-based multiscale methodologies have been proposed for transformer windings, allowing efficient simulation of coupled heat and fluid transport in highly complex domains (Meyer et al., 2021 in [9]). Despite these advances, the application of porous media for modelling holes where fluid flows has not been deeply studied with transformers' oil guides. In particular, there is a lack of studies addressing the use of porous representations of oil guides to mitigate flow stagnation and recirculation effects arising under forced OD cooling conditions, when pumps are employed. This solution has been proposed by the authors to adapt the design for a compact transformer, due to its demonstrated significant advantages. [1,2]

The present work addresses this gap by applying a porous media approach to model oil guides in a power transformer winding. The proposed methodology aims to improve oil flow distribution and thermal performance without requiring late-stage design modifications, such as increasing the number of oil guides or enlarging winding height due to additional axial channels. By tackling a recurrent thermal issue at the modeling stage, this approach provides a practical tool for enhancing transformer reliability while preserving compact and optimized winding designs.

## 2. Methodology

Based on the issues discussed in the previous section, the present methodology is developed to address the thermal deficiencies observed in oil-directed cooling of disc-type windings. Figure 1 illustrates the problem motivating this work, where multiple localized hot spots appear on the winding discs immediately above the oil guides. These hot spots are a direct consequence of an inadequate mass flow distribution within the winding, primarily driven by the inertia of the mineral oil circulating through the cooling channels. Under forced OD cooling conditions, the oil tends to preferentially flow through certain paths, limiting effective penetration into adjacent axial channels and promoting regions of low velocity, stagnation, or recirculation.

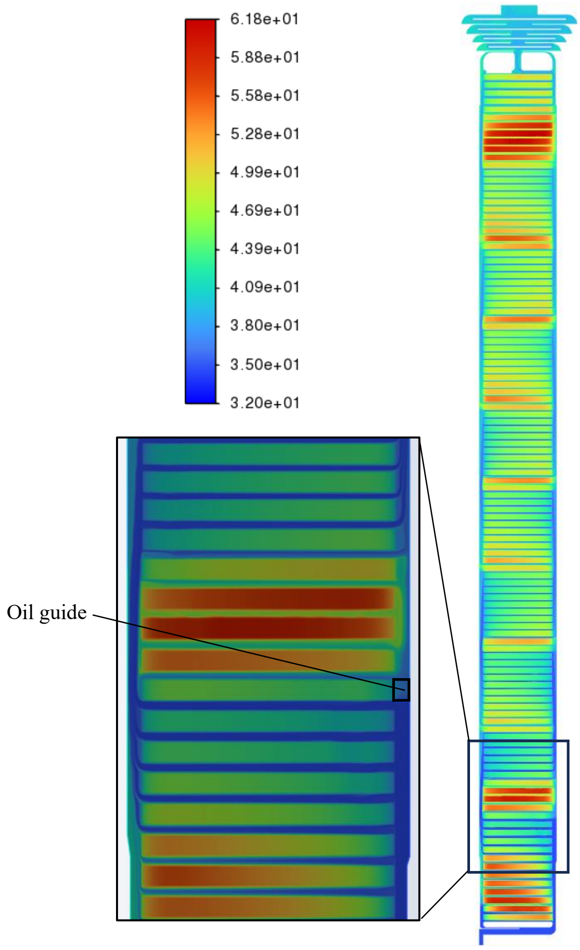


*Figure 1: Temperature rise [K] of the base case*

This work deliberately considers a winding with a significant number of oil guides. This choice is motivated by the need to investigate and demonstrate an improved solution for a configuration that is already relatively well guided, thereby validating an approach that can be generalized to a wide range of practical transformer designs. Rather than relying on additional structural modifications, the proposed solution aims to enhance flow distribution through modeling strategies applicable at the end of the design stage.

The initial phase of the procedure involves constructing the numerical model based on the geometry of the transformer. Later, the calculated parameters of the porous media are assigned to oil guides, substituting the original solid consideration in the domain. Consecutively, several simulations that consider the v-Δp relationship are carried out combinating this value with the ratio oil radial surface-total oil guide radial surface. Data are analyzed to find an optimum range of values to operate and design next conflict temperature distribution units.

The winding geometry studied is characterized by a radial width of 190 mm and a total height of 2,565 mm. The winding consists of 112 discs, each with a height of 13 mm and a width of 168 mm. Additionally, a paper insulation layer of 0.9 mm is incorporated around the discs.

As a first step, a two-dimensional axisymmetric CFD model of a disc-type winding belonging to a 281 MVA 412/220kV power transformer is developed. The model resolves the coupled thermofluid behavior of the mineral oil and solid components of the winding under forced OD cooling conditions.

A. CFD model

This baseline simulation intentionally reproduces a suboptimal thermal scenario, characterized by a non-uniform distribution of mass flow rates in the axial cooling channels. There are assigned no-slip walls and non-uniform source terms based on a previous calculated 178kW losses.

The discretized domain is above 327 kcells. The governing equations of the model are given by Eqs. (1)–(4), considering all the assumptions and conditions defining the numerical model. Equations (1)–(3) represent the conservation of mass, momentum, and energy, respectively, under laminar flow conditions. The buoyancy effects induced by temperature variations are taken into account through the Boussinesq approximation, which introduces a temperature-dependent body force in the momentum equation while assuming constant fluid properties elsewhere. Equation (4) defines the thermal boundary condition imposed at the solid walls, corresponding to a prescribed heat source of discs.

$$\boldsymbol{\nabla} \cdot (\rho \mathbf{u}) = 0 \tag{1}$$

$$\rho(\mathbf{u} \cdot \boldsymbol{\nabla} \mathbf{u}) = -\boldsymbol{\nabla} p + \boldsymbol{\nabla} \cdot [\mu(\boldsymbol{\nabla} \mathbf{u} + (\boldsymbol{\nabla} \mathbf{u})^T)] + \rho_0 \mathbf{g}[1 - \beta(T - T_0)] \tag{2}$$

$$\rho c_p(\mathbf{u} \cdot \boldsymbol{\nabla} T) = \boldsymbol{\nabla} \cdot (k \boldsymbol{\nabla} T) \tag{3}$$

$$-k_{\text{eff}} \frac{\partial T}{\partial n} = q'' \tag{4}$$

The thermal properties of the materials employed have been summarized in Table 1. The mass flow inlet condition is 19.5 kg/s at 349.1 K.

Table I. – Thermal properties of materials used

| Material | ρ (kg/m³) | Cp (kJ/kg·K) | K (W/m·K) | Viscosity (Pa·s) |
|---|---|---|---|---|
| Mineral Oil | $1081 - 0.7212 \cdot T$ | $859 + 3.51 \cdot T$ | $1.51 \cdot 10^{-1} - 7.101 \cdot 10^{-5} \cdot T$ | $4.75 \cdot 10^{-1} - 3.56 \cdot 10^{-3} \cdot T + 8.94 \cdot 10^{-6} \cdot T^2 - 7.51 \cdot 10^{-9} \cdot T^3$ |
| Guides | 1020 | 1000 | 0.15 | - |
| Strand | 5000 | 400 | 269(a)/ 0.57(r) | - |

B. Porous approach

The proof of concept presented in this work is based on modeling the oil guides as porous regions in order to reproduce the hydraulic behavior of perforated guides within a two-dimensional numerical framework. The objective of this formulation is to introduce a controlled pressure loss across the guides, allowing a limited fraction of the oil flow to pass through them while preserving their primary flow-directing function.

In the porous media, the effect of the solid matrix on the fluid flow is represented by an additional momentum sink term introduced in the Navier–Stokes equations. For incompressible flow, the momentum equation is Eq.(5).

$$\rho(\mathbf{u} \cdot \boldsymbol{\nabla} \mathbf{u}) = -\boldsymbol{\nabla} p + \mu \, \boldsymbol{\nabla}^2 \mathbf{u} - \mathbf{S}_p \tag{5}$$

Sp is expressed in Eq.(6) as the sum of a viscous (Darcy) contribution and an inertial (Forchheimer) contribution.

$$\mathbf{S}_p = \left(\frac{\mu}{K}\right) \mathbf{u} + C\rho|\mathbf{u}|\mathbf{u} \tag{6}$$

Where K is the permeability of the porous medium, accounting for viscous losses at low velocities, and
C is the inertial resistance coefficient, which dominates at higher flow velocities. This formulation allows the porous region to reproduce a prescribed pressure drop as a function of velocity.

The values of (μ/K) and Cρ appearing in the porous momentum source term were determined based on classical correlations reported in standard reference handbook [10] for pressure losses in internal flow duct geometries. The porous parameters were calibrated to reproduce realistic pressure drop–velocity relationships within the range of operating conditions relevant to oil-directed cooling. This approach ensures that the selected values of (μ/K) account for viscous effects at low velocities, while the Cρ term captures inertial losses dominant at higher flow rates.

The porosity ε of the medium is defined as the ratio between the void volume and the total volume of the porous region. Its value ranges from 0, corresponding to a fully solid guide, to 1, representing the absence of any guide where the mineral oil would be predominantly conveyed through a single radial channel, bypassing most axial cooling paths and resulting in excessively high temperatures throughout the winding. Here, intermediate porosity values are considered in order to replicate the behavior of oil guides with a finite number of perforations. The selected porosity is directly related to the geometrical constraints of the guide, such as its width, and to the allowable hole diameters. An equivalent perforation scenario is constructed by matching the ratio between the total hole area and the total radial surface area of the oil guide, ensuring that the porous representation reflects a physically realistic configuration. For this reason, the proposed methodology aims to identify an optimal porosity range that introduces sufficient hydraulic resistance to limit flow recirculation and stagnation near the guides, while simultaneously enforcing oil circulation through all winding sections. By allowing a controlled oil passage through the guides, the porous formulation improves mass flow distribution and thermal uniformity without compromising the guiding role of the cooling system or requiring structural modifications to the winding design.

## 3. Results

The numerical results obtained from the proposed methodology show a clear improvement in both thermal and hydraulic performance when the porous media approach is applied to the oil guides. Compared to the reference configuration, a noticeable homogenization of the disc temperatures is achieved, together with a more uniform distribution of mass flow rates in the axial cooling channels. These effects directly address the flow maldistribution issues previously identified and constitute the main objective of the present study.

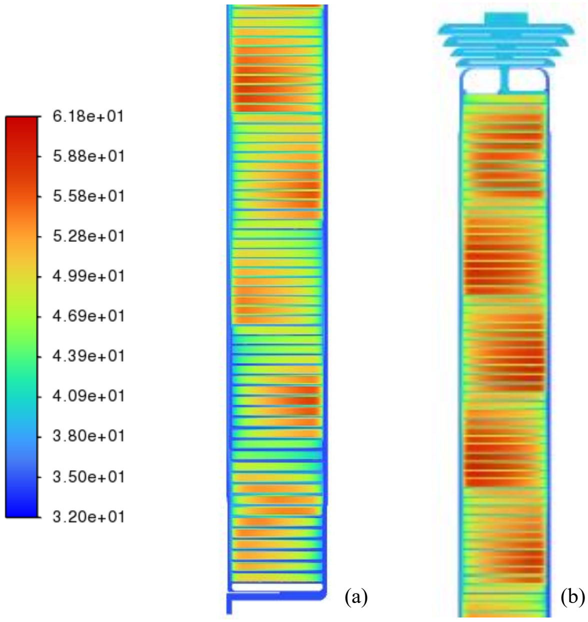


*Figure 2: Temperature Rise [K] of the porous model for ε=0.15 at bottom part (a) and top part of the winding (b)*

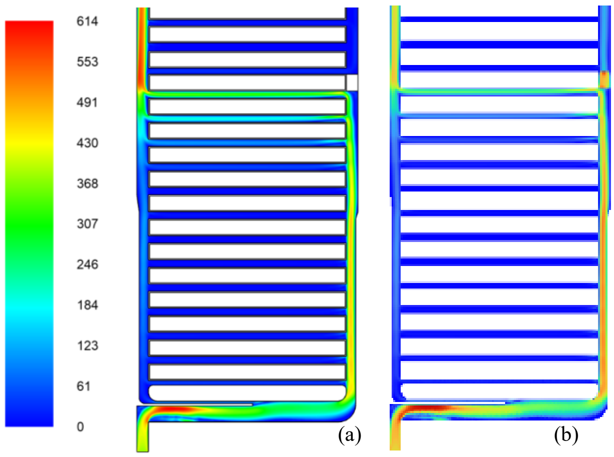


*Figure 3: Velocities field [mm/s] of the base case (a) and the porous approach (ε=0.15)*

Figure 2 illustrates the resulting temperature fields within the disc-type winding for a porous configuration analyzed in comparison to the base case. The reduction of high-gradient local hot spots in the discs immediately above the oil guides is clearly observed, leading to smoother axial temperature gradients along the winding height. In parallel, Figure 3 presents the corresponding mass flow rate distribution in the axial channels, highlighting a significant reduction in flow imbalance and the mitigation of stagnation and recirculation zones.

The analysis reveals that the most favorable results are obtained for porosity values close to 0.15. Within this interval, the porous oil guides introduce an optimal pressure loss that promotes effective oil redistribution without excessively restricting the overall cooling capacity. Higher porosity values tend to degrade the cooling performance by allowing excessive oil bypass through the guides, whereas lower porosity values behave closer to solid guides and result in a less efficient energy exchange. Cases where ε>0.4 present higher temperature values than the standards allow so they have been removed of the study.

Table 2 summarizes the hot-spot rise temperatures obtained for the different intermediate and physically realistic porosity values considered in this study. The trends observed in the table further confirm the existence of an optimal porosity range, where thermal performance is significantly improved without compromising the guiding function of the cooling system.

Table II. – Thermal results for porosity level

| ε | $HST_{rise}$ | Temperature discs Std Deviation | $V_{ax}$ Std Dev |
|---|---|---|---|
| 0 | 61K | 3.99K | 76.5mm/s |
| 0.15 | 59K | 3.71K | 59.9mm/s |
| 0.25 | 61K | 3.95K | 50.5mm/s |
| 0.35 | 64K | 4.52K | 33.3mm/s |

## 4. Conclusion

Power transformers are a key component of the electrical network. These machines lifetime is related to the temperature that achieve during the operation. In cases where the power is high and the cooling equipment requires OD regime can appear local hot-spot temperatures. These HST affect the lifetime and the distribution of temperatures and flow happened get sub-optimum refrigeration. This work pretends to illustrate an approach of holes in the oil guides of disc-type windings to improve the flow/temperatures distribution across the shell. The methodology followed has been based on a 2D axil-symmetric CFD study that considers the oil guides as a porous media where the ε and the Δp have been analyzed to achieve an optimum flow distribution in axial ducts to avoid or reduce stagnation points and recirculation effects that can occur.

A reduced deviation of temperature and velocity fields has been aimed. In this way, the present work demonstrated good performance of the technique and a general optimum value close to 15% for radial free surface to allow the flow continuity.

## Acknowledgement

The authors would like to gratefully acknowledge the support of the R&D Departments of Hitachi Energy Spain and Hitachi Energy Sweden for funding this work.

This research was also funded by the European Union's Horizon Europe Programme, through the Marie Sklodowska-Curie Grant 101,182,948, and by the Ministry of Science, Innovation and Universities, through the Project: Implementación Segura y eficiente del retrollenado de transformadores con líquidos aislantes sostenibles para avanzar hacia la economía circular (PID2023-150206OB-C22).

## References

[1] Kazmi, S. H. H., Laneryd, T., Giannikas, K., Ahrenfeldt, S. F., Sørensen, T. S., Olesen, T. H., & Holbøll, J. (2021). Cost optimized dynamic design of offshore windfarm transformers with reliability and contingency considerations. *International Journal of Electrical Power & Energy Systems*, *128*, 106684.

[2] Reyes, J., Oliva, M., Prieto, A., Fernandez, A., Cuesto, M., & Burgos, M. (2014, April). Compact Transformers for Offshore Wind Power Plants Applications. In International Conference on Renewable Energies and Power Quality (ICREPQ™ 14), Cordoba (Spain).

[3] CIGRÉ Working Group A2.37, 'Transformer Reliability Survey', CIGRÉ, Paris, France, Dec. 2015.

[4] S. Tenbohlen, J. Jagers and F. Vahidi, "Standardized survey of transformer reliability: On behalf of CIGRE WG A2.37," *2017 International Symposium on Electrical Insulating Materials (ISEIM)*, Toyohashi, Japan, 2017, pp. 593-596, doi: 10.23919/ISEIM.2017.8166559.

[5] A. Santisteban, A. Piquero, F. Ortiz, F. Delgado and A. Ortiz, "Thermal Modelling of a Power Transformer Disc Type Winding Immersed in Mineral and Ester-Based Oils Using Network Models and CFD," in IEEE Access, vol. 7, pp. 174651-174661, 2019, doi: 10.1109/ACCESS.2019.2957171

[6] H. Campelo para referirte a devanados tipo disco (H. M. R. Campelo, M. A. Quintela, F. Torriano, P. Labbé and P. Picher, "Numerical thermofluid analysis of a power transformer disc-type winding," 2016 IEEE Electrical Insulation Conference (EIC), Montreal, QC, Canada, 2016, pp. 362-365

[7] R. Altay *et al*., "Use of Alternative Fluids in Very High-Power Transformers: Experimental and Numerical Thermal Studies," in *IEEE Access*, vol. 8, pp. 207054-207062, 2020, doi: 10.1109/ACCESS.2020.3037672.

[8] Fdhila, R. B., Kranenborg, J., Laneryd, T., Olsson, C. O., Samuelsson, B., Gustafsson, A., & Lundin, L. (2011, September). Thermal modeling of power transformer radiators using a porous medium based CFD approach. In *Second International Conference on Computational Methods for Thermal Problems, Dalian, China* (pp. 5-7).

[9] O. H. H. Meyer, K. Y. Lervåg, y Å. Ervik, "A multiscale porous–resolved methodology for efficient simulation of heat and fluid transport in complex geometries, with application to electric power transformers," Appl. Therm. Eng., vol. 183, parte 1, p. 116133, ene. 2021, doi: 10.1016/j.applthermaleng.2020.116133.

[10] I. E. Idelchik, Handbook of Hydraulic Resistance, 3ra ed. Boca Raton, FL, USA: CRC Press, 1994.