# Simulation and Experimental Validation of the Core Temperature Distribution of a Three-Phase Transformer

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**Abstract:** This paper presents an application of COMSOL Multiphysics in the study of the temperature distribution of a 5kVA three-phase air-cooled transformer. A 3D, steady state model was used on the simulations. The interface with the surrounding air was modeled by Newton's Law of Cooling, discarding the need of solving the external airflow.

The simulation results agreed with the experimental measurements with a margin of 2.3 degrees Celsius with a remarkable short amount of simulation time. Given the fact that the time constants associated with the heat flow are greater than the simulation time, real-time control strategies could be implemented in the future.

**Keywords:** Transformers, heat transfer.

## 1. Introduction

The operating temperature of the insulating materials used in transformer cores and windings heavily influence the service life of the device [1]. However, the temperature distribution of a transformer under load is not easily obtained by purely analytical methods. This information is useful both in the design of new machinery and in the maintenance of existing devices: a designer can considerer the long-term economics tradeoffs with better accuracy and a maintenance engineer can predict the location of hot-spots that demand special care.

This paper explores the analysis of a three-dimensional, steady-state model of a 5kVA dry transformer with previously obtained electrical characteristics [2]. The results were compared with experimental measurements of temperature.

## 2. Theory

Three main sources of heat are present in the normal operation of a transformer: Joule losses are associated with the dissipation of energy as currents pass through the device's windings. Hysteresis is associated with the periodic spatial reorientation of the magnetic domains of the ferromagnetic material of core. Finally, eddy

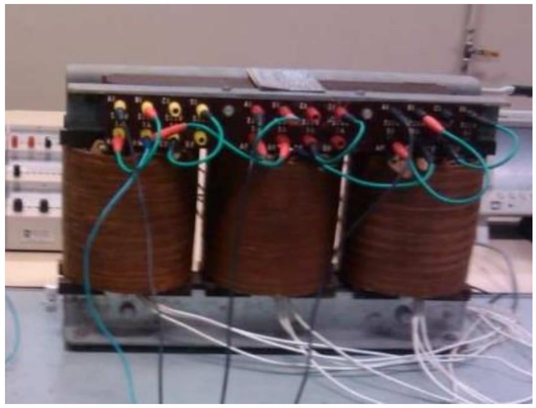

**Figure 1.** 5kVA Transformer. Source: [2].

currents are associated with electric currents within the core, induced by the temporal variation of magnetic flux density.

The dissipated power associated with the cited sources can determined from an electromagnetic simulation or analytically.

For the rigorous analysis of problem, one must consider the distribution of varying magnetic field in the transformer core to determine the distribution of the thermal power that heats the device. Regions with high values of magnetic flux density are associated with higher heating power. However, it is also observed that the heat flux inside the metal finds a much lower thermal resistivity than the flux that leaves the core to the surrounding air. Therefore, it is assumed that the distribution of thermal power can be approximated by a constant power density. This density can be easily calculated by dividing the core thermal power by the core volume. The power dissipation in the windings and in the core can be predicted by the equivalent circuit model.

The determination of the equivalent circuit parameters is a standard practice, based in short-circuit and open-circuit tests. In the aforementioned transformer, these tests were performed after the device was left on during a sufficient amount of time to allow its temperature to reach typical steady-state values, discarding the need of analytical corrections regarding the change of the equivalent circuit parameters with the temperature.

## 3. Use of COMSOL Multiphysics

### 3.1. Numerical Model

Two different approaches were explored in this study. In the first model, both the transformer and the surrounding air were included. This leads to a strongly coupled problem involving fluid dynamics and heat transfer. Analytical calculations predicted that the flow became turbulent after 15cm of vertical displacement for usual values of transformer temperature, meaning the real flow around a transformer is very turbulent. The laminar flow solver failed to converge unless the Grashof number were to be forced to unrealistic low values.

A simpler model was then conceived. The interface between the solid core and the surrounding air was modelled by Newton's Law of Cooling, that lumps the complexity of the outer flow in the parameter $h$, the convection heat transfer coefficient. The convergence of the solution was observed to be very rapid. **Figure 2** shows the resulting model, including the cylinders used to model the windings.

### 3.2 Governing Equations

Inside the core, the steady-state heat diffusion equation governs the heat flow:

$$\dot{q} = -k\nabla^2 T$$

$T\ [K]$ is the temperature, $k\ [Wm^{-1}K^{-1}]$ is the thermal conductivity of the (isotropic) material medium, $\nabla^2$ is the Laplace operator and $\dot{q}\ [Wm^{-3}]$ is the thermal power density. The latter is the source term of the heat transfer process.

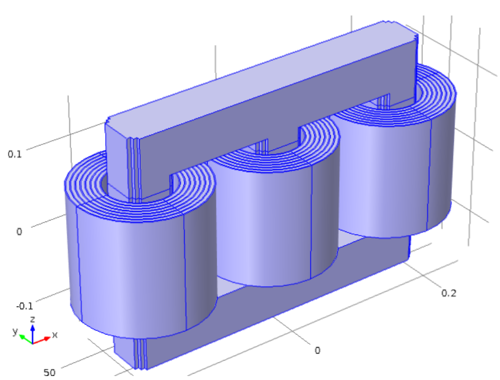


**Figure 2.** Geometry of the transformer model.

In this study, $\dot{q}$ is considered constant inside the core, but a coupled electromagnetic analysis may provide a better insight of the effect of the distribution of this term.

At the boundary with the air, the Newton's Law of Cooling holds true:

$$\vec{q} = h(T_s - T_{oo})$$

Where $\vec{q}\ [Wm^{-2}]$ is the connective heat flux, the heat flux trough the boundary. $T_{oo}\ [K]$ is the quiescent fluid temperature, $T_s\ [K]$ is the surface temperature and $h\ [Wm^{-2}K^{-1}]$ is the convection heat transfer coefficient.

To calculate $h$, one must find the Nusselt number $Nu_L\ [-]$, whose medium value for a finite vertical flat plane is given by [3]:

$$\overline{Nu_L} \approx \left[0.825 + \frac{0.387(Ra_L)^{\frac{1}{6}}}{\left[1 + \left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}\right]^{\frac{8}{27}}}\right]^2$$

$Ra_L\ [-]$ is the Rayleigh number associated with the vertical flat plane geometry:

$$Ra_L = \frac{g\beta(T_s - T_{oo})L^3}{\upsilon\alpha}$$

Where $g\ [m/s^2]$ is the intensity of gravity acceleration, $\beta\ [K^{-1}]$ is the thermal expansion coefficient, $T_{oo}\ [K]$ is the quiescent fluid temperature, $T_s\ [K]$ is the surface temperature, $L\ [m]$ is the characteristic length (for this case, the height of the plane), $\upsilon\ [m^2s^{-1}]$ is the kinematic viscosity and $\alpha\ [m^2s^{-1}]$ is the thermal diffusivity.

In addition, the Prandtl number is given by

$$Pr = \frac{\upsilon}{\alpha}$$

For the upper and lower surfaces of the core (with horizontal walls), the following relations apply, respectively,

$$\overline{Nu_L} = 0.15Ra_L^{1/3}$$
$$\overline{Nu_L} = 0.27Ra_L^{1/4}$$

Finally, one is able to determine the mean heat transfer coefficient in each boundary:

$$\bar{h} = \frac{k}{L}\overline{Nu_L}$$

With $h$ determined for all boundaries and $\dot{q}$ in the whole domain, the temperature distribution $T$ is iterated until convergence.

## 3.3 Simulation Results

For the solution of the stated problem, the heat transfer module was used. The 3D model presented usual convergence times of about 40 seconds in a $i7$, $12GB$ RAM personal computer.

**Figure 3** shows the resulting temperature distribution of the core. The global maximum is $34.76^oC$ and the minimum is $34.62^oC$. The small difference between the extremes is an indicator that the internal heat conduction finds less resistance than the interface with the convective flux.

The natural convection mechanism explains the lower temperatures in the lower side of the core. The air that is heated by the surfaces expands and is driven upwards by buoyancy forces, resulting in a temperature profile with colder air in bottom and an increasingly temperature with increasing height. This allows the lower walls to transfer heat to the fluid in an increased rate, as the temperature difference is higher.

The middle column of the core is a known problematic hotspot. The model is able to predict the tendency of a higher temperature in that region.

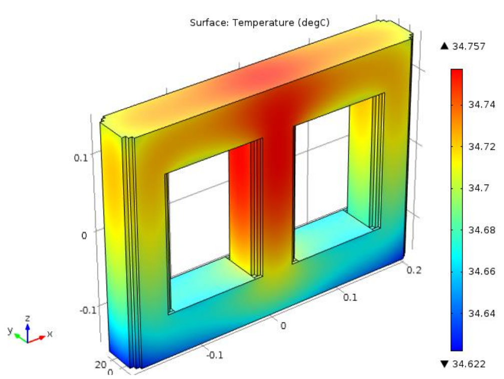


**Figure 3.** Resulting core temperature distribution.

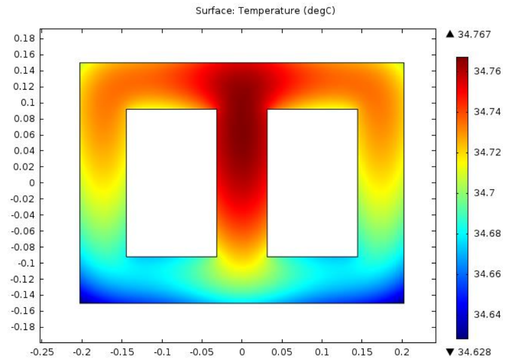


**Figure 4.** Temperature distribution of the central cross-section of the core.

**Figure 4** shows the central cross-section of the core with its associated temperatures. Their values are slightly greater than the temperatures on the surface.

## 4. Experimental Results

To perform the experimental measurements, six temperature sensors were embedded inside the core in the locations indicated by **Figure 5**. The probes have a $1^oC$ sensitivity, and each recorded $37^oC$ except for T5 (the one on the bottom of the middle column), that recorded $34^oC$ in the steady state. **Table 1** compares

**Table 1.** Temperatures in probe points.

| Probe | Measurement $[\,^oC]$ | Simulation $[\,^oC]$ | Difference $[\,^oC]$ |
|---|---|---|---|
| T1 | 37,0 | 34,7 | 2,3 (6,22%) |
| T2 | 37,0 | 34,8 | 2,2 (5,95%) |
| T3 | 37,0 | 34,7 | 2,3 (6,22%) |
| T4 | 37,0 | 34,7 | 2,3 (6,22%) |
| T5 | 34,0 | 34,7 | -0,7 (-2,06%) |
| T6 | 37,0 | 34,7 | 2,3 (6,22%) |

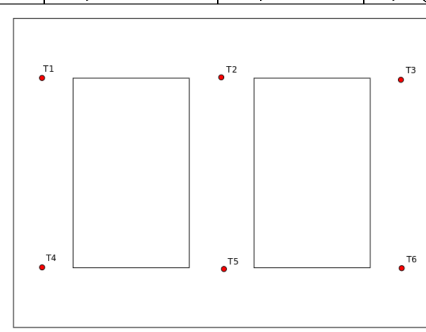


**Figure 5.** Location of the temperature probes.

the experimental and simulation results associated with the six probe points. An average error of $1{,}8^o C$ $(4{,}8\%)$ was found between the model and the real transformer.

## 5. Conclusions

Despite the number of simplifying assumptions regarding the construction of the model, a low margin of error was found between the experimental measurements and the predicted values of temperature.

The techniques utilized in the current study can be used to predict the thermal characteristics of transformers in the design stage with a better degree of confidence.

The simplistic approach resulted in very low convergence times for a Finite Element problem, a feature that can eventually be explored with the use of coupled search algorithms or real-time control strategies.

Future works can focus on improving the technique, such as the incorporation of the effects of radiation and the coupling of an electromagnetic simulation to determine a more realistic distribution of hear sources or the inferring of internal temperatures trough external measurements.

## 6. References

1. Smith, J. J.; Scott, J.A, Temperature Aging Characteristics of Class A Insulation, *American Institute of Electrical Engineers, Transactions of the*, **vol. 58**, pp. 435,444 (1939)
2. Saraiva N.V., *Desenvolvimento de um Sistema de Monitoramento Térmico Aplicado a Transformadores a Seco*, Undergraduate thesis. (in portuguese), Fortaleza, Ceará (2013)
3. F.P. Incropera, D.P. DeWitt, T.L. Bergman, and A.S. Lavine, *Fundamentals of Heat and Mass Transfer*, 6th edition, John Wiley & Sons, 2006.
4. NEMA standard MG-1 Motors and Generators
5. N. El Wakil, N.-C. Chereches, J. Padet, Numerical study of heat transfer and fluid flow in a power transformer, *International Journal of Thermal Sciences*, **Volume 45**, pages 615-626 (2005)

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