VALIDATION OF COMPUTATIONAL FLUID DYNAMIC ANALYSIS OF NATURAL CONVECTION CONDITIONS FOR A RESIN DRY-TYPE TRANSFORMER WITH A CABIN

by

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Many industrial products work under different constraints. Examples of these products include transformers and keeping them in certain operating temperatures is an important design constraint. However, since power transformers have different requirements, there are no standard products. For this reason, it is difficult and costly to test each one by considering these constraints and to design them accordingly. Satisfactory thermal analysis using a 3-D finite volume-based CFD model is an important step to understand natural convection and necessary design modifications under the desired conditions.
The aim of this study is to verify the performance and reliability of the design by comparing the experimental results with 3-D finite volume analysis results by considering cooling of a dry resin type transformer with a cabin. The effect of the cabin on the product in terms of natural heat convection is also evaluated.

Key words: *CFD analysis, natural heat convection, dry-type transformer, temperature distribution*

Introduction

A transformer is an electrical device that transfers electrical energy between two or more circuits through electromagnetic induction without changing the frequency and has no moving parts. Transformers can be classified in two main groups as dry-type (in ambient air) and oil-filled type in terms of insulation and cooling systems. Dry-type transformers are cooled by two basic heat transfer methods: air natural convection and air natural-air forced convection. Dry-type transformers are manufactured with cabins according to desired International Protection Marking standards (in this study, this is IP-31).

Convection is heat transfer due to bulk movement of molecules within fluids such as gases and liquids. Natural cooling is the result of decreasing density of heated air and movement in the opposite direction to gravity. This movement results in air reaching a certain velocity causing heat transfer by convection through the contact surfaces. As a result of this, the transformer is naturally cooled. Natural cooling is enhanced by leaving ventilation holes in the upper and lower parts of the cabin. The air that enters the bottom ventilation holes at ambient temperature heats up because of the energy loss of the transformer. The heated air moves to-

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wards the upper ventilation holes. While this cycle of movement goes on continuously, cooling of the transformer is ensured as a matter of course.

Designs of dry-type transformers are regulated by the standard IEC 70016-11. Ambient temperature values must be known in order to calculate the desired winding temperatures. It is not correct to assume that the temperature inside the cabin and the ambient temperature are equal for dry-type transformers. For this reason, determining the effect of the cabin geometry on the transformer's core temperature and choosing the most effective cabin geometry for optimum cooling performance is very important.

Literature review

Much research has been carried out on prediction of heat generation in the coils, and how the heat is distributed between them. Reviewed research articles that mention these matters can be presented in the following manner when briefly evaluated in terms of their main context.

Komurgoz and Guzelbeyoglu [1] analyzed the temperature distributions of the coils and core obtained by finite element method considering the cooling effect of the oil channels between the windings and the core. As well as the temperature distribution in the windings and the core, temperature distribution and movement of the surrounding air was also determined. The temperature level and the location of the hot spots were determined. The effect of air ducts on the coil temperature in constant and varying ambient conditions in dry-type transformers for different powers was analyzed by Lee *et al.* [2] who also compared calculated temperature values with the experimentally-measured temperature values.

Rahimpour and Azizian [3], and Eslamian *et al.* [4] investigated the effect of temperature variations on the coils with different numbers of air ducts in dry-type transformers. The effect of eddy losses and radiation on the temperature of the coil was also investigated. Moreover, it was proven that the paper bands used in coils have no effect on temperatures [3]. Dry-type transformers were investigated by Eteiba *et al.* [5] in terms of the temperature distributions of coils and cores at different ambient temperatures. The effect of air ducts with different dimensions on the temperatures of windings was also investigated.

A thermal model of the oil-filled-type transformer for oil natural convection cooling system was created and the determined values were compared with the test results from an identical transformer by Gastelarrutia *et al.* [6]. The temperatures and velocity distributions obtained from the calculations are visually specified in the sections taken from the transformer model. Cremasco *et al.* [7] studied the heat and flow analysis of a dry-type transformer, which was cooled by means of a fan in a cabinet. The CFD and thermal/pressure network models were used in the analysis and the results were compared. As a result of these obtained values, the aim was to optimize the cooling systems.

In 1994, Pierce [8] studied ventilated dry-type transformers and found that hottest spot allowances in IEEE standards for transformers larger than 500 kVA are too low and should be revised. He also developed a mathematical model to predict hottest spot temperature rises in ventilated dry-type transformers. Pierce [8] used a system of finite difference nodal equations to estimate hottest spot temperatures and revised the model using six layer test windings and a 2500 kVA prototype transformer.

Tripathi *et al.* [9] have obtained the temperature distributions of air in the room because of changing the input speeds and room dimensions (aspect ratio) for a closed room. Reynolds number and Gr/Re^2 numbers were modified for three different aspect ratios for the room and as a result the streamline and isotherm charts of the room were obtained.

Hannun *et al.* [10] have studied to increase the cooling performance of a 250 kVA oil-type transformer by means of the earth-air heat exchanger (EAHE) method. Here, the EAHE method was compared with the results of the study using the previously made nanofluid and pure oil. As a result of this study, it was seen that the EAHE method provides more efficient cooling. Also, the pipe diameters and air inlet velocities used in EAHE method were investigated to see the effect of transformer on cooling performance.

Materials and method

This phase can be evaluated in the following stages:
– Deciding on the basis of the model.
– Designing solution steps for the model.
– Solving the model using suitable software.
– Experimental set-up modeling from real system considerations.
– Manufacturing of the experimental set-up.
– Carrying out experiments.
– Collection of the experimental results.
– Comparing and representing the analytical and empirical results.

Mathematical model

The mathematical model for the thermal analysis of a cast resin dry-type transformer was developed to obtain the temperature distribution in the cabin. Some mechanical parts, such as clamps and bolts, were ignored in the model for simplification of the model and experimental set-up.

The structure of a transformer is complex, and some assumptions are required. For the aspect of heat analysis, four main components of the transformer can be considered: iron core, low voltage coils, high voltage coils, and air ducts. With this simplified structure, heat transfer fundamentals can be assessed as follows.

Accordingly, the general equations for the temperature distribution and fluid motion in the transformer are shown below. Equations are derived from the conservation laws in steady-state 3-D [11, 12]:
– mass conservation equation

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \tag{1}$$

– momentum conservation equation

$$\rho\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) + S_x \tag{2a}$$

$$\rho\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) + S_y \tag{2b}$$

$$\rho\left(u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = -\frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) + S_z \tag{2c}$$

– energy conservation equation

$$\rho c\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z} \right) = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + q^* + \phi \tag{3}$$

where T [K] represents the temperature, p [Nm^{-2}] – the pressure, q^* [Wm^{-3}] – the heat source, k [Wm^{-1}K^{-1}] – the thermal conductivity, ρ [kgm^{-3}] – the density of material, c [Jkg^{-1}K^{-1}] – the specific heat, and μ [kgm^{-1}s^{-1}] – the dynamic viscosity of fluid. Also, u, v, w are the velocity components in x-, y-, and z-directions. The S_x, S_y, S_z are the mass forces per unit volume in x-, y-, and z-directions, respectively. The ϕ is the viscous dissipation defined:

$$\phi = \mu\left\{ 2\left[\left(\frac{\partial u}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial z}\right)^2 \right] + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 \right\} \tag{4}$$

The numerical simulation of heat transfer was carried out with ANSYS 14.5. A 3-D view of a three-phase cast resin dry-type transformer is used in the analysis [13].

To solve conservation equations, many boundary conditions must be applied to the surfaces of the model. Winding losses, convection and radiation relations are used to obtain a complete graph of the temperatures at every location in the model. In natural convection problem solutions, temperature and velocity of fluid are interdependent, so all basic equations are iteratively and simultaneously solved. From the solution of the equations, it is possible to determine the heat transfer coefficients between the surfaces and the fluid, to obtain the flow fields and to find the temperature fields of the whole system as solids and fluids.

Natural convection: The heat transfer rate of convection is obtained using the equation below [12]:

$$q''_{\text{conv}} = h(T_{\text{s}} - T_{\text{air}}) \tag{5}$$

where q''_{conv} [Wm^{-2}] represents heat transfer rate per unit area at the outer surface, h [Wm^{-2}K^{-1}] – the heat transfer coefficient for convection from outer surface, T_{s} [K] – the local temperature of surface, and T_{air} [K] – the ambient temperature.

The theoretical equations for convective heat transfer are quite complex [11, 12]. The resulting transport equations are usually experimentally-obtained formulations. These formulations are not essential here. The main equations used in the natural convection heat transfer are as follows:

Heat transfer coefficient, h:

$$h = \frac{\text{Nu}\, k_{\text{air}}}{L_c} \tag{6}$$

Grashoff, Rayleigh, and Prandtl numbers:

$$\text{Gr}_L = \frac{g\beta(T_{\text{s}} - T_{\text{air}})L_c^3}{v^2} \qquad \text{Ra}_L = \text{Gr}_L \text{Pr} \qquad \text{Pr} = \frac{c\mu}{k_{air}} \tag{7}$$

where g [ms^{-2}] represents acceleration of gravity, β [K^{-1}] – the volumetric expansion of fluid, v [m^{2}s^{-1}] – the kinematic viscosity of fluid, μ [kgm^{-1}s^{-1}] – the dynamic viscosity of fluid, c [Jkg^{-1}K^{-1}] – the specific heat, and L_c [m] – the characteristic length of geometry.

Radiation: Outer surface is a vertical cylindrical surface and can be assumed as a vertical plate. Two types of heat transfer can occur on the outer surface, including radiation and natural convection.

For the outer surface, radiation can be expressed using the equations [11, 12]:

$$q_r'' = \varepsilon\sigma(T_s^4 + T_{air}^4) = h_r(T_s - T_{air}) \tag{8}$$

$$h_r = \sigma\varepsilon(T_s + T_{air})(T_s^2 + T_{air}^2) \tag{9}$$

where q_r'' [Wm^{-2}] – the heat transfer rate per unit area by radiation, h_r [Wm^{-2}K^{-1}] – the local heat transfer coefficient for radiation from outer surface, and ε is emissivity coefficient of surface. Also, T_s [K] – the local temperature of the surface, T_{air} [K] – the ambient temperature, and $\sigma = 5.67 \cdot 10^{-8}$ W/m^{2}K^4 is Stephan Boltzmann's coefficient.

The CFD analysis using FLUENT

In the analysis, firstly a 3-D model of the internal volume which is the gas for the fluid analysis is created. For creation of this model, designed solid volumes were subtracted from the total volume of the cabin rather than the volume defining the boundary conditions. AUTODESK INVENTOR software was used for all these stages, see fig. 1.

The created 3-D mesh structure is presented in fig. 2. The mesh structure plays an important role in the calculations. The mesh elements are volume and they are defined and placed semi-automatically by the ANSYS/FLUENT software. The mesh structure of the problem is prepared using the *curvature size* function. Mesh structure is mostly composed of *tetrahedral mesh*. A total of 7293011 elements and 1599753 points are used in the model. Figure 3 shows temperature distribution in the cabin. Knowing these distribution and temperature values are important before manufacturing the transformer and its cabin. These predicted parameters improve the design and shortened the test times.
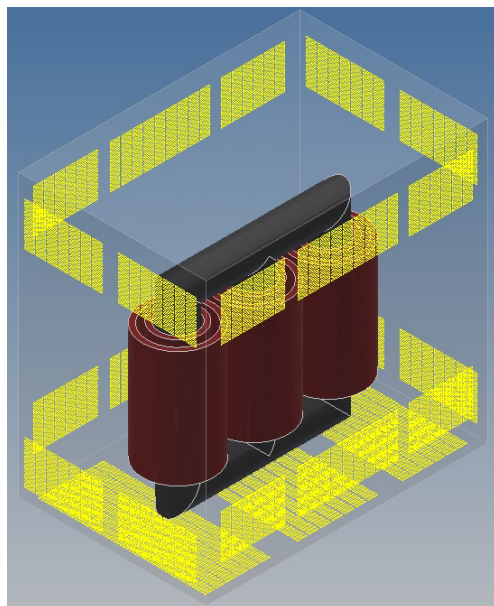

Figure 1. The 3-D Model of the transformer for the ANSYS Fluent Analysis (Prepared fluid flow volume)
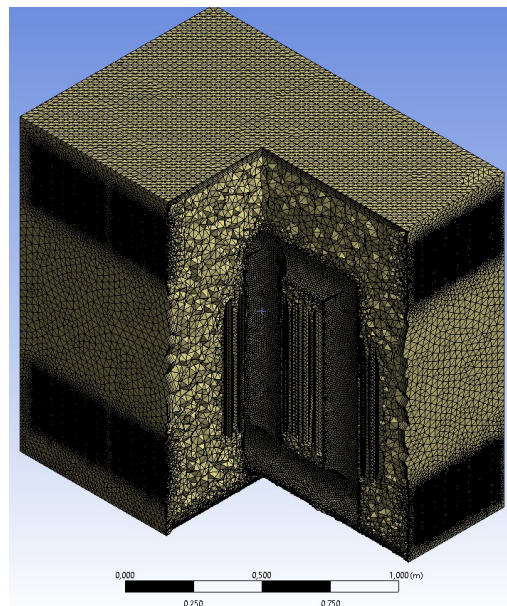
Figure 2. Mesh structure of the 3-D model for Fluent analysis

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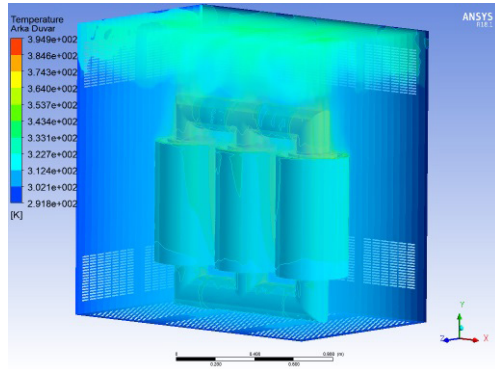
**Figure 3. Temperature distribution of
3-D model** (*for color image see journal web site*)

In this regard, FLUENT (ANSYS) was chosen among possible software programs as it is proven to be successful and accepted. Then, the values of these boundary surfaces were determined and entered into the program for the analysis. When entering the limit surface, the measured values of a similar previously-manufactured transformer are used (250 kVA 11/0.4 kV Dyn11 BEST dry-type transformer).

Following the construction of this model design and determination of the requirements for the CFD analysis, the following sample forms for gradients of internal volume air temperatures, figs. 4(a) and 4(b), were observed.
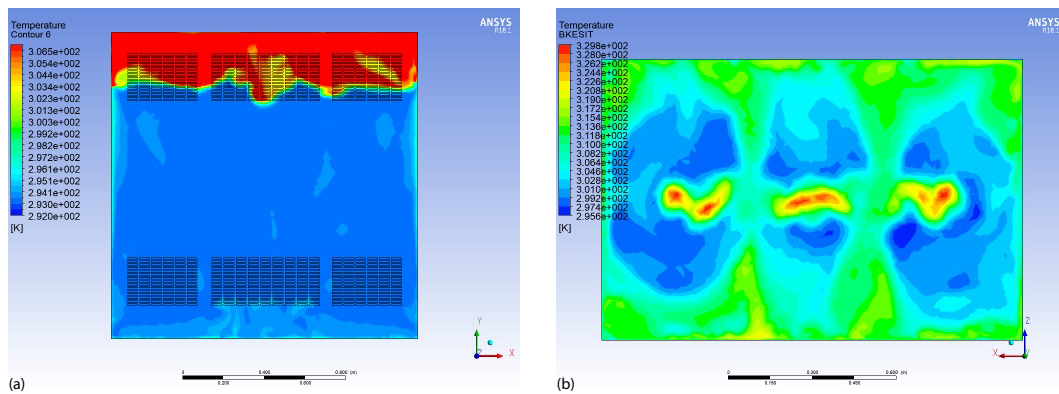
Figure 4. (a) Cross-section (X-Y) analysis of the prepared model, (b) cross-section (X-Z) analysis of the prepared model (*for color image see journal web site*)

Experimental set-up

In order to verify the success of the model, a real cabin was prepared by considering the actual transformer dimensions and design. For design and construction of the experimental set-up, measurements are intended to be made easily and to form the closest values to the true temperatures. It is assumed that most of the losses that occur here (eddy losses and noise losses are neglected) are converted to heat. Three quartz resistances (each 1 kW) were used to represent the cores and they were placed in the specially-designed cylindrical volumes. These cylindrical volumes also have the actual dimensions of the winding volume and are shaped with suitable geometries to allow heat flow in the upper and lower cores.

Figures 5(a) and 5(b) shows the cross-section (X-Z) and (X-Y) of the internal structure of the prepared model, respectively.

Thermocouple sensors were also attached to the tensioned 0.3 mm diameter wires that were connected to the co-ordinates of the specified points to form each measurement range, and the measurements continued every 30 seconds until the system temperature values became stable. The appearance of the data collection devices (HOBO data logger) and thermocouples is shown in figs. 6 and 7.

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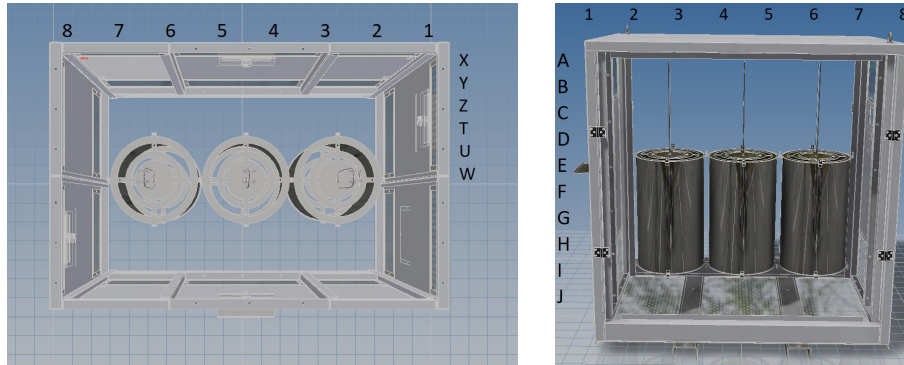
Figure 5. A view of the internal structure of the prepared model (a) in (X-Z) direction and (b) in (X-Y) direction

Figure 6. Data collection devices and test set view during measurements

Figure 7. The view of the location of the thermocouples during measurements

Numerical analysis and experimental results

For certain co-ordinates, the experimental values and numerical values could be compared with fig. 8 and tab. 1. This comparison verifies the thermal model and its analysis. So, these verifications indicate that design and manufacturing of the system can be supported and improved with the CFD analysis.

Table 1. Some temperatures values for comparison

A	X		Y		Z	
	CFD	Exp.	CFD	Exp.	CFD	Exp.
1	34.95	31.83	39.63	37.84	35.97	37.96
2	34.25	34.65	37.32	37.46	34.25	36.30
3	37.39	35.71	38.76	38.52	37.88	37.16
4	37.32	35.82	39.69	39.50	38.14	38.28
5	36.78	35.38	37.10	38.52	37.76	38.00
6	38.50	34.73	38.29	38.41	37.90	37.47
7	34.51	33.99	37.51	37.03	34.30	35.50
8	33.33	31.96	39.90	37.68	35.44	36.64

(a)

	1			2			3			4			5			6			7			8
A	31,830	32,770	33,710	34,650	35,008	35,157	35,71	35,747	35,783	35,62	35,473	35,527	35,58	35,163	34,947	34,75	34,483	34,237	33,99	33,313	32,637	31,96
	32,473	33,081	33,689	34,297	34,682	35,068	35,483	35,460	35,437	35,413	35,336	35,258	35,180	35,599	34,898	34,757	34,418	34,079	33,740	33,263	32,787	32,310
	33,117	33,392	33,668	33,943	34,381	34,819	35,257	35,179	35,090	35,007	34,994	34,989	34,980	34,914	34,849	34,783	34,352	33,921	33,490	33,213	32,937	32,660
B	33,760	33,703	33,647	33,990	34,070	34,550	35,08	34,887	34,743	34,6	34,660	34,720	34,79	34,790	34,800	34,81	34,287	33,763	33,24	33,163	33,087	33,01
	33,223	32,882	32,541	32,200	32,934	33,669	34,403	34,339	34,274	34,210	34,304	34,399	34,493	34,497	34,500	34,503	33,761	33,019	32,277	32,384	32,492	32,600
	32,687	32,061	31,436	30,810	31,799	32,788	33,777	33,791	33,806	33,820	33,949	34,078	34,207	34,203	34,200	34,197	33,236	32,274	31,313	31,606	31,898	32,190
C	32,15	31,240	30,330	29,42	30,663	31,907	33,15	33,243	33,337	33,43	33,593	33,757	33,92	33,910	33,900	33,89	32,710	31,530	30,35	30,827	31,303	31,78
	29,470	28,869	28,268	27,667	28,666	29,664	30,663	30,654	30,646	30,637	30,727	30,817	30,907	31,146	31,384	31,623	30,630	29,637	28,643	28,932	29,221	29,510
	26,790	26,498	26,206	25,913	26,668	27,422	28,177	28,066	27,954	27,843	27,860	27,877	27,893	28,381	28,869	29,357	28,550	27,743	26,937	27,038	27,139	27,240
D	24,11	24,127	24,143	24,16	24,670	25,180	25,69	25,477	25,263	25,05	24,993	24,937	24,88	25,617	26,353	27,09	26,470	25,850	25,23	25,143	25,057	24,97
	24,300	24,322	24,344	24,367	24,788	25,209	25,630	25,450	25,270	25,090	25,062	25,034	25,007	25,477	25,947	26,417	25,973	25,530	25,087	24,956	24,824	24,693
	24,490	24,518	24,546	24,573	24,906	25,238	25,570	25,423	25,277	25,130	25,131	25,132	25,133	25,337	25,540	25,743	25,477	25,210	24,943	24,768	24,592	24,417
E	24,68	24,713	24,747	24,78	25,023	25,267	25,51	25,397	25,283	25,17	25,200	25,230	25,26	25,197	25,133	25,07	24,980	24,890	24,8	24,580	24,360	24,14
	24,413	24,442	24,471	24,500	24,770	25,040	25,310	25,203	25,097	24,990	25,063	25,137	25,210	25,098	24,986	24,873	24,772	24,671	24,570	24,371	24,172	23,973
	24,147	24,171	24,196	24,220	24,517	24,813	25,110	25,010	24,910	24,810	24,927	25,043	25,160	24,999	24,838	24,677	24,564	24,452	24,340	24,162	23,984	23,807
F	23,88	23,900	23,920	23,94	24,263	24,587	24,91	24,817	24,723	24,63	24,790	24,950	25,11	24,900	24,690	24,48	24,357	24,233	24,11	23,953	23,797	23,64
	23,903	23,904	23,906	23,907	24,148	24,389	24,630	24,673	24,717	24,760	24,829	24,898	24,967	24,860	24,753	24,647	24,498	24,349	24,200	23,961	23,722	23,483
	23,927	23,909	23,891	23,873	24,032	24,191	24,350	24,530	24,710	24,890	24,868	24,846	24,823	24,820	24,817	24,813	24,639	24,464	24,290	23,969	23,648	23,327
G	23,95	23,913	23,877	23,84	23,917	23,993	24,07	24,387	24,703	25,02	24,907	24,793	24,68	24,780	24,880	24,98	24,780	24,580	24,38	23,977	23,573	23,17
	24,770	24,746	24,721	24,697	24,723	24,750	24,777	25,086	25,394	25,703	25,567	25,430	25,293	25,368	25,442	25,517	25,358	25,199	25,040	24,684	24,329	23,973
	25,590	25,578	25,566	25,553	25,530	25,507	25,483	25,784	26,086	26,387	26,227	26,067	25,907	25,956	26,004	26,053	25,936	25,818	25,700	25,392	25,084	24,777
H	26,41	26,410	26,410	26,41	26,337	26,263	26,19	26,483	26,777	27,07	26,887	26,703	26,52	26,543	26,567	26,59	26,513	26,437	26,36	26,100	25,840	25,58
	26,407	26,438	26,469	26,500	26,511	26,522	26,533	26,791	27,049	27,307	27,168	27,029	26,890	26,897	26,903	26,910	26,784	26,659	26,533	26,326	26,118	25,910
	26,403	26,466	26,528	26,590	26,686	26,781	26,877	27,099	27,321	27,543	27,449	27,354	27,260	27,250	27,240	27,230	27,056	26,881	26,707	26,551	26,396	26,240
I	26,4	26,493	26,587	26,68	26,860	27,040	27,22	27,407	27,593	27,78	27,790	27,680	27,63	27,603	27,577	27,55	27,327	27,103	26,88	26,777	26,673	26,57
	26,170	26,212	26,254	26,297	26,699	27,101	27,503	27,420	27,337	27,253	27,228	27,202	27,177	27,118	27,059	27,000	26,772	26,544	26,317	26,338	26,359	26,380
	25,940	25,931	25,922	25,913	26,538	27,162	27,787	27,433	27,080	26,727	26,726	26,724	26,723	26,632	26,541	26,450	26,218	25,986	25,753	25,899	26,044	26,190
J	25,71	25,650	25,590	25,53	26,377	27,223	28,07	27,447	26,823	26,2	26,223	26,247	26,27	26,147	26,023	25,9	25,663	25,427	25,19	25,460	25,730	26

(b)

Temperature
Contour 6

3.065e+002
3.054e+002
3.044e+002
3.034e+002
3.023e+002
3.013e+002
3.003e+002
2.992e+002
2.982e+002
2.972e+002
2.961e+002
2.951e+002
2.941e+002
2.930e+002
2.920e+002
[K]
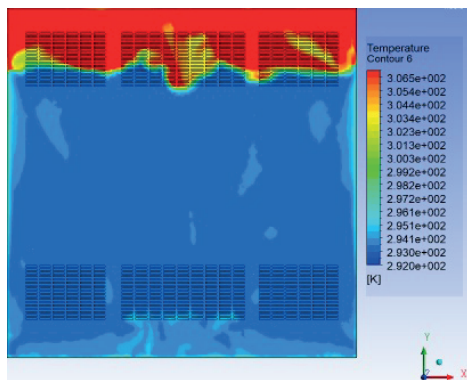
Figure 8. Comparison of test results and CFD analysis $Z = 0.45$ m (X cross-section)
(*for color image see journal web site*)

This study has shown that when the CFD analysis and the experiments can be performed correctly, the results can be taken into consideration and used for design and improvements. However, in order to be able to test each cabin according to the experiment, approximately 480 (6 × 10 × 8) points were measured in spite of symmetry acceptance. This was completed with 60 measurements. Approximately 45 minutes of measurement

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time was required excluding preparations for each measurement. This indicates the cost of time and labor.

Conclusions and further studies

As a result of this CFD analysis and experimental work, the variation of temperature distributions in the cabin was determined for a dry-type transformer with cabin. The obtained CFD analysis data and the experimental data comply with each other. It offers important indications that CFD analysis can be a significant contributor to transformer cabin design with new dimensions and specifications and may be a decisive step in decision-making. Thus, cabin design can be completed in a shorter time, and only with the last analysis. In addition, studies may be recommended for further work to ensure a more efficient natural flow by modifying the design and geometry of the cabin (cabin roof, air inlet and outlet locations).

Acknowledgment

Nomenclature

c – specific heat, $[\mathrm{Jkg^{-1}K^{-1}}]$
g – acceleration of gravity, $[\mathrm{ms^{-1}}]$
h – heat transfer coefficient for convection from outer surface, $[\mathrm{Wm^{-2}K^{-1}}]$
h_r – local heat transfer coefficient for radiation from outer surface, $[\mathrm{Wm^{-1}K^{-1}}]$
k – thermal conductivity, $[\mathrm{Wm^{-1}K^{-1}}]$
L_c – characteristic length of geometry, [m]
q – heat transfer rate per unit area at the outer surface, $[\mathrm{Wm^{-2}}]$
q^* – heat source, $[\mathrm{Wm^{-3}}]$
S_x, S_y, S_z – mass forces per unit volume in x-, y-, z-directions
T – temperature, [K]
T_{air} – ambient temperature, [K]
T_s – local temperature of surface, [K]
u, v, w – velocity components in x-, y-, z-directions

Greek symbols

β – volumetric expansion of fluid, $[\mathrm{K^{-1}}]$
μ – dynamic viscosity of fluid, $[\mathrm{kgm^{-1}s^{-1}}]$
$\mu\phi$ – viscous dissipation
ε – emissivity coefficient of surface
ν – kinematic viscosity of fluid, $[\mathrm{m^2s^{-1}}]$
ρ – density, $[\mathrm{kgm^{-1}}]$
σ – Stephan Boltzmann's coefficient, $(= 5.67 \cdot 10^{-8}\ \mathrm{W/m^2\ K^4})$

Subscripts

air – ambient (air)
c – characteristic
r – radiation
s – surface
x, y, z – Cartesian co-ordinates

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