U.P.B. Sci. Bull., Series C, Vol. 72 , Iss. 4 , 2010 ISSN 1454-234x

DIMENSIONAL OPTIMIZATION OF FRONTAL RADIATORS OF COOLING SYSTEM FOR POWER TRANSFORMER 630 kVA 20/0.4 kV IN TERMS OF MAXIMUM HEAT TRANSFER

Ştefan D.L. ȚĂLU[1], Mihai D.L. ȚĂLU[2]

Obiectivul acestei lucrări este de a analiza prin Metoda Elementului Finit (FEM) şi de a optimiza dimensional radiatoarele frontale ale sistemului de răcire pentru transformatorul electric de putere TTU 630 kVA 20/0.4 kV din punct de vedere al transferului termic maxim.

Analiza cu Elemente Finite a fost realizată cu ajutorul programelor software SolidWorks 3D CAD Design şi COSMOSFlow Works 2008. Rezultatele metodei propuse în proiectarea economică a transformatorului electric de putere 630 kVA 20/0.4 kV reduc semnificativ costurile de fabricație ale transformatorului.

The objective of this paper is to analyze through the Finite Elements Method (FEM) and to dimensional optimize the frontal radiators of cooling system for electric power transformer by type TTU 630 kVA 20/0.4 kV in terms of maximum heat transfer.

Finite Elements Analysis was performed using SolidWorks 3D CAD Design and COSMOSFlow Works 2008 Software. The proposed method results in the economical design of the electric power transformer by type 630 kVA 20/0.4 kV significantly reduce the cost of manufacturing transformer.

Keywords: power transformer, cooling system radiators, Finite Element Method

1. Introduction

The electric power transformer is one of the most important components in a power system [1, 2]. The electric power transformer design is one of the most complex electrical equipments design problems, which requires a complex interdisciplinary collaboration between engineers, analysts and designers [3].

The electric power transformer optimization is an important research field at international level [4]. The optimum design through the Finite Elements Analysis of an electric power transformer can significantly reduce the weight, the power consumption, the cost of manufacturing, and increase security and even the reliability of the entire transformer unit [5].

[1] Ph.D., Assoc. Professor, Department of Descriptive Geometry and Engineering Graphics, Faculty of Mechanical Engineering, Technical University of Cluj-Napoca, Romania, e-mail: stefan_ta@yahoo.com

[2] Ph.D., Assoc. Professor, Department of Applied Mechanics, Faculty of Mechanical Engineering, University of Craiova, Romania, e-mail: mihai_talu@yahoo.com

Heat transfer problems in electrical power transformers have been analysed for more than 50 years [6]. In most of these analyses, calculations were based on the averaging of the Nusselt numbers values [6].

The numerical calculations, generally, is a complex task, especially for three-dimensional models [6, 7].

The cooling system of the power transformer is designed for normal operations. But actually, the transformer might run on over load for a longer duration or frequently for shorter durations [8].

An important problem at the electric power transformer optimum design is to dimensional optimizing the cooling system radiators [9-18].

The structure of a transformer winding is complex and does not conform to any known geometry in the strict sense [6, 7].

This paper presents the dimensional optimization of frontal radiator of cooling system for electric power transformer by type 630 kVA 20/0.4 kV in terms of maximum heat transfer.

The electric power transformer by type TTU 630 kVA 20/0.4 kV is shown in Fig. 1 [19].

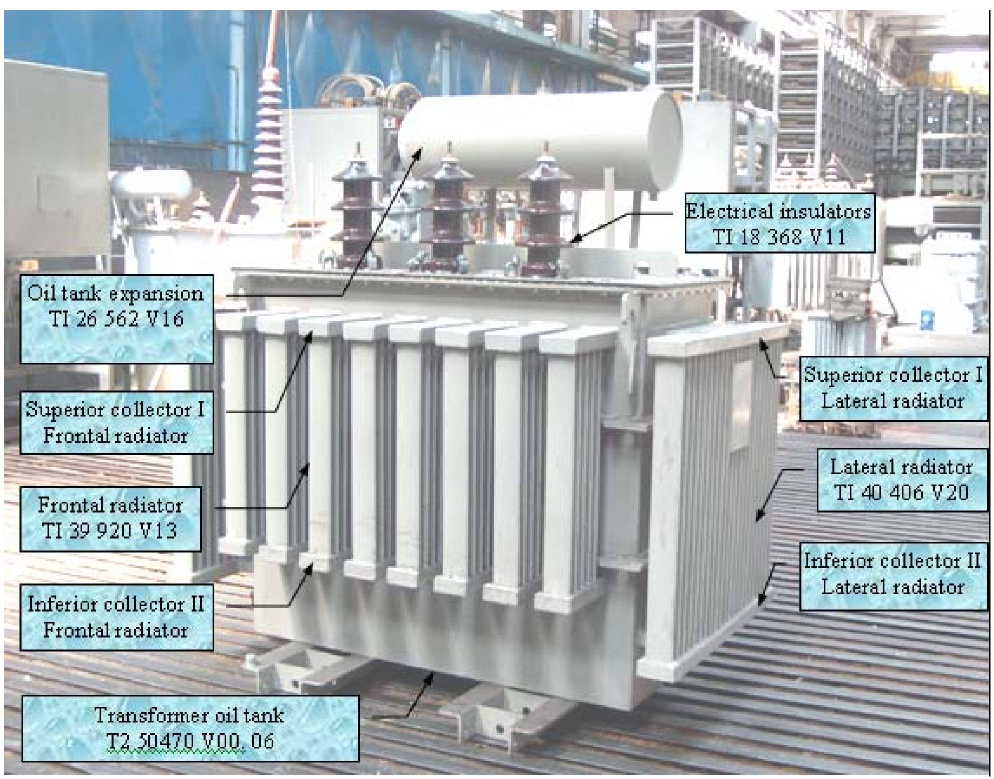

Fig. 1. The electric power transformer by type TTU 630 kVA 20/0.4 kV

2. Thermal modelling

Thermal analysis represents the study of heat transfer through devices. Thermal modelling involves the developing of a mathematical model to predict the temperature profile of a device that uses the principle of thermal analysis.

The thermal model depends on the principles used in design and precision values used for parameters. These thermal models are based on conventional heat transfer theory, transformer thermal tests and reports, application of the lumped capacitance method, the thermal-electrical analogy, and the concept of nonlinear thermal resistances between different locations within a power transformer [6, 7].

In our study the transformer geometry is divided into a finite number of elements and in each of the elements the flux density is found using the FEM.

The thermal model for the entire transformer geometry is composed by assembling together the thermal behavior of the components.

The 3D model consists of two subregions: a) the first subregion (the transformer) was discretised into 500,000 Hex8 elements; b) the second subregion (the surrounding air) was discretised into 300,000 Hex8 elements. According with the *EquiAngleSkew* mesh quality-type specification, more than 90 % of the cells had a value less than or equal to 0.25 (classified as very good elements).

3. Mathematical model

The temperature distribution within the device and its surroundings can be expressed by solving the energy equation [6]:

$$\nabla(K\nabla T) + q_v = \rho_0 \cdot c \frac{DT}{Dt}, \tag{1}$$

where T is the temperature [K], k stands for thermal conductivity [W/mK], q_v represents the source term rate [W/m^3]. The density ρ was assumed to be constant [kg/m^3], c is the specific heat [J/kgK], and t is time [s].

The derivative on the righ-hand side is the substantial derivative:

$$\frac{DT}{Dt} = \frac{\partial T}{\partial t} + w_x \frac{\partial T}{\partial x} + w_y \frac{\partial T}{\partial y} + w_z \frac{\partial T}{\partial z} = \frac{\partial T}{\partial t} + \nabla T \cdot w, \tag{2}$$

where w_x, w_y, w_z are the velocity components of vector w in the x, y, z direction [m/s], respectively, and x, y and z represent the Cartesian coordinates.

The energy equation (1) is complemented by the continuity and the momentum equations.

The continuity equation for incompressible fluids is expressed as:

$$\nabla \cdot w = 0, \tag{3}$$

The momentum equation (Navier-Stokes equation) is expressed as:

$$\rho_0 \frac{Dw}{Dt} = F - \nabla p + \mu \nabla^2 w, \tag{4}$$

where p is the pressure [N/m^2], F represents the body force term which in the present case has only a vertical component $F_z = \rho g$ in the z-direction [N/m^3], g is gravity acceleration [m/s^2], and μ is dynamic viscosity [Ns/m^2].

The Boussinesq approximation was adopted for the buoyancy term in equation (4).

The boundary conditions prescribed are:
a) external boundary conditions.
- Pressure boundary conditions were prescribed on all external walls of the surrounding air. It requires the specification of a static pressure and temperature of 'backflow' at the outlet boundary.
- a standard k-ε model was used to model turbulence within the cooler.
b) internal boundary conditions.
Along each interface, including the interface between the transformer and the surrounding air, standard continuity boundary conditions were prescribed.

The convergence criterion was 0.01 %. The errors δ_T and δq are defined as:

$$\delta_T = \frac{|T_i - T_{i+1}|}{T_i} \cdot 100 \ [\%]; \ \delta_q = \frac{|q_i - q_{i+1}|}{q_i} \cdot 100 \ [\%], \quad (5)$$

where T_i, T_{i+1}, q_i, q_{i+1} represented the average temperatures and heat fluxes in two subsequent steps.

The numerical model requires an iteration loop in order to obtain the solution. If each independent submodel is fully converged, the iteration process converges faster by performing less steps.

The error δ_{1T} was calculated based the temperature profile obtained from the transformer with prescribed average heat transfer coefficients and the temperature profile from the first iteration. The error δ_1q was calculated based the heat flux profile in the air subregion with a prescribed temperature profile from the initial step and the heat flux profile from the next loop.

The mathematical objective function was to optimize the dissipative heat transfer customized on system components.

4. Measurements and experiments

The positions of temperature measuring sensors were made according the scheme of the experiment [19].

Ten sensors was placed inside the transformer; additional eight measuring points were: the oil entering (top) and exiting (bottom) the radiator, the top oil (two position – in the pocket and in the central horizontal position), four positions at different height of the outer surface of the radiator, ambient temperature.

During the transient thermal processes the following 12 local temperatures were measured: two positions at which hot-spot could be expected (sensors 1 and 2); oil in the cooling channel between the inner and the outer winding parts (sensors 3 and 4); oil near (2 mm) the outer winding surface (sensors 5); oil at 5 mm from the outer winding surface (sensor 6); one position at the inner winding surface (sensor 7); one position at the outer winding surface (sensor 8); the oil entering (top) and exiting (bottom) the radiator, the top oil in the pocket and the ambient. The values of other temperatures were measured only in thermal steady-states at different transformer constant loads.

The series of heating experiments was done with different load profiles [19].

5. The dimensional optimization of frontal radiator of cooling system in terms of maximum heat transfer

5.1. The dimensional optimization of frontal radiator of cooling system

The oil flow inside the oil tank is a complicate process, dependent on the temperature, viscosity and whether the oil flow is natural or forced. The transformer system cooling is a hydraulic circuit with natural convection [19].

The cooling system is made by: walled metal tank fitted with radiators (frontal radiators T1 39 920 V13 placed front-back and lateral radiators T1 40 406 V20 placed side left-right); system isolated for oil cooling circulating (Fig. 2).

The experimental measurements indicate that in a high thermal functioning, the input oil into the frontal radiator at a temperature of T = 95 °C with a heat transfer by convection at the free surface of the frontal radiator in contact with air at a temperature of T = 55 °C and an input speed into radiator v = 10 [mm/s], there is a oil cooling long before the full length through the radiator elements to be finished. Moreover, the heat exchange is very low in the last 3-4 elements making their presence to be unnecessary.

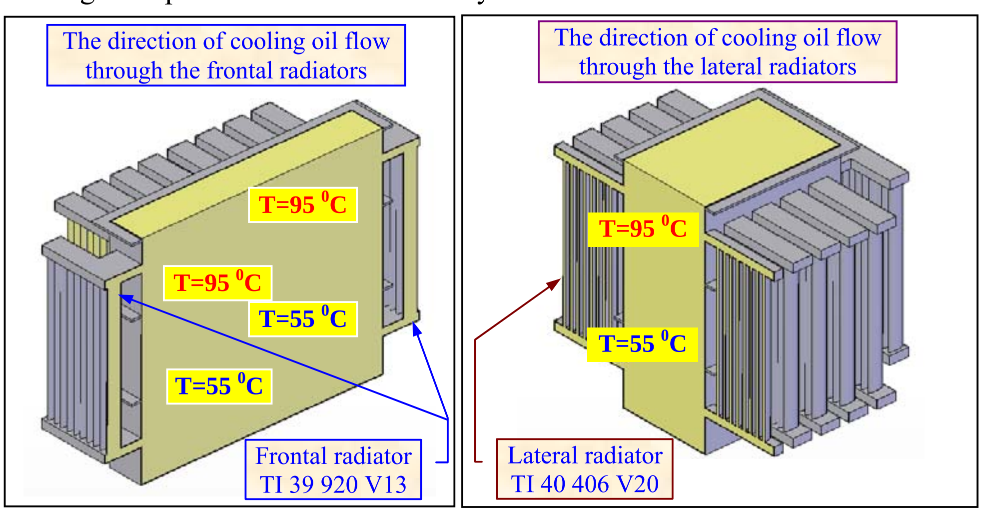

Fig. 2. The direction of cooling oil flow through the frontal and lateral radiators

That’s why, by shortening the length element with ΔL = 28 % (from the initial length L = 720 mm at proposed length L = 520 mm) and the elimination of the last 4 elements (their number was initially n = 9) is obtained the same transfer in terms of thermal heat (in terms of the cooling oil), so there is a reduction with Δn ≅ 30 % of the number of elements (Fig. 3).

In Fig. 3 is shown a section through the symmetry plane for the modified radiator with a number of n = 5 elements and L = 520 mm.

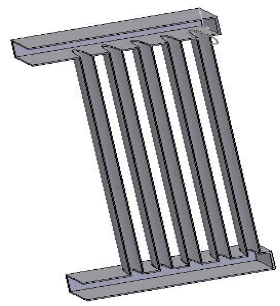

Fig. 3. The frontal modified radiator with n = 5 elements and L = 520 mm

After this changing over the frontal radiator, the survey realized by graphical representations of isothermal surfaces, shows that the oil cooling up to the air temperature T = 55 °C occurs near the exit section elements.

The distance from the end of a surface element, corresponding for a temperature T = 55 °C is less than the first element and increase to around element 5, up to approximately ΔL = 20 % of its length (Fig. 3).

The isotherm surface (for constant temperature) at T = 328.01 K shown in Fig. 4a, and for T = 328.001 K shown in Fig. 4b, indicate major modifications of isothermal positions for small differences in temperature of cooling oil, moving it to exit of radiator (Fig. 4b).

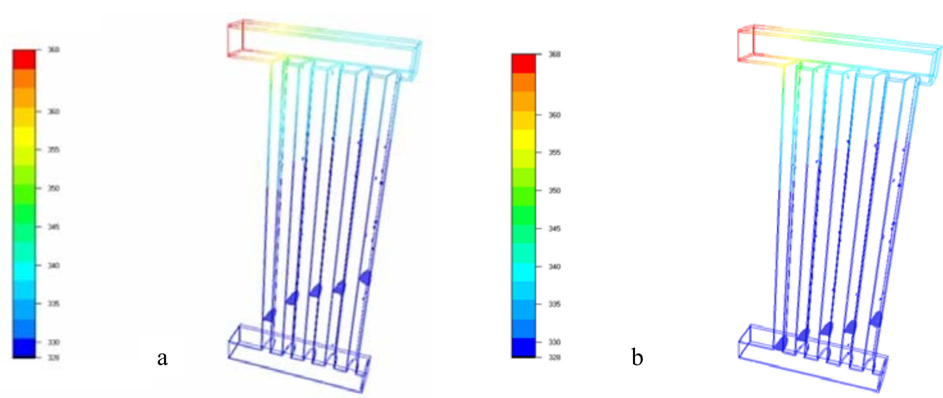

Fig. 4. The isotherm surface for: a) T = 328.01 K; b) T = 328.001 K

Therefore was adopted a more finely mesh of the temperature difference ΔT, when the thermal field distribution was studied for lower temperatures below the cooled oil that leaves the frontal radiator. Also, it is noted that if is increased this distance relative to end out of the radiator, concerning the specified isothermal surfaces, is due to variable oil flow through the 5 elements.

This flow can be equalized through additional constructive solutions that must be studied in terms of economic efficiency, to reduce the cost of transformer cooling system manufacturing. To highlight the temperature variation of along the cooling transfer process, isothermal surfaces were traced with a mesh from degree to degree near the input oil to the radiator, and the output section of the elements was decreased with a mesh in thousandths of degree.

5.2. Other constructive variants concerning modification of the frontal radiator considering the leveling of the oil flow flowing through elements

Next constructive step is to adopt a constructive solution so that the flow of oil heated to maximum temperature T = 95 °C within the superior collector at a speed of v = 7 [mm/s] to penetrate into the vertical elements of radiator with approximately equal flow rates, without additional technological and constructive radiator costs. This would allow more uniform heat dissipation on the radiator elements and can decrease the number of elements.

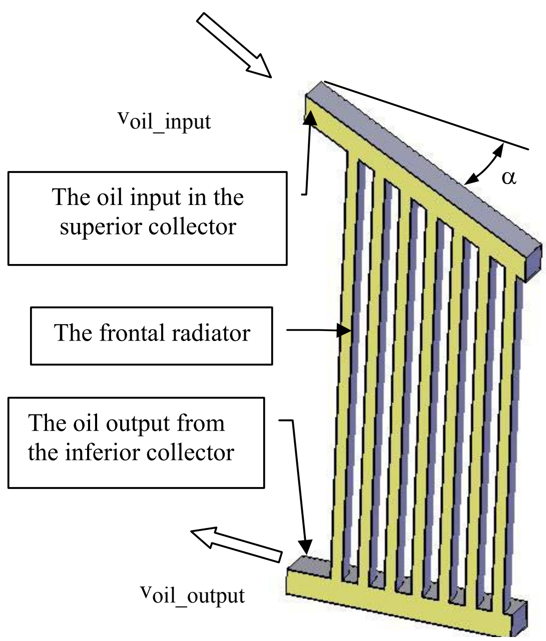

Fig. 5. The frontal radiator with 7 elements

In next analysis is considered a natural convection for radiator with an air temperature of T = 55 °C. In a first analysis the number of radiator elements was reduced to n = 7 items, from a number of n = 9 elements (Fig. 5).

It takes a constructive solution to tilt the superior collector maintaining the first element length at L = 750 mm. In conclusion the radiator elements length decreases to the outside as shown in Fig. 4b.

To determine the optimal inclination angle α of superior collector was calculated the distribution of temperature field by graphical representation of isothermal surfaces for different values of cooling oil temperature.

The aim is to determine the surface position that is reached by oil cooling temperature compared to the output section from the inferior collector.

There are shown the results of calculations for an inclined collector with: α = 15°, α = 20° and α = 30°.

After calculation it was found that the optimal angle of inclination of the superior collector is α = 20°. Also it is found that in case of inclination of the superior collector with α = 30°, the oil is not completely cooled, this leaving the radiator with an excess of temperature above ΔT = 1.15 °C, relative to the air temperature that cools the radiator, and so this leads to an unaccepted functioning.

5.2.1. The heat exchange calculation results of the frontal radiator for an inclination of the superior collector with α = 15°

The isotherm surface for T = 328.1 K is shown in Fig. 6a and for T = 328.001 K is shown in Fig. 6b.

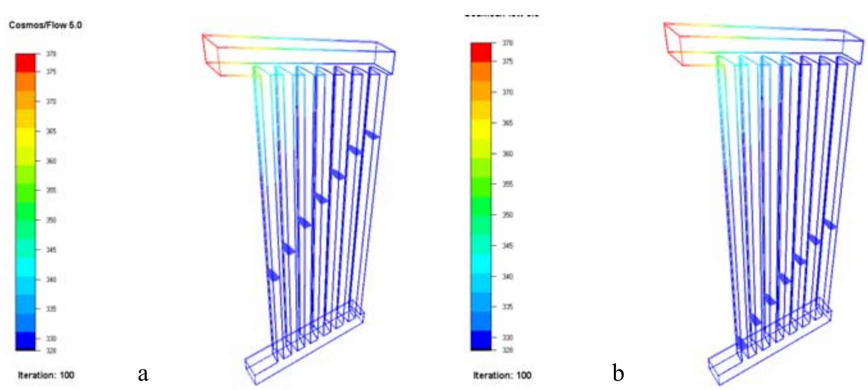

Fig. 6. The isotherm surface for: a) T = 328.1 K; b) T = 328.001 K

5.2.2. The heat exchange calculation results of the frontal radiator for an inclination of the superior collector with α = 20°

Since this is the optimal variant the results will be shown in Fig. 7 to Fig. 9.

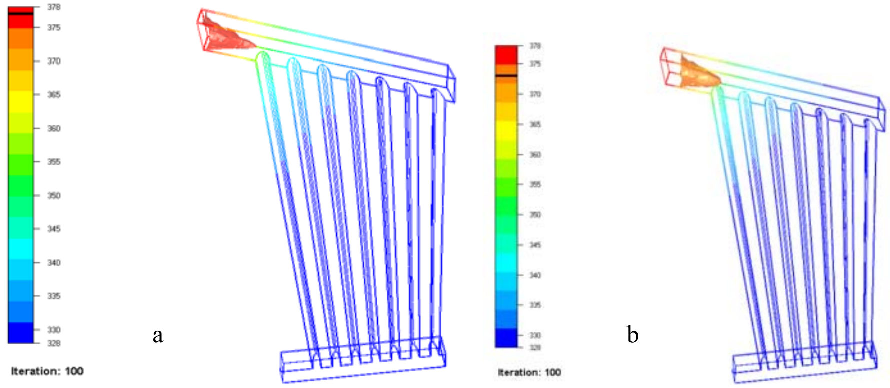

Fig. 7. The isotherm surface for: a) T = 377 K; b) T = 373 K

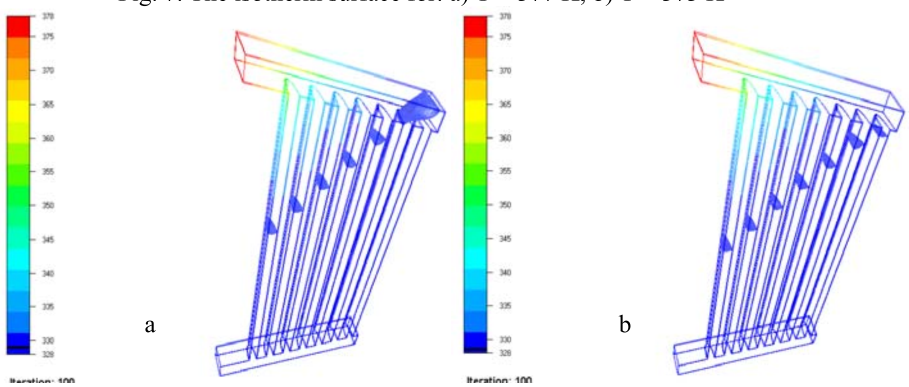

Fig. 8. The isotherm surface for: a) T = 329 K; b) T = 328.5 K

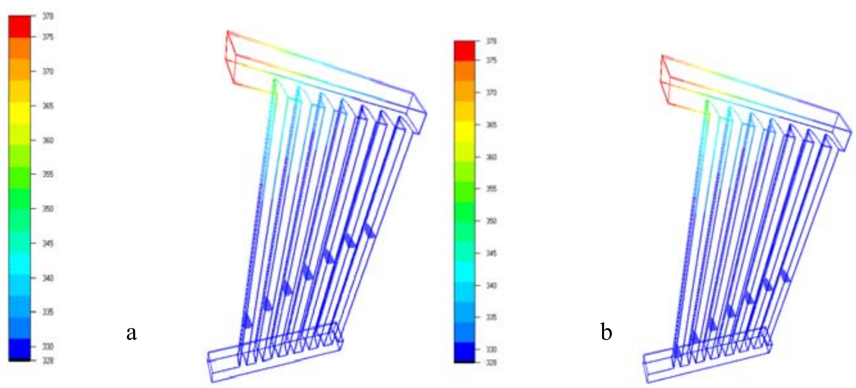

Fig. 9. The isotherm surface for: a) T = 328.01 K; b) T = 328.001 K

5.2.3. The heat exchange calculation results of the frontal radiator for an inclination of the superior collector with $\alpha = 30°$

The isotherm surface for T = 328.1 K is shown in Fig. 10.

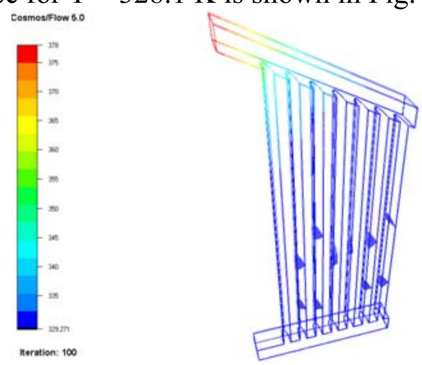

Fig. 10. The isotherm surface for T = 328.1 K

6. The temperature distributions for the frontal radiator in the initial and optimized variant

The temperature distributions for the frontal radiator in the initial and optimized variant are shown in Fig. 11a and Fig. 11b.

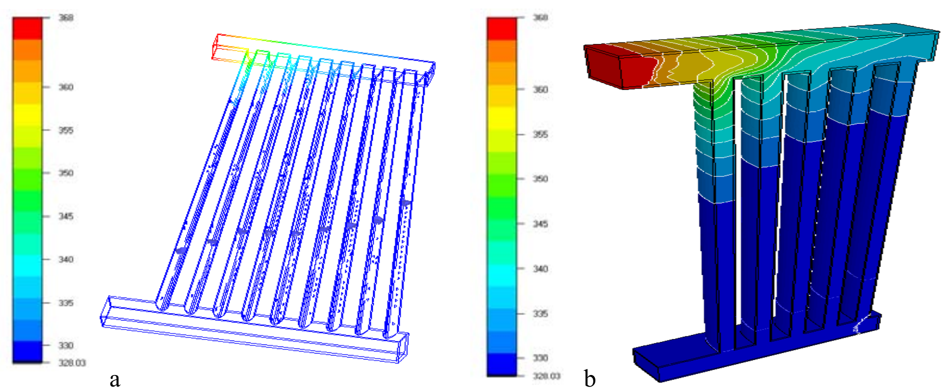

Fig. 11. The temperature distributions of the frontal radiator: a) initial variant; b) optimized variant

7. Conclusions

This paper analyze through the Finite Elements Method (FEM) and dimensional optimize the frontal radiator of cooling system for power transformer 630 kVA 20/0.4 kV in terms of maximum heat transfer.

The model are validated using experimental results, which have been obtained from a series of thermal tests [19].

The error caused by each of approximations was precisely quantified, using the data of measurements on the power transformer with a large number of temperature sensors placed inside the tank and in the winding [19].

As a result of optimization has been obtained: - reducing the cooling elements; - reducing their size; - reconfiguring design; - optimal location of radiator front and back on the oil tank; - dimensional change of the oil tank [19].

Dimensional changes made to the optimized cooling, increased oil cooling efficiency and bring significant cost savings by: - reducing the amount of ferrous material used (metal sheets, pipes); - reducing the amount of oil processed; - reducing the working temperatures by cooling hydraulic oil cooling circuit of the transformer; - reducing the total weight of the product, using a smaller amount of ferrous materials in construction and oil; - reducing labor for transformer manufactured [19].

8. Acknowledgments

This work has partly been funded by the Contract Research Program Partenerships in Priority Areas, through Romanian Ministry of Education and Research, Program RELANSIN, Contract no. 21070 / 14 IX 2007, 2007 - 2009, "Monitoring the efficiency of the cooling of high power transformers" and Grant PN–II–ID–PCE–2007–1, code ID_1107, 2007 – 2010, through Romanian Ministry of Education, Research and Youth - The National University Research Council.

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