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Ivankov V. F.[1], Basova A. V.[2]

[1]PhD, Chief of bureau of PJSC «ZTR», Ukraine, E-mail: victor.ivankov@ztr.com.ua
[2]Leading engineer-designer of PJSC «ZTR», Ukraine

CALCULATION OF CFD-THERMAL MODELS OF OIL-COOLED TRANSFORMER EQUIPMENT

The purpose *of the study is to ensure designing of full-function and stable CFD-simulation procedure for integrated thermal models of the transformers and the reactors, as well as to receive the approval of method of quality and abilities using the calculation examples of full-scale models of the equipment, along with autonomous models of coil-type windings having various design versions of heat-transfer intensification.*

Research Methods. *Computational Fluid Dynamics (CFD) method of mathematical simulation of nonlinear processes as concerns hydrodynamics and heat transfer in the transformer equipment using finite-element analysis is employed.*

The results obtained. *The paper presents the main elements of technique for creation of mathematical models; it also contains the examples of CFD-calculations as referred to axisymmetrical integrated models of furnace transformer and gapped-core shunt reactor, as well as the models of windings having design approaches of heat exchange intensification owing to «labyrinth» (partitions) and «alternation» (of number and locations) of axial cooling ducts.*

Scientific novelty. *Scientific value of applied methodological approach lies in the fact that the developed models are the integrated ones, i.e., they consider geometry, loss, thermal parameters not only of the windings, but also of the main structural elements and cooling system. This ensures the quality and the accuracy of simulation of heat-and-mass transfer processes in complex structure of oil ducts and coils in the windings, enables to avoid erroneous «zigzag» oil flow movement through the groups of coil regular structures (without labyrinth and «alternation» of number and locations of axial ducts under conditions of transformer oil natural cooling as was deduced in the certain studies.*

Practical significance. *Integrated models ensure calculation of oil temperature distribution within active part, including winding fields, oil temperature field between the tank and the windings, temperatures at oil outlet from the tank (top) and oil inlet into the tank (bottom). Calculations allow estimation of mean temperature distribution over the cross-section of winding coils, mean winding temperatures by means of averaging of the temperatures within the coils, detection of location and maximum temperature on the surface of conductors relevant to the most heated coil. The latter is treated as winding hot spot temperature (HST) and used to evaluate the aging of the contacting insulation. Determination of winding hot spot locations and temperatures (HST) is used as support data for installation areas of fiber optic probes for measurement during type testing, as well as in operational monitoring systems of the equipment. The results presented above are practically applied for industrial designing and testing of transformers and reactors.*

Key words: *transformers, heat-and-mass transfer, CFD-simulation.*

INTRODUCTION

An important condition for ensuring reliability and duration of operation (load capacity) of the transformer equipment is efficient removal of active energy released as the heat in the magnetic system (MS), the windings, the conductive elements of active part structure, and the tanks. Namely, efficiency of heat removal in the windings determines essentially technical, mass-and-overall and economical characteristics of the equipment. Therefore, within designing availability of reliable calculation methods of winding heating is of great importance [1]. This is especially true in the cases of approaches of heat transfer intensification in the coils due to oil labyrinth flow in the coil groups, provision of axial ducts with alternation of their number and locations along the coil width, etc.

Known methods of oil heating calculations, transformer equipment windings within steady-state temperature mode are conventionally divided in the following groups:

– «empirical method of overheating» [1–5] based on application of heat equation, and empirical heat transfer coefficients averaged over the coils' surfaces, taking into account oil temperatures in place of coils arrangement along the winding height and summation of temperature rises of coil conductor surface over the oil, temperature gradient along insulation thickness of elementary conductors and common insulation of the conductors. Empirical methods are widely used in industrial designing [6], however, their application is limited to the range of empirical data by type, size and design of the windings; in many cases these methods do not allow the required accuracy to determine hot-spot locations (HST) of the windings and their temperature;

– methods of nonlinear thermal-hydraulic circuits both within the windings [7–9], and for common thermal-hydraulic circuit of the transformer, including external cooling system (CS) [10]. When used, the complex processes in continuous media as described by equation system (1) – (3), are represented simplistically by zero-dimensional thermal and hydraulic elements having the lumped parameters, that do not allow to determine the local values of temperature and velocity;

– methods of field simulation of thermal, hydrostatic and hydrodynamic winding fields [11–14] based on the

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numerical solution of the problems (1) – (3) using various additional simplifications as to their formulation; modern advanced CFD methods (Computational Fluid Dynamics) of mathematical modeling of hydrodynamics and heat transfer processes in the transformers, in particular, using the system of finite element analysis (FEA) [9, 15–23].

A similar group of methods is also emphasized in the summary paper [24], where the first of these methods has been defined as the empirical method of «correlation»; there are also large-scale and detailed modern studies as regards to CFD-modeling, investigation of transfer thermal processes, measurements of windings HST, including the method using fiber optic sensors.

Methodological approaches as to the CFD-modeling of power transformer thermal modes of using the complex models of transformer equipment composed of the MS, the conductive structural elements, the windings and the external cooling systems are presented in [16–21].

At consideration of mentioned works as regards to CFD-modeling, the following notes should be made.

In contrast to [16–21], [9, 15, 22–24], the complex CFD-modes of the transformers are omitted, and there are no studies as regards to electrical reactors.

In [16], one of methodological approaches is used for consideration of development and investigation of the systems of consistent field macro- and micro-models of the devices, the windings, the coil groups. However, experience of practical calculations has shown that this approach has the restricted application. Computation based on micro-models of winding equivalent parameters and their further application in the complex thermal macro-models has been problematic.

At the same time, simulation of the windings, the coil groups by means of consideration of their autonomous models having specified boundary conditions is appropriate [9, 22–24].

In a sense, the most stable thermal-hydraulic processes of oil motion (velocity fields) and the distribution of heating (temperature fields) are demonstrated in all of these studies using the windings with «arranged» direction of cooling oil. Typically, this is achieved by means of so-called labyrinth movement of oil in groups of horizontal ducts along winding height separated by the guiding spacers. In the number of studies [19, 20, 22, 23], it has been turned up that oil velocity vectors can change oil direction in the case of natural convection of oil in the windings with regular structure of horizontal and vertical ducts. So, in the paper [19, 20] «Analysis of flow pattern in the system of interconnected ducts allows detecting of spontaneous zigzag flowing of oil in groups, that directly affects the coil temperature». It should be noted that in the certain experimental studies of such nature of the velocity field is reported. The numerical studies conducted by the authors of this paper have shown that such results can be obtained by faulty settings of computational process.

The above mentioned problem is to be focused on creation of adequate mathematical model of oil flow in the system of interconnected horizontal and vertical ducts of the winding by means of invariant software. This issue was especially considered in the study [17, 18]. The studies were carried out using conventional winding models with limited coil number (10, 3) placed in the thank with external SW. On assumption as for laminar nature of oil flow it was determined that in horizontal ducts oil flow makes a loop-like movement with gradual increase of oil penetration depth to the coil center as it flows from the bottom upwards along the vertical ducts. Oil flow in the duct prompts the flow during formation of Reyleigh-Bernard convection cells [25]. In [25] the effect of destruction and detachment of oil boundary layer at the area nearby the vertical surfaces of the coils is also noted, which does not mean the beginning of turbulent (eddy) motion of oil, but is caused by mixing of oil particles having different temperatures. In both of mentioned studies [17, 18], there were no results as referred to straight-through oil flow in the horizontal ducts. It is emphasized that numerical studies were carried out using the winding fragments consisting of limited number of coils.

But further in the studies [19, 20], during investigation of complete integrated model of power transformer 140 MVA, it was found in HV winding consisting of 156 coils that «in horizontal and vertical ducts of the winding the steady-state structures in the form of zigzag and/or loop-like oil flow within the groups of horizontal ducts are created.» The resulting numerical result is considered to be erroneous.

The relevance of the study is determined by the need to creation of high-performance transformer equipment with increased specific electromagnetic and thermal loads, reliability of which is achieved also by means of heat transfer intensification in the windings.

The purpose of the study is to ensure designing of full-function and stable CFD-simulation procedure for integrated thermal models of the transformers and the reactors, as well as to receive of the approval of method quality and abilities using the calculation examples of full-scale models of the equipment, as well as autonomous models of coil-type windings having various design versions of heat-transfer intensification.

KEY ELEMENTS OF PROCEDURE

For the purpose of formation of mathematical models and CFD-studies of oil-cooled transformer equipment the following method basic elements (including the papers [16-21], are presented as thesis).

1 Thermal processes in oil-cooled electrical devices in the most complete formulation should be considered using known Navier-Stokes equations of motion and continuity of cooling liquid.

$$\rho(\vec{v}\cdot\nabla)\vec{v} = -\nabla\cdot(PI) + \nabla\cdot\bar{\tau} + \rho\vec{g} \qquad ,$$

$$\bar{\tau} = \mu\left[\left(\nabla\vec{v} + \nabla\vec{v}^{T}\right) - \frac{2}{3}\nabla\cdot\vec{v}\,\hat{I}\right], \qquad (1)$$

$$\nabla \cdot (\rho \vec{v}) = 0\,, \tag{2}$$

to be supplemented by energy-conservation equation

$$\nabla \cdot (-\lambda \nabla \theta) = Q_v - \rho C (\vec{v} \cdot \nabla \theta), \tag{3}$$

where the following is designated: θ, P and $\vec{v}$ – fields of temperatures, pressures and velocities of cooling medium, $Q_V(\theta)$ – apparent densities of heat sources, $\rho(\theta)$, $\mu(\theta)$, $C(\theta)$ and $\lambda(\theta)$ – oil density, its dynamic viscosity, heat capacity and thermal conductivity, $\vec{g}$ – gravity vector, matrix $\hat{I}$ determines the direction of unit vector of selected coordinates system.

2 Complex three-dimensional structure of core-type transformer equipment is reduced to complex axisymmetrical models in view of the fact that MS cores, windings, insulating cylinders nearby the windings and structure of yoke insulation have the pronounced cylindrical symmetry.

3 Dimensions of cylindrical tank models are determined based on the number of cooling oil in the tank of the device under consideration. Heat dissipation of the tank into ambient air is modeled by specified factors of heat transfer from the horizontal and vertical surface, taking into account the radiation and the convective heat exchange with air. In cases of multi-phase designs the single-core thermal structure is formed (with proportional release of active losses).

4 The winding models do not consider the discrete structure of vertical rods (or supports in the form of «bridges») and horizontal spacers between the coils.

5 For qualitative (comparative) studies, for example, of possible ways of intensification of heat transfer in the windings, the models of autonomous models of the windings or the coil groups with appropriate boundary conditions are employed.

6 It is advisable to build up the special grid-scale models based on the objectives of investigations and assumptions of laminar or turbulent nature of oil flow.

7 To consider nonlinear properties of transformer oil, the experimental data are used. [25]

8 For complex CFD-models of the transformer equipment, two approaches to consider CS are approbated. *The first* approach [16–20] lies in the fact that external CS is modeled as the cylindrical element with appropriate volume of oil that determines its dimensions as to design model. The characteristic of heat removal known from engineering calculations is specified for CS element [26]. The points of CS connection to the tank correspond to actual design. The width of the gap of CS design model branch pipes is determined based on condition of equity of total flow passage of the branch pipes in the model gap. As to the *second* approach [21], the boundary conditions in the form of velocity and temperature of inlet oil are specified. In both approaches, the thermal parameters of CS and inlet oil are determined by the appropriate calculation using the empirical methods [6, 26].

9 At setting of heat sources, the losses in MS, structural elements, windings and tank are assumed to be known (constant), and could be estimated using the complex of re-calculation [6] or best estimate calculations using FEA [27].

10 Both at calculation of equipment integrated models and winding autonomous models, one of the key issues is equivalenting of the parameters of complex discrete structures of the winding coils due to the fact that number of coils over winding height may be several hundred, and number of elementary wires in each coil, for example, as referred to CTC, could reach up to hundred wires.

The coils of transformer and reactor windings are wound in radial direction using different types of conductors: conventional conductors (CC), divided (DT) or transposed (CTC) conductors. Elementary conductors can have enamel or paper insulation, DT and CTC conductors have external turn insulation. Two horizontal rows of elementary CTC conductors are divided from each other by paper, cardboard or fiberglass spacers. During numerical studies, the mentioned complex discrete structure is presented as homogeneous bodies with equivalent thermal conductivity in horizontal and vertical directions.

Effective thermal conductivity l_{eff} of the material (corresponds to the term «coefficient of thermal conductivity») is estimated as the ratio of thickness L of the material sample to its thermal resistance *R* and the area in direction of heat flow *ДS* [28]:

$$\lambda_{eff} = \frac{L}{\Delta S \cdot R_{eff}}\,. \tag{4}$$

The laws for estimation of total thermal resistance in case of parallel and series connection of individual thermal resistances similar for linear electric circuits are employed. If heat flow is directed along the layers, λ_{eff} should be calculated in the same way as electrical conductivity of the circuit with parallel resistance, in case of flow directed perpendicularly to the layers – according to series circuit.

Resistance of the material based on estimation of effective thermal conductivity:

$$R_{eff} = \frac{L}{\Delta S \cdot \lambda_{eff}}\,. \tag{5}$$

For schematic contact between two bodies (Fig. 1), calculation of effective thermal conductivity in the axial and radial directions is analyzed.

In the axial direction *z* there is series connection of two samples having thicknesses L_1, L_2 in direction of heat flow, with the same section *A·B,* when thermal conductivity of each sample λ_1, λ_2 is:

$$R_{eff}^{ser} = \frac{1}{A \cdot B}\left(\frac{L_1}{\lambda_1} + \frac{L_2}{\lambda_2}\right). \tag{6}$$

For schematic contact between two bodies (Fig. 1), calculation of effective thermal conductivity in the axial and radial directions is analyzed.

In the axial direction z there is series connection of two samples having thicknesses L_1, L_2 in direction of heat flow, with the same section $A \cdot B$, when thermal conductivity of each sample λ_1, λ_2 is:

$$R_{eff}^{ser} = \frac{1}{A \cdot B}\left(\frac{L_1}{\lambda_1} + \frac{L_2}{\lambda_2}\right). \quad (6)$$

Then, the effective thermal conductivity of the sample having total thickness L_1+L_2 and cross-section $A \cdot B$ is:

$$\lambda_{eff}^{ser} = \frac{(L_1 + L_2)\lambda_1\lambda_2}{L_1\lambda_2 + L_2\lambda_1}. \quad (7)$$

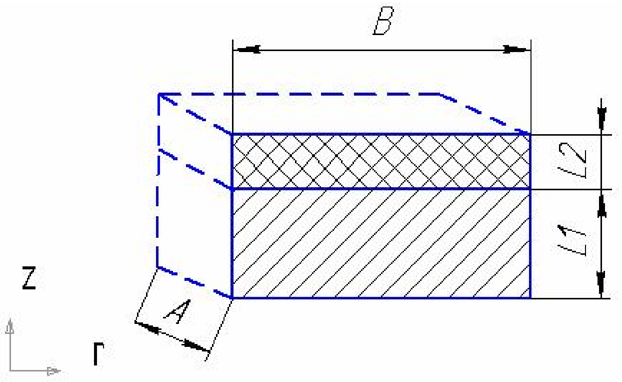

Fig. 1 – The model of thermal contact between two bodies

In the radial direction r there is parallel connection of two samples having thickness B in the direction of heat flow, with cross-sections proportional to lengths L_1, L_2:

$$R_{eff}^{par} = \frac{B/A}{L_1\lambda_1 + L_2\lambda_2}. \quad (8)$$

Then, the effective thermal conductivity of the sample having the thickness B and total cross-section $A \cdot (L_1+L_2)$ is:

$$\lambda_{eff}^{par} = \frac{L_1\lambda_1 + L_2\lambda_2}{L_1 + L_2}. \quad (9)$$

Obtained relationships allow estimation of the parameters of anisotropic thermal conductivity depending on the specific parameters of the coils and used conductors.

As an example, Fig. 2 shows the calculation results of autonomous coils made of CTC, which ensure verification of the present method of equivalent estimation of discrete structure of coil conductors using anisotropic thermal conductivity.

11 The experience of calculations has shown the significance of quality settings of computational processes which should ensure stable solutions of nonlinear systems (1) – (3) and elimination of problem as to «spontaneous zigzag oil flowing through the ducts groups» (without labyrinth and alteration of number and locations of axial cooling ducts) under conditions of natural cooling with transformer oil. [19, 20, 22, 23]. The above mentioned problem is to be focused on creation of adequate mathematical model of oil flow in the system of interconnected horizontal and vertical ducts of the winding by means of invariant software.

In the judgment of the authors the main method of solution of the problem under consideration is application

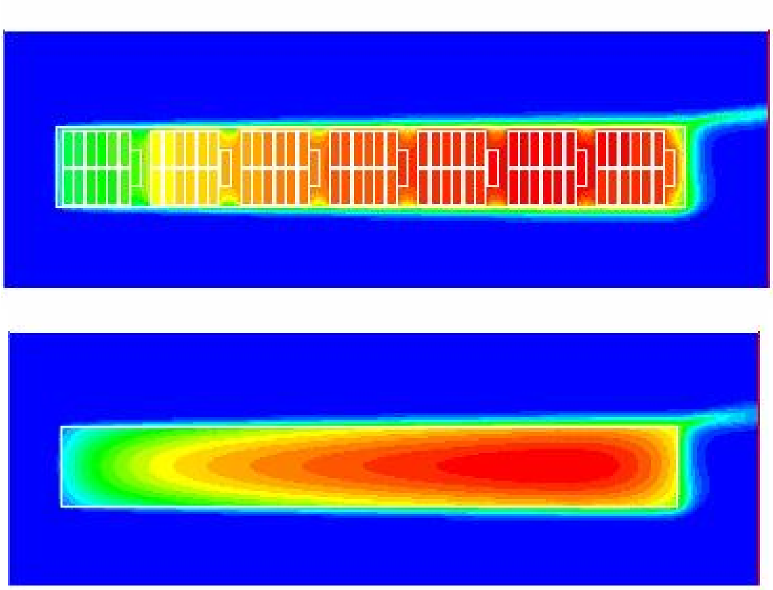

Fig. 2 – Distribution of temperature field of DC coil in oil: at the top – with discrete conductor specification at the bottom – with equivalent anisotropic conductivity

of improved oil flow models if compared with standard models. In particular, use of recommendations [29] related to simulation of heat transfer in the ducts with intensifiers by means of application of k-e, k-w models of turbulence and wall functions separating the purely turbulent motion zone which comply with logarithmic law, and the zone of viscous sub-layers close to wall surface was found to be reasonably effective.

After design experiments as to use of turbulence models, for example, k-e with different wall functions, the desired result was obtained for the scalable wall function (SWF). The main idea of SWF is to restrict relative size of wall viscous layer. This statement has showed impact-decreasing effect of oil rate in the horizontal duct in regard to coil heating. Effect of oil boundary layers detachment nearby the vertical surface of the coils is observed [25]. Presence of insignificant areas of stagnant oil in the ducts does not cause coil overheating; zigzag oil flow along the groups of winding ducts is eliminated. Moreover, distribution of maximum and average temperature rise of the coils over the height becomes almost linear, that is in line with experimental studies [2].

CALCULATION EXAMPLES OF INTEGRATED CFD-MODELS OF TRANSFORMERS AND REACTORS

As an example, Fig. 3 shows the sketch of the design model of one of the cores (phase) of of furnace transformer EOCNK-45000/34.5.

Core losses in the magnetic system, the coils of internal EW winding, the external LV2 winding and in the tank have been estimated using appropriate calculations for the transformer under consideration. The special element which simulates CS heat transfer is included into the model. The positions of oil inlet and outlet from the tank into the CS represent the actual condition; at the area of inlet into the tank an additional oil head is specified to simulate forced oil circulation in the system due to installed pumps.

The geometry of the transformer model and calculation results are shown in Fig. 4.

As the results of calculation during steady-state thermal mode the following is determined: distribution of oil temperature in the active part, including the winding fields, temperature field between the tank and the windings, the temperature at the points of oil outlet from the tank (top) and oil inlet into the tank (bottom); distribution of average temperatures over the section of the winding coils; the average temperatures of the windings as averaging of the temperatures in the coils, maximum temperature on the surface of the conductors of the most heated coil treated as HST during estimation of aging of insulation in contact.

Application of temperature fields of coils and oil in the winding allows compliance with the requirements of IEC 60076-7 standard [30] as for estimation of HST temperature rise above oil temperature in the windings directly, but not in simplified way [1–6] – by calculation or based on measured temperatures in central and top parts of the tank.

Measurement results obtained during testing including those of fiber optic sensors at the area of upper winding coils, correspond to calculation data with appropriate accuracy.

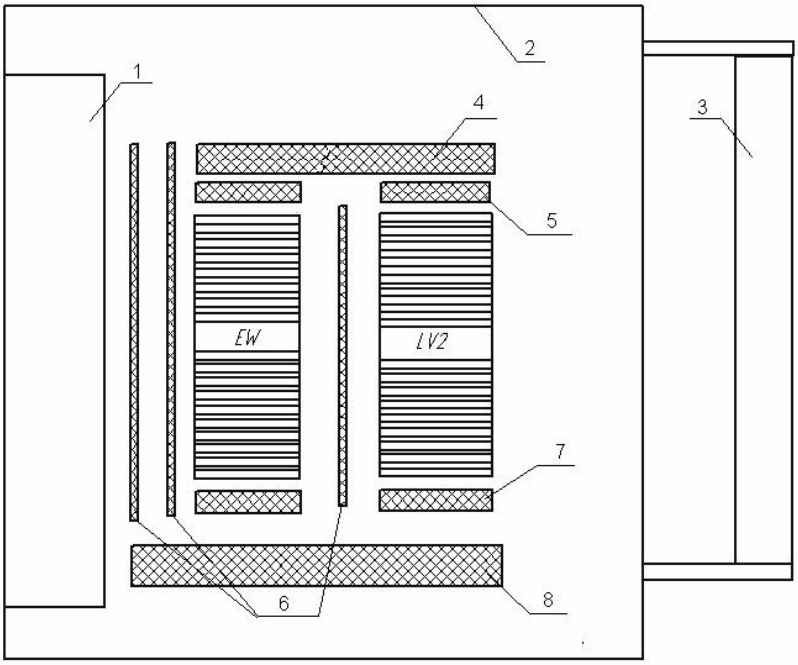

Fig. 3 – Sketch of CFD-model of the transformer: 1 – MS core; 2 - tank, 3 – CS; 4 – common pressing ring made of electric cardboard, 5 – top yoke insulation, 6 – cylinders of the main insulation, 7 – bottom yoke insulation, 8 – lower support segment from of electric cardboard

Under similar assumptions, CFD-model of the reactor type ROM-80000/765 is considered (system of natural air cooling ONAN) – Fig. 5. In contrast to the CFD-model of the transformer, the reactor model has external CS with boundary conditions at area of oil inlet into the tank.

The model takes into account the core of discrete discs, the tie rod, the vertical cardboard cylinders of the main insulation, the elements of upper and lower yoke insulation, the common pressing ring made of electric cardboard. The reactor winding is represented by four concenters separated by axial ducts with «bridge» -type spacers. The geometry of the reactor and the temperature field model are shown in Fig. 5a.

The mentioned Figure should be provided with further clarifications. The tie rod located inside the core has a complex, but not cylindrical shape, which does not allow proper heating based on specified losses, so it is omitted in the geometry of design model, and oil duct between the rod and the internal surface of the core corresponds to the actual condition.

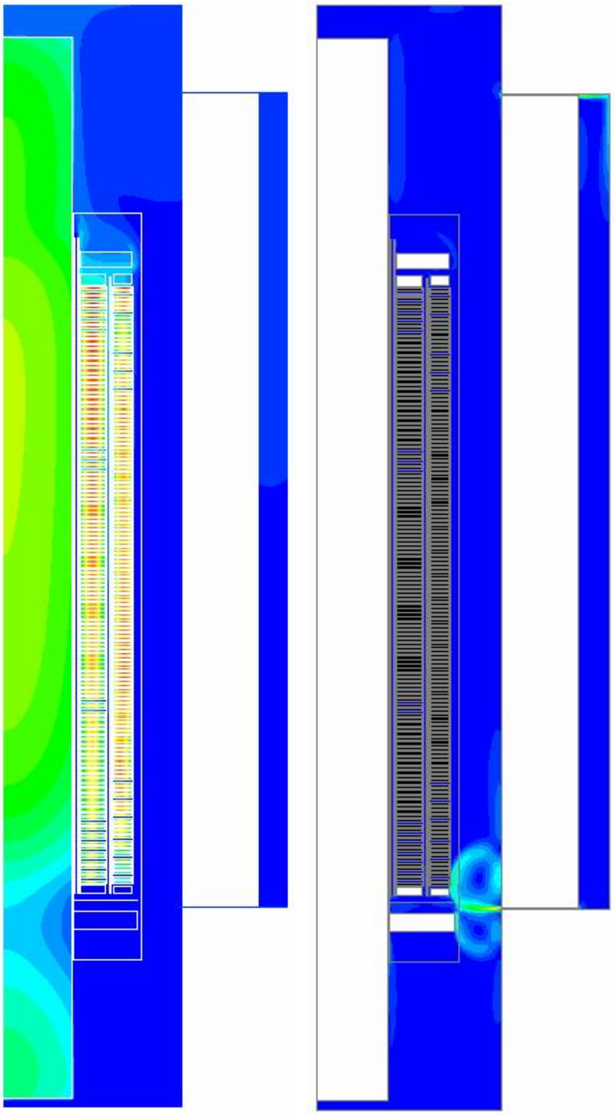
a) b)

Fig. 4 – CFD-model of the transformer EOCNK - 45000/34.5:
a) – temperature fields, b) – velocity fields

Oil velocity field in the tank and the active part of the reactor is shown in Fig. 5b.

The enlarged fragment of the reactor upper is shown in Fig. 6.

Detailed analysis of temperature fields and rates of cooling oil over entire height of EW internal winding, in LV2 external winding of the transformer, as well as in winding of the reactor, including the fragment of its upper part, is the evidence of achieving the quality simulation of heat transfer in both integrated models of the equipment and also as referred to the effectiveness of applied mathematical CFD-simulation techniques. Oil movement in the windings has no numerical effects of cross-through flow of oil.

Type testing of the rector has also confirmed the appropriate compliance of calculation with measurements of oil temperature in the tank, average winding temperature and HST of winding

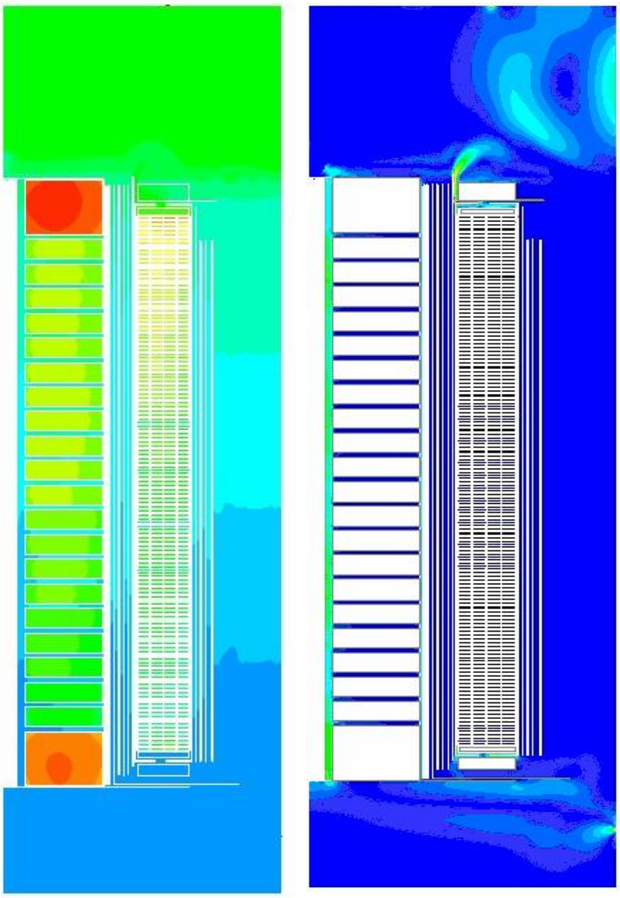
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Fig. 5 – CFD-model of the reactor ROM-80000/765:
a) – temperature field, b) – velocity field

CALCULATION EXAMPLES CFD-MODELS OF AUTONOMOUS WINDING

Calculation of temperature rises of common winding (CW) with labyrinth (with the partitions) and of series winding (SW) with «alternation» of number and locations of axial cooling ducts of autotransformer rated for capacity 83.3 MVA is investigated as an examples of CFD-models of autonomous windings. Both methods of heat transfer improvement are well-known, employed for production of power transformers and reactors, and represented in the industrial procedures [1-6] with application of «overheating empirical method.» However, empirical methods do not allow estimation of HST of the coils with required accuracy, and this is the task of CFD-calculations.

CW winding has been simulated as autonomous group of upper coils. At the right and the left (along the coil ends) the model is limited by vertical insulation cylinders, on the top – by pressing rings, at the bottom the section is made at the center of height of lower coil model. Dimensions of the coils, vertical and horizontal cooling ducts correspond to design sizes; the geometry of the coils has simplified (rectangular) shape; filling the coil with the conductors is considered in specified thermal properties of the coils. Upper top coils generate the upper passage of labyrinth oil movement. Labyrinth oil flow is formed by means of horizontal partitions arranged in external vertical cooling duct above coil 1 and below coil 8.

Oil temperature at inlet to the bottom planes of vertical cooling ducts of the model is determined based on method [26]. Oil velocity in the lower ducts of the model is assumed from known assumption that oil consumption is proportional to the winding losses.

Calculation results are shown in Fig. 7. It has been determined that the maximum HST was in the fourth top coil. Its absolute temperature makes up 94,4°C, which is appropriate at ambient temperature 20°C due to permissible value 78 K of HST temperature rise above ambient temperature.

Obtained result is explained as follows. To top three coils of upper path of the labyrinth the higher horizontal ducts are adjacent than those adjacent to the coils 4–8. Increased oil rates in these ducts are characterized by reduced hydraulic resistance of oil, as well as by forced acceleration of oil rate due to oil labyrinth flow – Fig. 7b. The factors mentioned, as well as uneven losses in the coils caused by eddy currents in the coil conductors due to axial and radial components of magnetic induction have formed the conditions under which the coil 4 is the most heated one. Labyrinth oil flow has an effect both on both the uneven temperature field of oil, conductors of the coils – Fig. 7a, and also on oil rate field in vertical and horizontal ducts – Fig. 7b.

SW winding with alteration of number and locations of axial cooling ducts was studied using the same approach – Fig. 8. The coil pairs with small horizontal duct between them are arranged along the winding height. In the top coil of each pair there are two internal axial ducts; in the bottom coil – one duct. Such arrangement of axial ducts provide the conditions similar to labyrinth oil flow. This causes increase of oil rate both in said internal axial ducts and in adjacent areas of horizontal ducts – Fig. 8b, due to unevenness of additional losses in the coils, both over coil height (maximum losses occur in the conductors of the first coil) and in different groups of the conductors along radial dimension of each coil. These factors create the conditions of uneven temperature field in the coils and within the surrounding oil – Fig. 8a. These factors create the conditions of uneven temperature field in the coils and within the surrounding oil – Fig. 8a. HST of upper coils makes up 94,7°C.

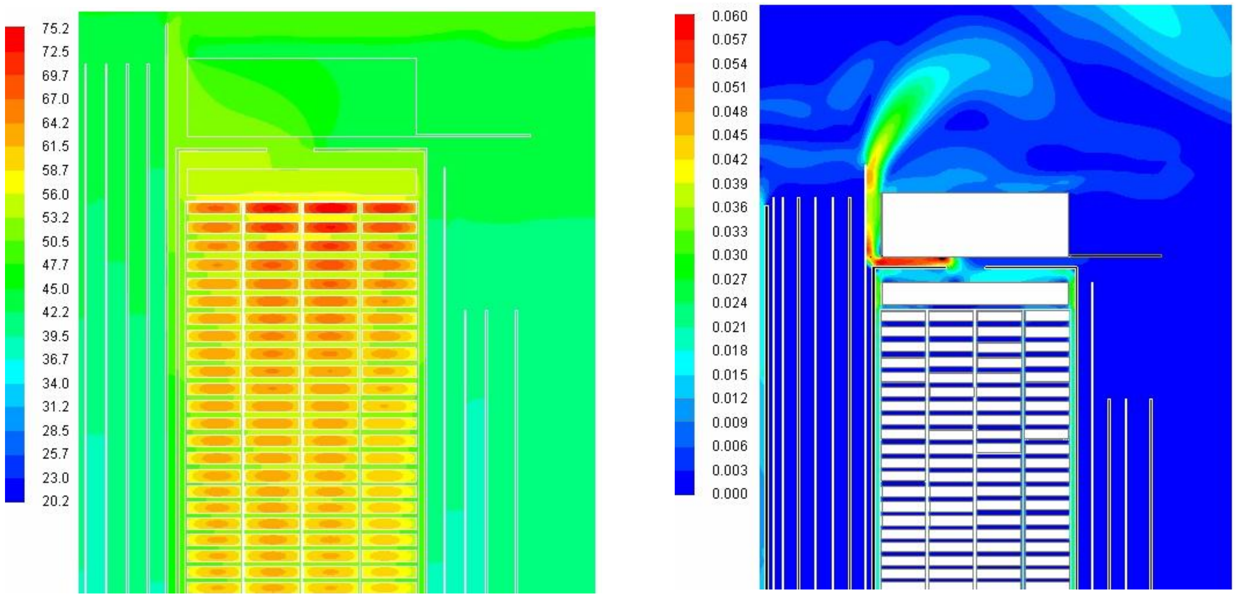

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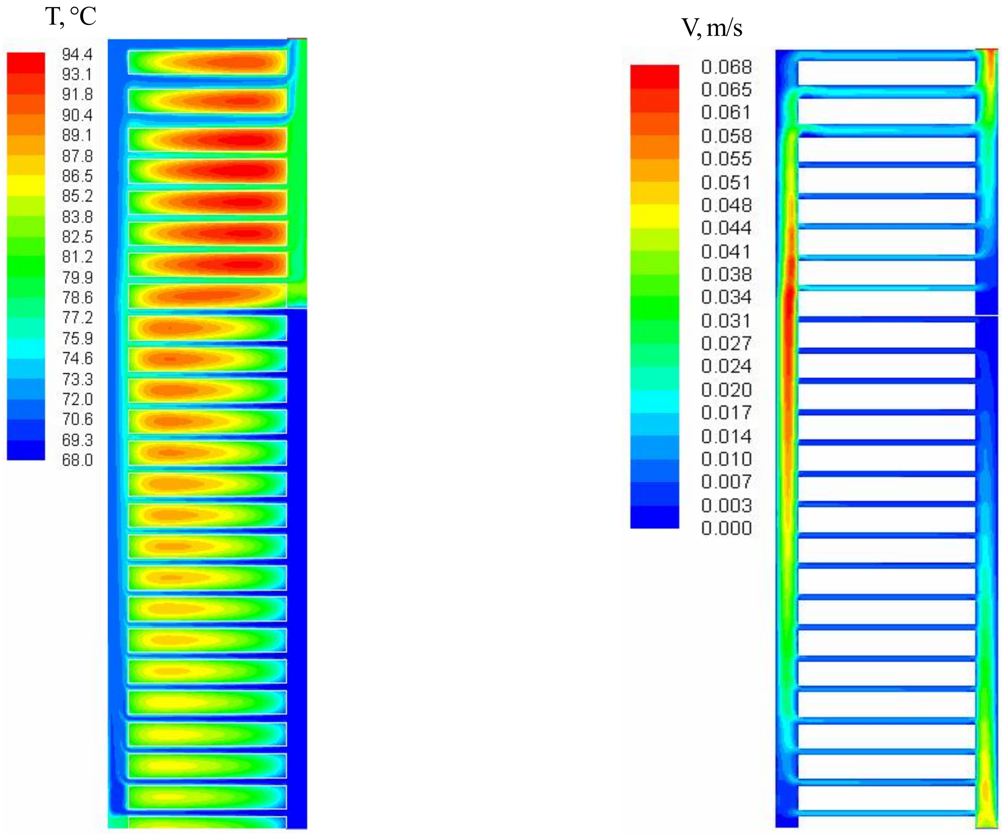
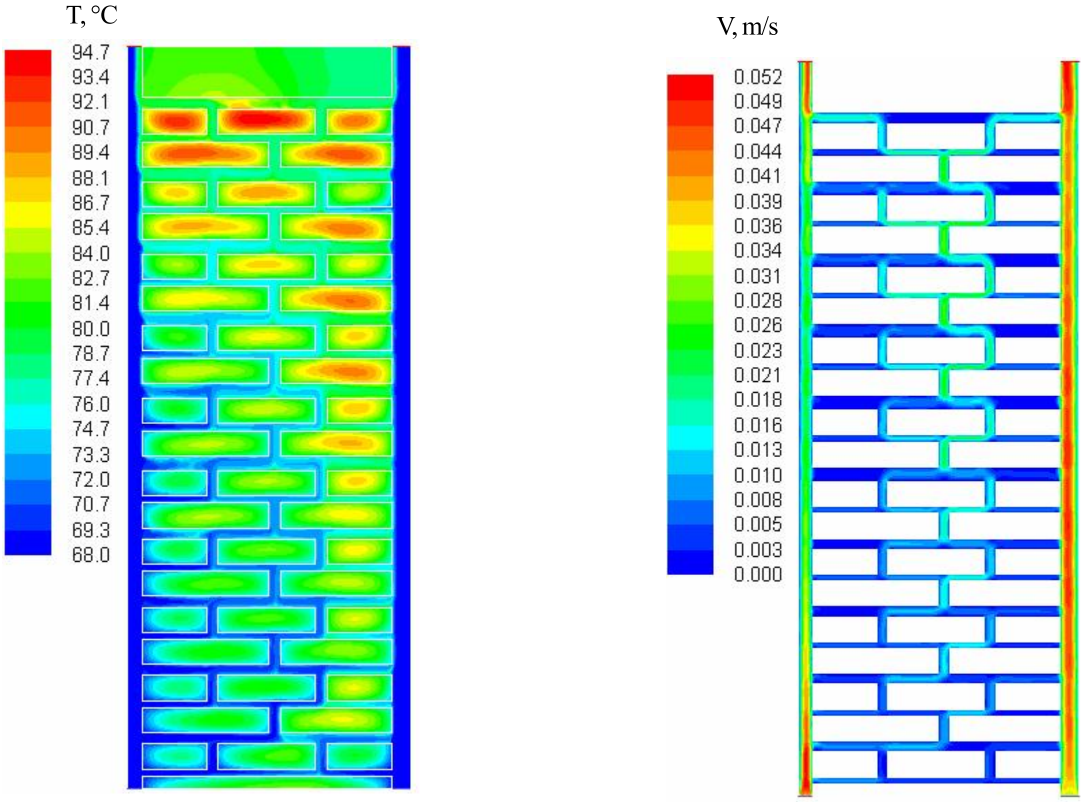
Fig. 6 – Fragment of CFD-model of the reactor ROM-80000/765: a) temperature field, °C; b) oil velocity field, m/s



a) b)

Fig. 7 – Model of upper part of CW winding with «labyrinth»: a) temperature field, °C; b) oil velocity field, m/s



a) b)

Fig. 8 – SW having «alternate arrangement» of vertical ducts: a) temperature field, °C; b) oil velocity field, m/s

Medium voltage windings (MVW) having nine coils of upper passage of «labyrinth», and low voltage windings (LV) with additional vertical duct at upper four coils of the transformer also rated for 83.3 MVA have been estimated. The results are shown in Fig. 9 and 10.

It has been determined that in MV winding with «labyrinth», the most heated coils are the first, the third and the fourth (from the top) having the same HST temperature 93,7°C.

Upper coils in LV winding have rather low heating, it makes up 94,9°C in the sixth coil, and 96,7°C in the seventh coil.

Labyrinth oil flow in MV winding and presence of additional axial ducts at upper four coils of LV winding create uneven temperature and rate (velocity) fields similarly to winding structures shown in Fig. 7, 8, and this determines specific location of windings' HST and their temperature values. It should be noted that it would be problematic to determine with required accuracy the locations and HST temperatures using presented calculation examples of CFD-models of autonomous windings by means of empirical procedures [1–6].

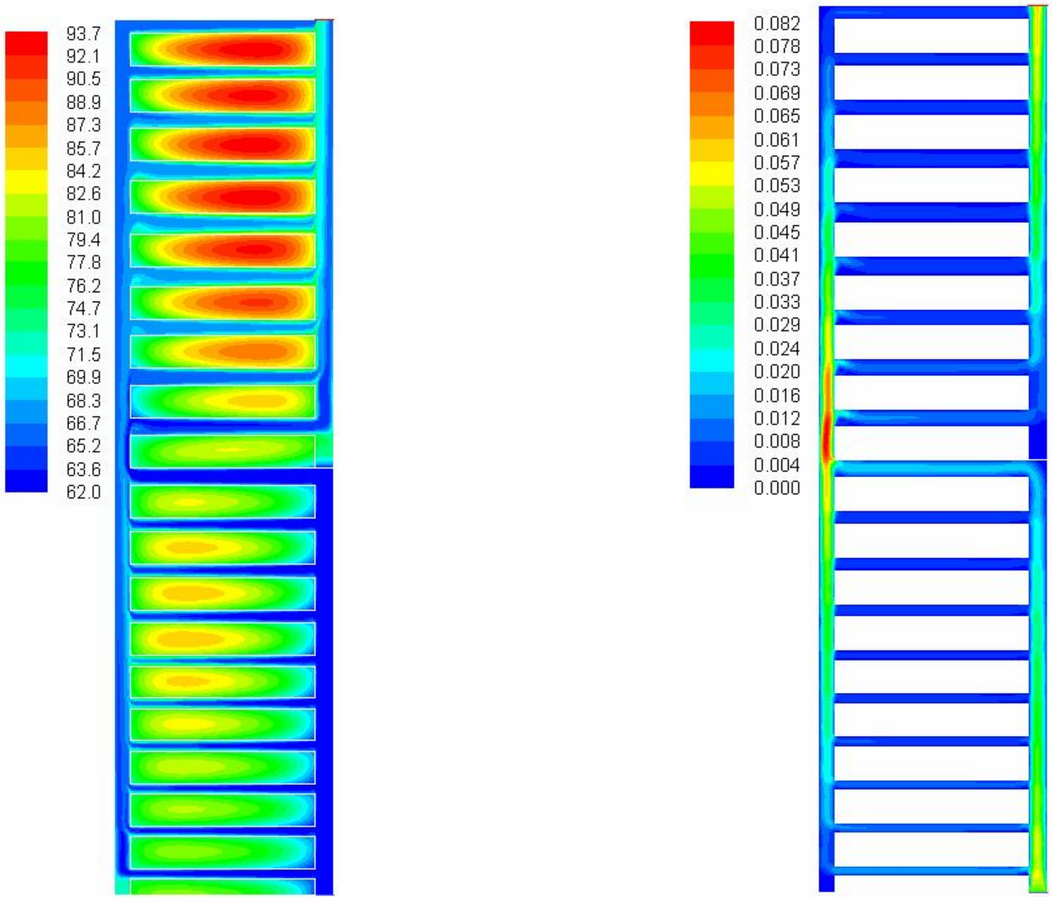
The obtained results have confirmed the reduction of HST heating and average winding temperature rises at the expense of adopted methods of heat transfer improvement, and are used to justify the locations of installation of fiber optic sensors for the measurement both during transformer type testing and within operation.

CONCLUSION

Complex CFD-models of oil-cooled transformers equipment using magnetic systems, main structural elements, windings, tanks and external cooling systems and external cooling systems have been developed, the results of which are employed in practice of industrial designing and testing of the equipment.

The study ensures quality simulation of heat and mass transfer in integrated models of the transformer equipment that is the evidence of the effectiveness of applied mathematical methods as regard to CFD-simulation.

For the conditions of natural oil flow, recommendation is given as to application of turbulence models, for example, k-e with scalable wall function (SWF). This statement has showed impact-decreasing effect of oil rate in horizontal duct in regard to coil heating. Effect of oil boundary layers detachment nearby the vertical surface of the coils is observed. Presence of insignificant areas of stagnant oil in the ducts does not cause coil overheating; zigzag oil flow along the groups of winding ducts is eliminated.



a) b)

Fig. 9 – Model of MV winding with «labyrinth»: a) temperature field, °C; b) oil velocity field, m/s

Calculation examples using autonomous CFD-models of windings with different method of heat transfer improvement by means of specific design solutions: «labyrinth» oil flow, alternate arrangement and introduction of additional vertical ducts along the coil width, represents the possibility of improved estimation of hot spot temperatures of the windings, and validation of the points to be used for measurement of local temperatures using fiber optic sensors.

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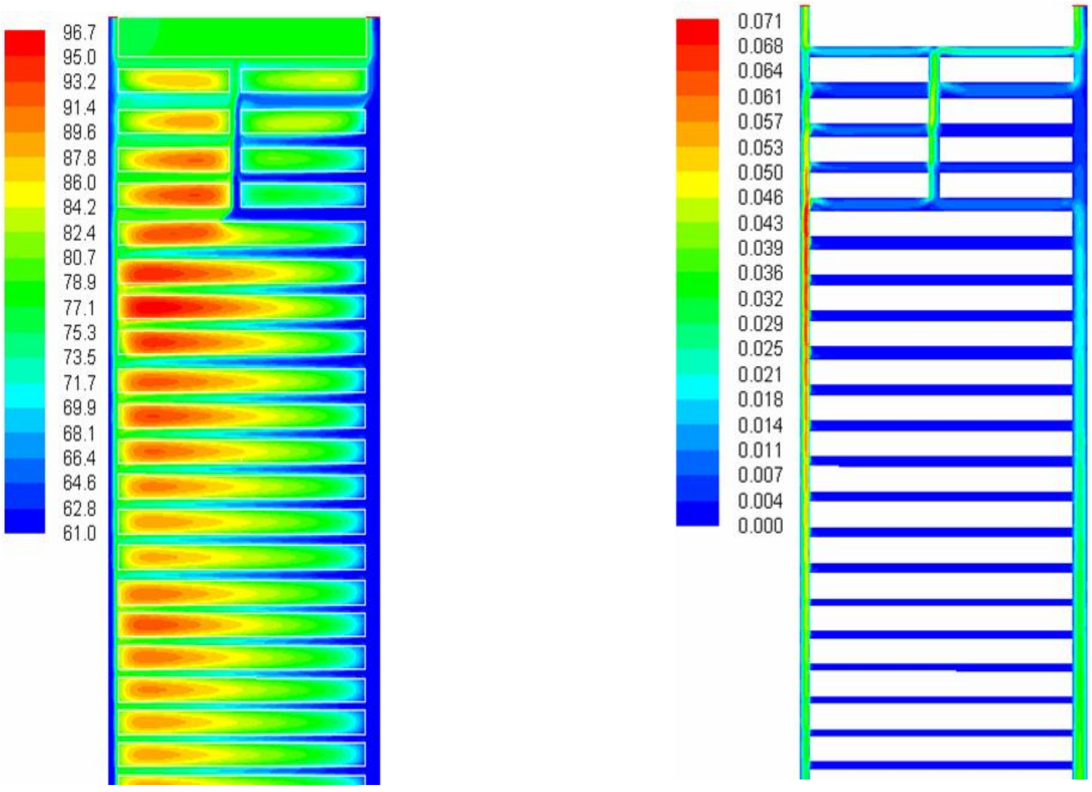

a) b)

Fig. 10 – Model of LV winding with additional upper duct at the top four coils: a) temperature field, °C; b) oil velocity field, m/s

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Іванков В.Ф.[1], Басова А.В.[2]
[1]Канд. техн. наук, начальник бюро ПАТ «Запоріжтрансформатор», Україна
[2]Провідний інженер-конструктор ПАТ «Запоріжтрансформатор», Україна

РОЗРАХУНОК ТЕПЛОВИХ CFD-МОДЕЛЕЙ ТРАНСФОРМАТОРНОГО УСТАТКУВАННЯ З МАСЛЯНИМ ОХОЛОДЖЕННЯМ

***Мета роботи** полягає в забезпеченні розрахункового проектування повнофункціональної і стійкою в обчислювальному процесі CFD-методикою моделювання комплексних теплових моделей трансформаторів і реакторів, а також в апробації її якості і можливостей на прикладах розрахунків натурних зразків устаткування,* *а також автономних моделей котушкових обмоток з різними конструктивними способами інтенсифікації теплообміну.*

Методи досліджень. *Використаний CFD-метод (Computational Fluid Dynamics) математичного моделювання нелінійних процесів гідродинаміки і теплообміну в трансформаторному обладнанні з застосуванням систем скінчено-елементного аналізу.*

Отримані результати. *Представлені основні елементи методики формування математичних моделей і приклади CFD-розрахунків осесиметричних комплексних моделей перетворювального трансформатора і шунтувального реактора з проміжками в стрижні магнітної системи, а також моделей обмоток з конструктивними способами інтенсифікації теплообміну за рахунок «лабіринту» (перегородок) та «почережності» (числа та місць) осьових охолодних каналів.*

Наукова новизна. *Наукова цінність використаного методологічного підходу полягає в тому, що розроблені моделі є комплексними, тобто враховують геометрію, втрати, теплові параметри не тільки обмоток, а й основних елементів конструкції і системи охолодження. Науковою новизною роботи є досягнення авторами певним якісним налаштування обчислювального процесу сталого рішення засобами інваріантної системи чисельного моделювання нелінійних рівнянь Нав'є-Стокса. Це забезпечило якість і точність моделювання процесів тепломасопереносу в складній структурі масляних каналів і котушок в обмотках, дозволило уникнути отриманого в деяких дослідженнях помилкового «зигзагоподібного» руху масла по групах регулярних структур котушок (без лабіринту і без «почережності» числа та місць осьових каналів) за умов природного охолодження трансформаторним маслом.*

Практична значимість. *Комплексні моделі забезпечують розрахунок розподілу температур масла в активній частини, включаючи області обмоток, поле температур масла між баком і обмотками, температури в місцях виходу масла з бака (верх) і входу в бак (низ). Розрахунки дозволяють визначити розподіл середніх температур по перетину котушок обмоток, середні температури обмоток шляхом усереднення температур в котушках, визначення місця і максимальну температуру на поверхні провідників найбільш нагрітої котушки. Останні, які тлумачаться як температури найбільш нагрітої точки (ННТ) обмоток, використовуються при оцінці старіння доторкної ізоляції. Визначення місць і температур ННТ обмоток використовуються для обґрунтування місця установки оптоволоконних датчиків для вимірів при типових випробуваннях і в експлуатаційних системах моніторингу обладнання. Представлені результати застосовані в практиці промислового проектування і випробування трансформаторів і реакторів.*

***Ключові слова**: трансформатори, тепломасоперенос, CFD-моделювання.*

Иванков В. Ф.[1], Басова А. В.[2]

[1]Канд. техн. наук, начальник бюро ПАО «Запорожтрансформатор», Украина

[2]Ведущий инженер-конструктор ПАО «Запорожтрансформатор», Украина

РАСЧЕТ ТЕПЛОВЫХ CFD-МОДЕЛЕЙ ТРАНСФОРМАТОРНОГО ОБОРУДОВАНИЯ С МАСЛЯНЫМ ОХЛАЖДЕНИЕМ

Цель работы *заключается в обеспечении расчетного проектирования полнофункциональной и устойчивой в вычислительном процессе CFD-методикой моделирования комплексных тепловых моделей трансформаторов и реакторов, а также в апробации ее качества и возможностей на примерах расчетов натурных образцов оборудования, а также автономных моделей катушечных обмоток с различными конструктивными способами интенсификации теплообмена.*

Методы исследований. *Использован CFD-метод (Computational Fluid Dynamics) математического моделирования нелинейных процессов гидродинамики и теплообмена в трансформаторном оборудовании с применением систем конечно-элементного анализа.*

Полученные результаты. *Представлены основные элементы методики формирования математических моделей и примеры CFD-расчетов осесимметричных комплексных моделей печного трансформатора и шунтирующего реактора с зазорами в стержне магнитной системы, а также моделей обмоток с конструктивными способами интенсификации теплообмена за счет «лабиринта» (перегородок) и с «чередованием» (числа и мест) осевых охлаждающей каналов.*

Научная новизна. *Научная ценность использованного методологического подхода заключается в том, что разработанные модели являются комплексными, то есть учитывают геометрию, потери, тепловые параметры не только обмоток, но и основных элементов конструкции и системы охлаждения. Научной новизной работы является достижение авторами определенными качественными настройками вычислительного процесса устойчивого решения средствами инвариантной системы численного моделирования нелинейных уравнений Навье-Стокса. Это обеспечило качество и точность моделирования процессов тепломассопереноса в сложной структуре масляных каналов и катушек в обмотках, позволило избежать полученного в некоторых исследованиях ложного «зигзагообразного» движения масла по группам регулярных структур катушек (без лабиринта и без «чередования» числа и мест осевых каналов) при условиях естественного охлаждения трансформаторным маслом.*

Практическая значимость. *Комплексные модели обеспечивают расчет распределения температур масла в активной части, включая области обмоток, поле температур масла между баком и обмотками, температуры в местах выхода масла из бака (верх) и входа в бак (низ). Расчеты позволяют определить распределение* *средних температур по сечению катушек обмоток, средние температуры обмоток путем усреднения температур в катушках, определение места и максимальной температуру на поверхности проводников наиболее нагретой катушки. Последние, трактуемые как температуры наиболее нагретой точки (ННТ) обмоток, используются при оценке старения соприкасающейся изоляции. Определение мест и температур ННТ обмоток используются для обоснования места установки оптоволоконных датчиков для измерений при типовых испытаниях и в эксплуатационных системах мониторинга оборудования. Представленные результаты применены в практике промышленного проектирования и испытания трансформаторов и реакторов.*

***Ключевые слова**: трансформаторы, тепломассоперенос, CFD-моделирование.*

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