The Heating Mode Of Cable Transformer With Cooling System

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***Abstract*—Cable transformer is a variant of power transformer, which primary and secondary windings are cores and shields of power cable respectively. The maximum permissible operating current in power cable with XLPE-insulation is mainly limited by the maximum permissible temperature of XLPE-insulation. Thus, the effective cooling system is necessary for cable transformer to allow high values of operating current.**

In this study, we will analyze the heating mode of cable transformer with different cooling systems and recommend the most suitable one from the point of heating mode in operating conditions, construction, maintenance and cost-effectiveness. In order to solve the complex physical problem, including thermodynamic, flow and electromagnetic parts we will use COMSOL Multiphysics.

Keywords—* *Cable transformer, power cable, maximum temperature, convection, air, buoyancy, inlet, outlet, gap, cooling

Cables with XLPE-insulation are widely used in power transmission lines. In [1] Titkov had developed the model, considering the influence of a heat generation in cable shields on a heating mode of cable line in general. Heating modes of cables, laid in steel or plastic protective tubes at 0.5-1.5 meters underground were considered by Dudkin and Titkov in [2]. They had used COMSOL for solving a complex problem, including coupled thermal and electrodynamic tasks. They had modeled gas flow in terms of buoyancy-driven natural air convection within the protective tube. That study had shown a possibility to simplify problem by using the correction coefficient for thermal conductivity of air, assuming the influence of the natural air convection on a total equivalent thermal conductivity of the air within protective tube. Such an approach cannot be implemented in this study because our cable transformer has a complex geometry and disposed in open air space.

The cable transformer considered in this study consists of a central cylinder with diameter D = 1.1 m and height H = 3.61 m with a three layers of cable winding. A cable, spirally wound on a cylinder may be assumed as a complex of tors, having one central axis. Thus, we can use axisymmetric geometry in order to significantly simplify the model creation and optimize the calculation. The model geometry in axial symmetry is shown on Fig.1.

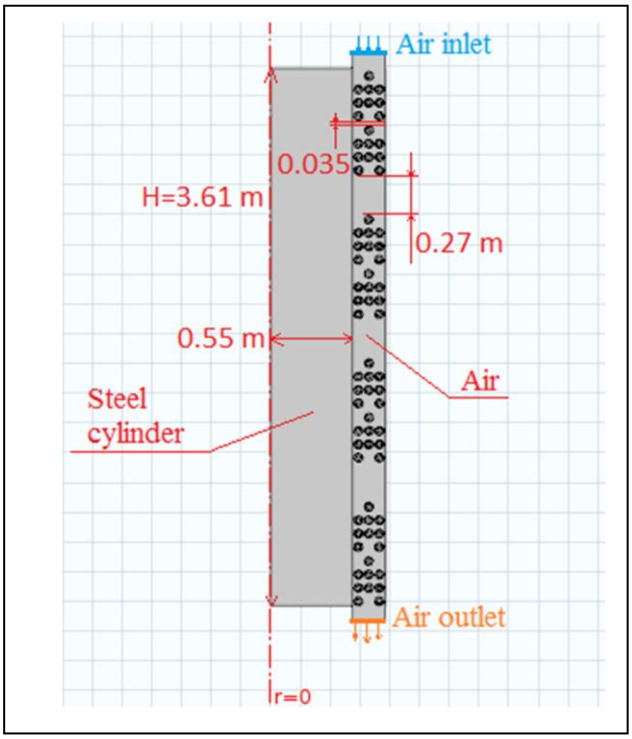

Fig. 1. *General view*

The geometry of cable group is shown on Fig.2.

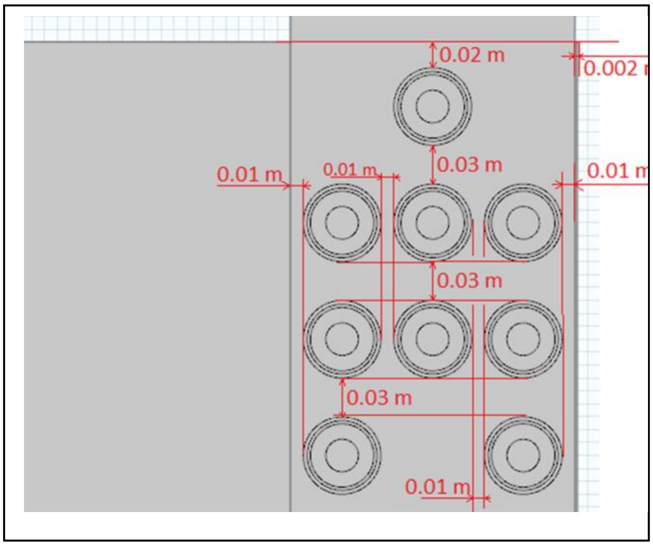

Fig. 2. *Design of a cable group*

The design of cable cross-section is shown on Fig.3.

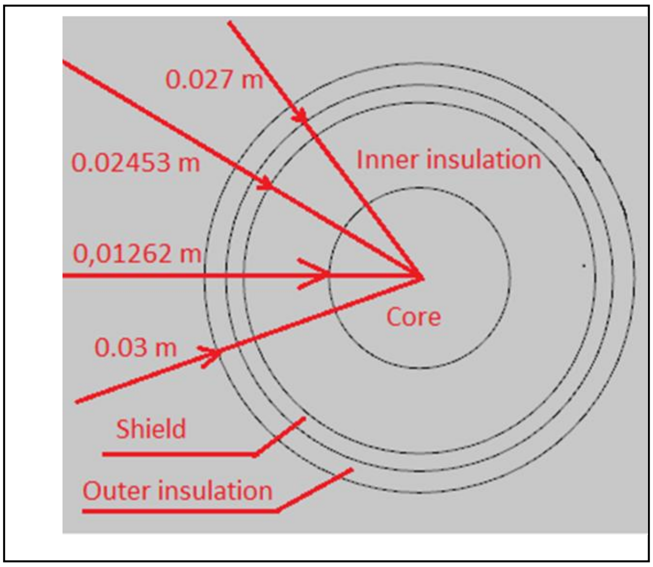

Fig. 3. *Cable cross-section design*

There is no correction coefficient, assuming the influence of natural air convection on the equivalent thermal conductivity of air, surrounding three-layer spiral of cable, wound on a central cylinder. Moreover, since the obtaining of the correct solution of the complex problem, including buoyancy-driven natural air convection requires significant effort and is not critically important for this study (natural air convection is not able to provide effective cooling of windings), we will not analyze the case of natural air convection. Instead, we will consider forced convection of the air. Such approach has significant pluses. Firstly, forced convection provides considerably more intensive heat transfer, than natural convection does. Secondly, forced airflow system does not require closed circulation, cooling, purification and fire safety systems. The only thing needed is an air pump with a volume flow rate big enough to provide necessary cooling.

We assume the most difficult operating mode of our cable transformer in terms of heating mode – there is a current of one kA both in cable cores and in shields. Since the areas of cable core's and shield's crossings are 500 square millimeters and 400 square millimeters respectively, we set the current densities of 2000000 and 2500000 Amperes per square meter in subdomains of cores and shields respectively. We solve the electrodynamic task for the shields and cores only. In order to create forced airflow we should add the tube, covering cable wires of our transformer as it shown on Fig. 2. In order to avoid energy losses in the tube, caused by an eddy currents the tube is made of acrylic plastic. We set velocity inlet as a boundary condition on the inlet and set speed of 0.5 m/s. The outlet is pressure outlet; the pressure on the outlet is zero Pa. The outer boundary of the plastic wall has convective heat transfer with outer air, so we set pre-defined convection coefficient h for the external air convection for the vertical wall. The wires and shields are made of copper, the cable inner and outer insulation is polyethylene, the central cylinder is steel monolith, the outer wall is acrylic plastic. All the material properties are taken from the COMSOL material library. Thermal boundary condition of the inlet is temperature of 293.15 K, one of the outlet is the Outflow. The flow boundary conditions on walls are defined by pre-defined wall functions. All calculations have been commenced by the Stationary solver. The results are presented on a Fig. 4 and Fig.5.

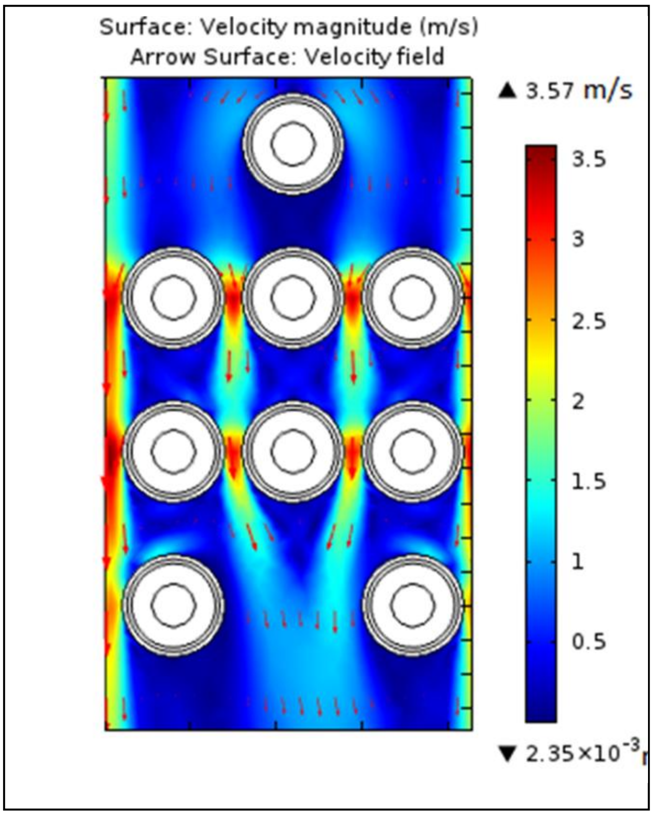

Fig. 4. *Air velocity field near the outlet, air velocity 0.5 m/s, gaps 0.1 m.*

As it shown above, the air velocities in gaps between cables and between cables and walls are significantly higher, than in front or after cables. The temperature field near the outlet is shown on Fig.5.

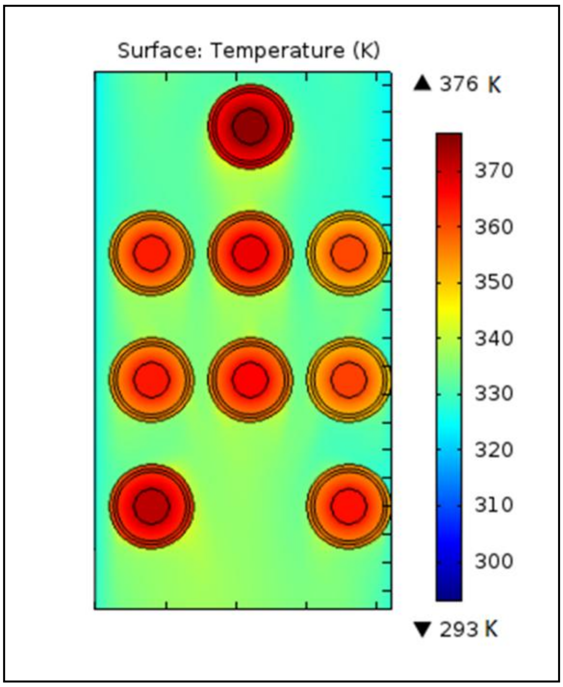

Fig. 5. *Temperature field near the outlet, air velocity 0.5 m/s, gaps 0.1 m.*

As illustrated above, forced air convection provides significant cooling, the maximum temperature of the XLPE-insulation is 376 K, which is close to the maximum permissible temperature of 363.15 K, but still greater. Therefore, we need to improve our cooling system, which we may do in different ways.

The first way is increasing the gaps between cables. At first, we increase the horizontal gaps from 0.01 m to 0.02, then to 0.03 m and then to 0.04. The results for the case with the gaps of 0.04 m are shown on a Fig. 6 and Fig. 7.

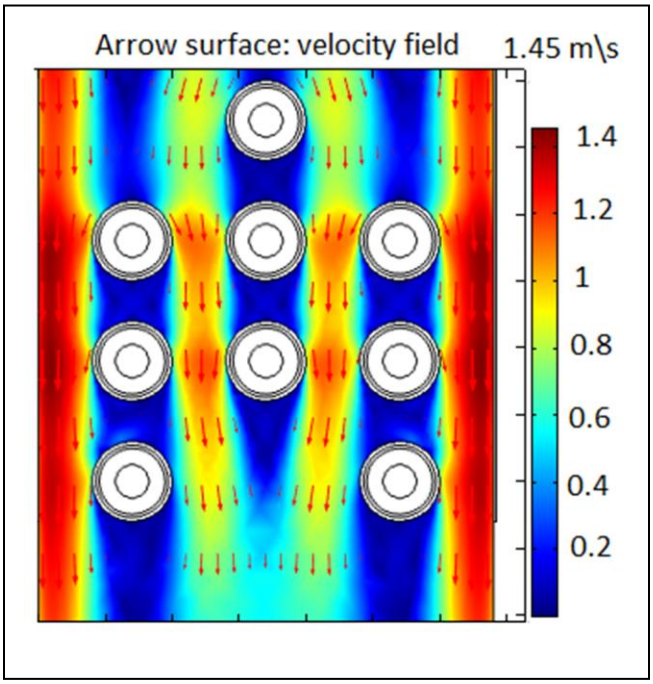

Fig. 6. *Air velocity field near the outlet, air velocity 0.5 m/s, gaps 0.4 m.*

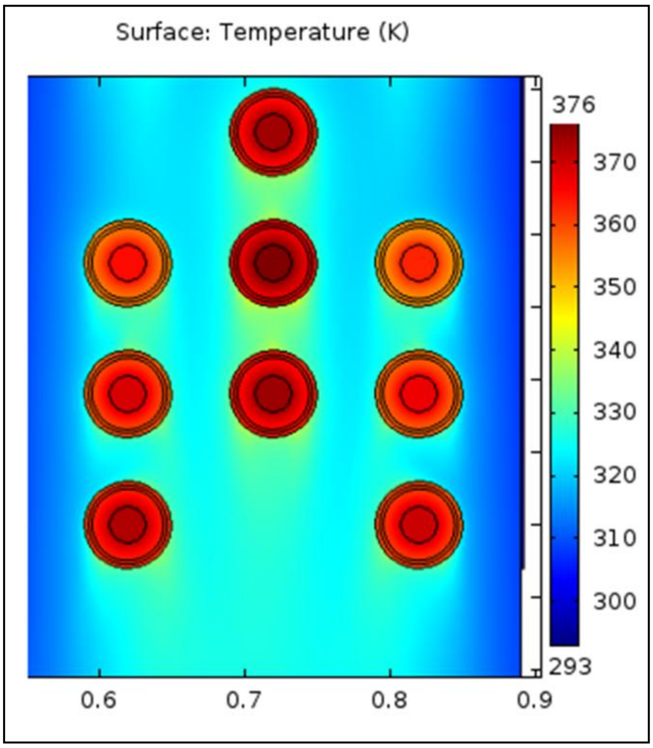

Fig. 7. *Temperature field near the outlet, air velocity 0.5 m/s, gaps 0.4 m.*

However, the flow velocities between cables decreases, the maximum temperature in all cases considered is 376 K. This may be explained by decreasing of the heat transfer between cables and the air, which compensates the positive effect from the increasing of the volume airflow rate. Moreover, by enlarging gaps we increase cross-section of the tube, which means increasing of volumetric flow rate and, as a consequence, price of air pump needed, not to mention increasing the dimensions of the cable transformer. Therefore, since the increasing of the gaps cannot help us to optimize the cooling, we will return to original gaps in further calculations.

The second way is increasing the airflow velocity on the inlet. The results of calculation with airflow velocity of 0.7 m\s are presented on a Fig. 8 and Fig. 9.

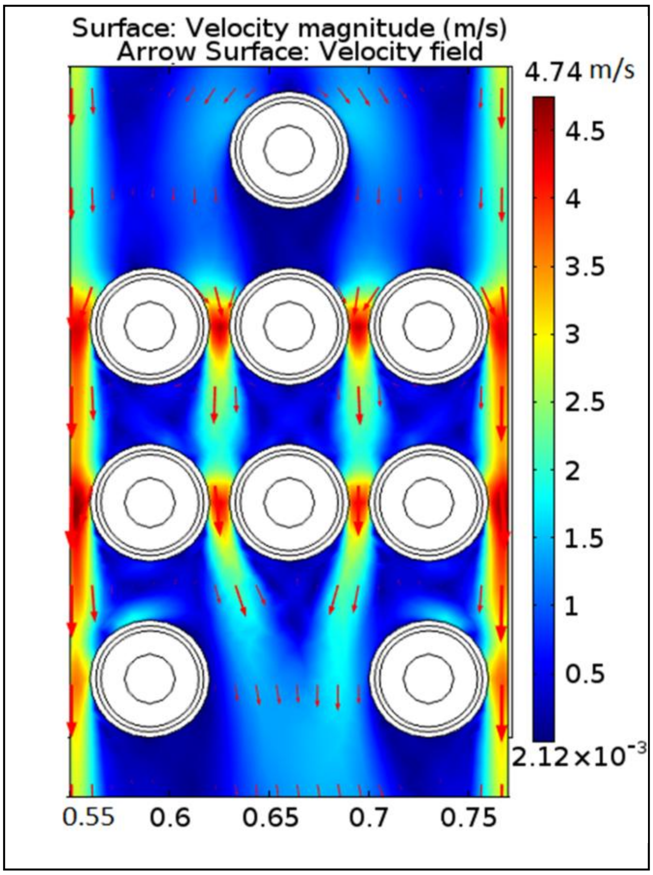

Fig. 8. *Air velocity field near the outlet, air velocity 0.7 m/s, gaps 0.1 m.*

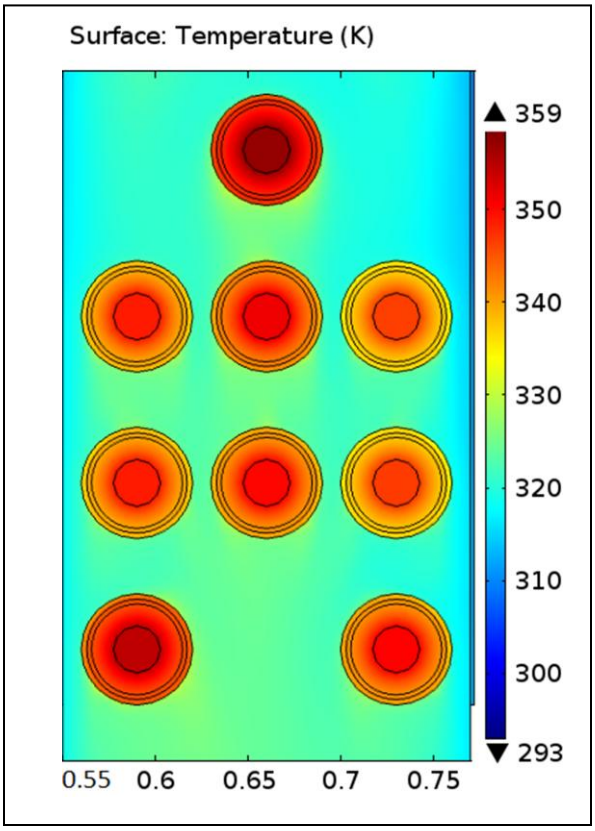

Fig. 9. *Temperature field near the outlet, air velocity 0.7 m/s, gaps 0.1 m.*

As we can see from Fig. 9, the maximum cable insulation temperature is 359 K, which means the airflow velocity of 0.7 m/s does provide necessary cooling.

Another way of optimizing the cooling is using two air pumps, creating two airflows, directed up and down respectively and meeting right in the middle of cable windings, as shown on a Fig. 10. The outlet is also disposed near the middle of the transformer.

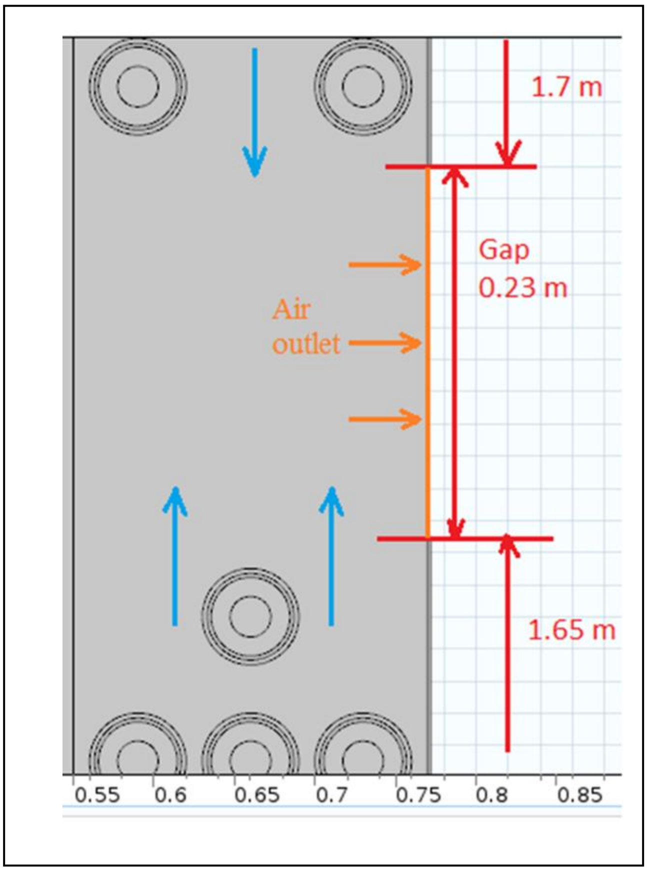

Fig. 10. *Geometry of the outlet in the moddle of windings*

The results of calculation with airflows velocities of 0.5 m\s are presented on a Fig. 11.

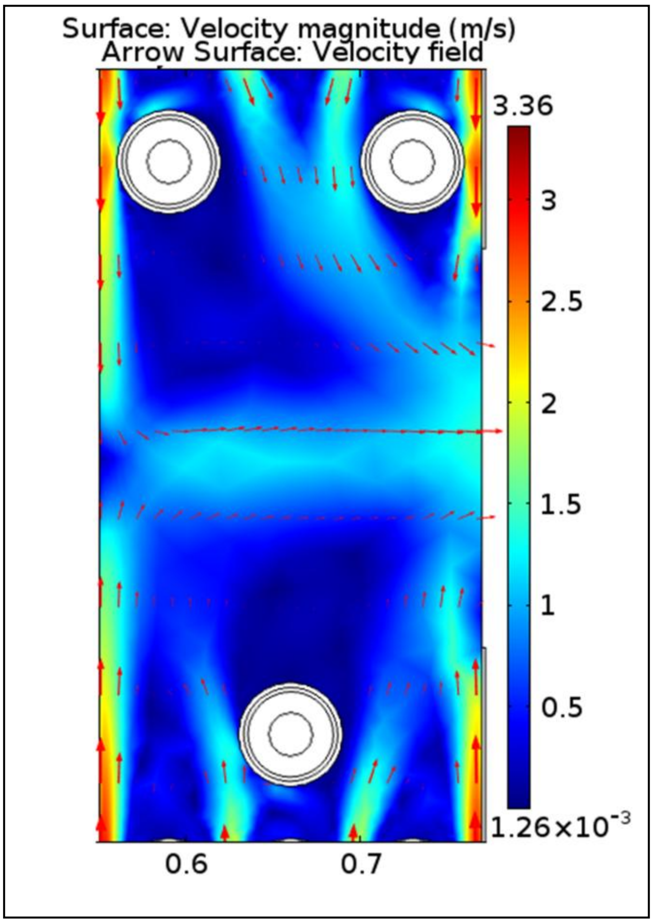

Fig. 11. *Air velocity field near the outlet, air velocity 0.5 m/s, gaps 0.1 m/s*

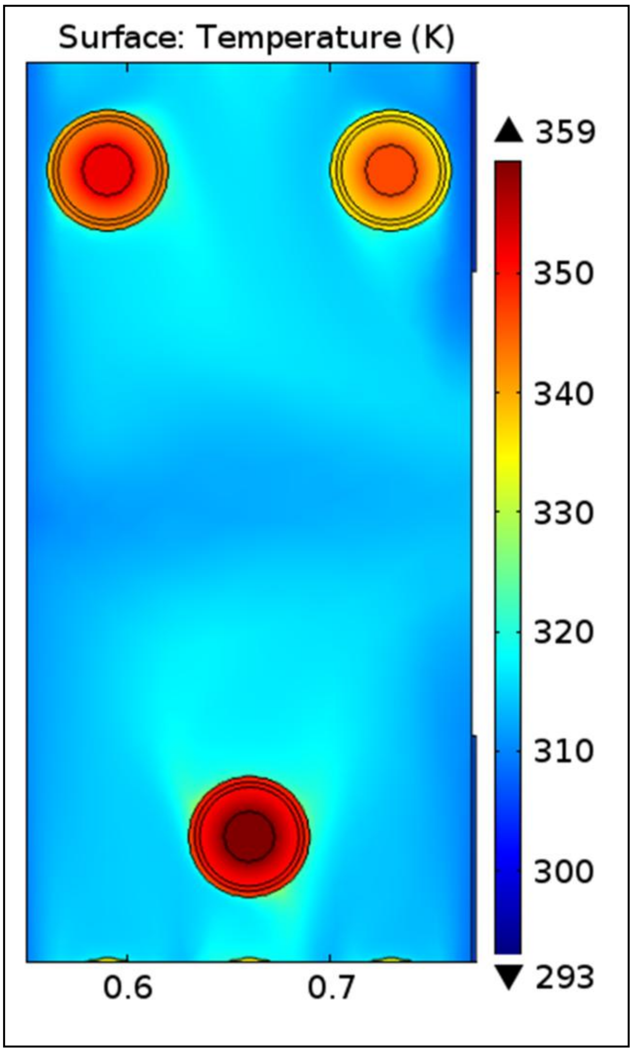

Fig. 12. *Temperature field near the outlet, air velocity 0.5 m/s, gaps 0.1 m.*

Fig. 12 illustrates, that two airflows with a speeds of 0.5 m/s provides the same cooling, that one airflow with a speed of 0.7 m/s does. The area of airflow channel cross-section

$$S_{channel} = \pi \cdot ((R_{cylinder} + 3 \cdot r_{cable} + 4 \cdot w_{gap})^2 - \\ - R_{cylinder}{}^2) = 2.006(m^2) \qquad (1)$$

Where $R_{cylinder}$ =0.55 m; r_{cable} = 0.03 m; w_{gap} = 0.01 m. Thus, the volume flow rate of an air pump in case of inlet velocity of 0.5 m/s is

$$V_{rate} = S_{channel} \cdot 0.5 = 1.003(\frac{m^3}{s}) \qquad (2)$$

and the volume flow rate of an air pump in case of inlet velocity of 0.7 m/s is

$$V_{rate} = S_{channel} \cdot 0.7 = 1.404(\frac{m^3}{s}) \qquad (3)$$

From the economic point of view purchasing and maintaining of one air pump with volumetric flow rate of 1.404 m3/s is more cost-effective than of two air pumps with volumetric flow rate of 1.003 m3/s.

To conclude, we have analyzed the heating modes of cable transformer, which cable winding cooled by the forced airflow. We have considered different gaps between layers of cable windings, different flow speeds on the inlet and their influence on the maximum temperature of XLPE-insulation of cables. We have also compared different schemes of cooling systems, for instance, using one and two air pump respectively. The results of calculations commenced in this study allow us to recommend cooling system with the best parameters from the economical and technical point of view. Forced airflow systems do not require closed circulation, cooling, purification and fire safety systems. For this reasons we recommend forced airflow cooling system with optimized parameters.

REFERENCES

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