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NUMERICAL MODELLING AND ANALYSIS OF COOLING SYSTEM OF ELECTRICAL TRANSFORMER DIPPED INTO POLYMERISED RESIN

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Abstract: This paper discusses a numerical model of the heat dissipation processes in an electrical transformer dipped into polymerised resin. The transformer is cooled by both natural convection (via the ambient air) and forced convection (via the water cooling system attached to one of the transformer casing walls). Two cases have been compared, *i.e.* the cooler connected to the bottom or the top wall of the transformer container, respectively. In order to improve the modelling of the natural convection problem, an independent geometrical model of the surrounding air was created and considered separately. The continuity of temperature and heat flux along the interface between the transformer and air was enforced by an iterative procedure. This procedure allowed one to calculate and then prescribe local heat fluxes to the external walls of the transformer. The numerical results obtained in this project have yielded information on the efficiency of the analysed cooling system.

Keywords: dry electrical transformer, heat transfer, natural convection, coupled analysis

1. Introduction

Electrical transformers are commonly used nowadays to provide an appropriate electric supply for many machines used in industry. In many cases these transformers operate in quite rigorous conditions, which result in difficulties in cooling their coils below an acceptable temperature level. For instance, in mining, transformers may specifically be used to power the combined cutter loaders. However, many strict conditions need to be fulfilled in the mining environment. Typically, all devices must be fire resistant and impervious to high humidity. For this reason transformers have to be placed in hermetic containers, which make their cooling very challenging. A number of companies began an investigation of this cooling process using a *scaled down* transformer. Additionally, in order to fulfil these difficult operating requirements, the model transformer has been put into a metal container and dipped into polymerised resin. This method is widely used in modern industry and gives appropriate fire and ground water protection [1, 2]. As a result of all these endeavours, the transformers might be less efficient at heat dissipation and the maximum temperature of the winding insulation could be exceeded. Hence, to achieve an acceptable working temperature inside the transformer, a cooling system is attached to one of the external walls of the transformer container. Such cooler consists of a steel cooling coil dipped into an aluminium block. A number of experiments was then carried out to find the operating temperatures within the model transformer, which could later be used to verify a numerical model of the transformer.

Heat transfer problems in electrical transformers have been analysed for more than 70 years. However, in most of these analyses, calculations were based on the averaging of the Nusselt numbers values, *e.g.* [3]. Moreover, the reference equations cannot be used for special cases concerning transformers applied in the mining environment. Articles can be found in the technical literature which present numerical solutions for magnetic fields [4], and also a few references which consider local heat fluxes. The numerical calculations generally require the application of Computational Fluid Dynamics (CFD), which is not an easy task, especially for three-dimensional models. For this reason, the research undertaken here has been performed using the commercial CFD package FLUENT [5].

Preliminary results of this project [6] have shown that it is necessary to improve the earlier model of heat dissipation controlled by natural convection within the environment. Hence, a more realistic model which includes the air surrounding the transformer with its cooler was created. The continuity of temperature and heat flux on the interface was then enforced in an iterative procedure [7]. The main objective of this paper is the analysis of the cooling system efficiency, if the cooler is attached to the bottom and then top wall of the transformer casing. Additionally, this project considers heat exchange between the transformer casing with a water cooling system and the calm ambient air using CFD.

2. Geometry and discretisation

The geometrical model in this investigation consists of two subregions. The first is the transformer and the cooler. Due to the complicated shape of the three-phased transformer, a three-dimensional model was created (see Figure 1). The most important elements of the transformer ($0.194\text{m}\times 0.102\text{m}\times 0.1525\text{m}$ – length × depth × height), such as the coils, core, transformer base and mounting, steel container, *etc.*, were kept in their original shapes and dimensions, but some other elements, of lesser importance to the heat transfer problem, were neglected. The transformer was placed into the casing, of the dimensions $0.233\text{m}\times 0.146\text{m}\times 0.1525\text{m}$, and then dipped into polymerised resin. The cooling system consists of a steel cooling coil dipped into an aluminium block ($0.250\text{m}\times 0.170\text{m}\times 0.035\text{m}$). The cooler was initially attached to the bottom and then to the top wall of the transformer casing (see Figure 2). This model was discretised into almost 330 000 Hex8 elements. According to 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). The *EquiAngleSkew* parameter is a normalised measure of skewness. Detailed information on the geometry of the system and its discretisation is given in [8].

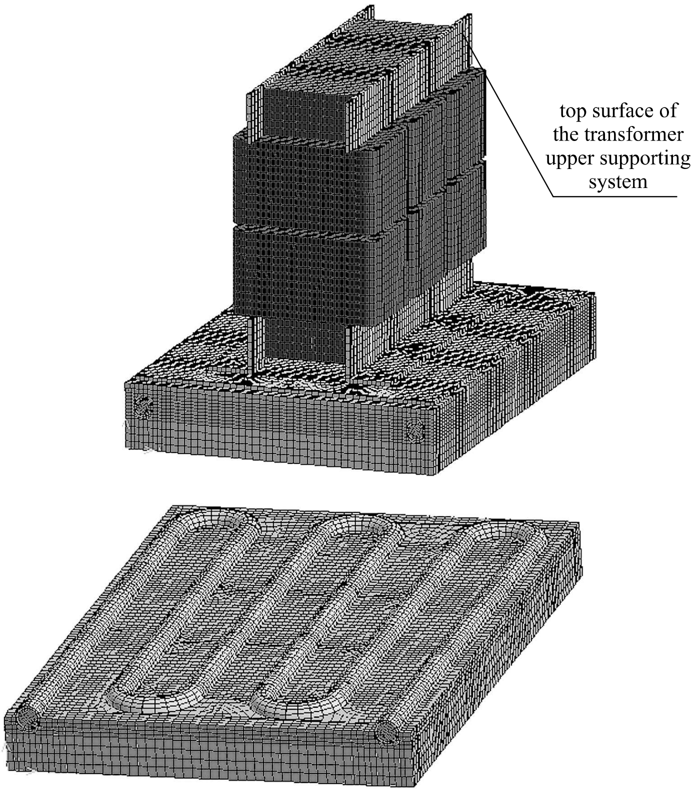

Figure 1. Geometrical model of selected elements of the analysed transformer with the lower cooling system: core with coils and supporting system (top), half of the cooler (bottom)

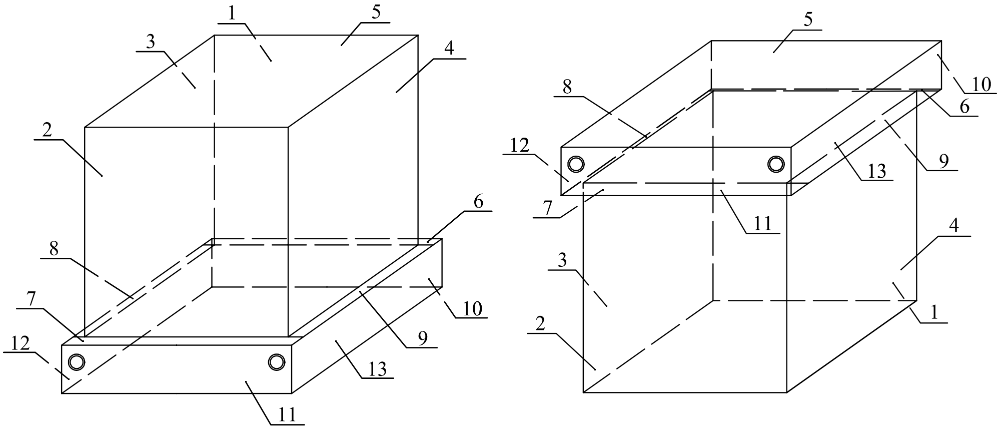

Figure 2. Geometrical model of the transformer casing with cooling system; wall labels are listed in Table 4

The second subregion consists of the surrounding air, with dimensions 2.233 m × 2.146 m × 1.1705 m. Results presented in Section 4 confirm that the above dimensions are appropriate. For the air submodel, very fine mesh was generated as well. This mesh-independent subregion was discretised into 500 000 Hex8 elements. According to the strictest quality-type specifications, more than 94% of the cells had a value less than or equal to 0.25, and were classified as very good elements. Additionally, taking into account the average mesh quality, the transformer with cooling system and the surrounding air meshes had a value less than or equal to 0.03, which is a far better value than recommended by the FLUENT manufacturer (0.4) [5]. More detailed information on the air geometry and its descretisation is presented in [7].

The interfaces between the two coupled subregions were the external walls of the transformer casing and its cooling system. It is important to mention that the mesh generated on these surfaces was different for each subregion, since these submodels were built up and analysed separately.

3. Mathematical model

The temperature distribution within the device and its surroundings can be determined by solving the energy equation [9]:

$$\nabla(k\nabla T)+q_v=\rho_o c\frac{\mathrm{D}T}{\mathrm{D}t}, \tag{1}$$

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 right-hand side is the substantial derivative:

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

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

The thermal properties of the solids in the transformer were gathered from the standard literature, while those of the resin originated from its supplier (see Table 1).

Table 1. Thermal conductivity of solid materials; * – equivalent value for windings

Material	Copper	Aluminium	Resin	Carbon steel
Conductivity [W/mK]	200*	171	1.04	35

The internal heat generation rate q_v included in Equation (1) represents the amount of heat uniformly generated within the transformer windings, but also within the transformer core. It is defined as a ratio of the power P generated within the object to its volume V. Therefore, energy sources can be calculated from the following equation:

$$q_v=\frac{P}{V}. \tag{3}$$

Rates of the source terms were determined according to measurements of the electric operating parameters during open-circuit and short-circuit tests, and are listed in Table 2.

Table 2. Internal heat sources generated within the windings and the core

	Coils			Core
	left	middle	right	
q_v [W/m^3]	130000	70000	130000	30200

For the remaining elements (resin, case, cooling coil, air, *etc.*), rates of the source term are equal to zero.

For the fluids (*i.e.* water and air) considered in the analysis, the energy Equation (1) should be complemented by the continuity and the momentum equations. The mass conservation or continuity equation for incompressible fluids is as follows [10]:

$$\nabla \cdot \boldsymbol{w} = 0, \tag{4}$$

while the momentum equation (Navier-Stokes equation) can be expressed as [10]:

$$\rho_0 \frac{\mathrm{D}\boldsymbol{w}}{\mathrm{D}t} = \boldsymbol{F} - \nabla p + \mu \nabla^2 \boldsymbol{w}, \tag{5}$$

where p is the pressure [N/m^2], $\boldsymbol{F}$ 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 (5). Thus, density takes the usual form:

$$\rho = \rho_0(1 - \beta(T - T_0)), \tag{6}$$

where β is the thermal expansion coefficient [1/K], T_0 and ρ_0 represent the so-called operating parameters.

To determine the temperature distribution within the transformer and the surrounding air, it is necessary to complete the above equations with appropriate boundary conditions. The following boundary conditions were prescribed:

- external boundary conditions
  - Pressure boundary conditions were prescribed on all external walls of the surrounding air. This is a typical boundary condition for flows that can reverse direction at the boundary. It requires the specification of a static pressure and temperature of 'backflow' at the outlet boundary. Since all reported calculations refer to experiments performed in the lab, these parameters were set to 101325 Pa and 292 K, respectively. All other flow quantities were extrapolated from the interior values.
  - Parameters of the flowing water at the inlet were set to: temperature 286 K and velocity 0.66 m/s. A standard k-ε model was used to model turbulence within the cooler (Re=4500).
- internal boundary conditions

  Along each interface in the problem, including the interface between the transformer and the surrounding air, standard continuity boundary conditions were prescribed (*i.e.* both temperatures and heat fluxes have to be the same on each side of the interface). However, it was noticed during thermal measurements that the connection between the aluminium cooler and the steel container was not ideal. Therefore, a thermal contact resistance between these two surfaces was occurring. The resistance of a thin air layer (thickness of 0.1mm) was taken into account by determining an equivalent thermal conductivity in the z-direction for the bottom wall of the steel container. This value was used as a tuning parameter for the model, and its sensitivity was discussed in [8, 6]. In the considered case (cooler at the top), an equivalent thermal conductivity was calculated for the top wall of the transformer casing. This top surface consists of the following parts: the steel top walls of the container side walls, top wall of the resin filling and top wall of the upper supporting system (see Figure 1). The calculations were also performed for an ideal metal-metal contact between walls of the upper supporting system and the cooling system.

The continuity conditions at the interface between the two subdomains (the transformer and the surrounding air) were enforced through an iteration process. This process can be summarized as follows: The starting boundary temperature profile was calculated using an average heat transfer coefficient h on each transformer wall. Its value was determined by using a formula for the Nusselt number, as explained in [7]. The temperature profile obtained was then prescribed to the second subregion (the surrounding air). A FLUENT analysis of the air subregion provides the heat flux boundary profile within the air, which was then prescribed back to the transformer. The next step was to calculate the interface temperature again by analysing the transformer. This iteration process is continued in succession until the temperature and heat flux profiles in two subsequent steps were sufficiently close. The convergence criterion was 0.01%. The errors δ_T and δ_q were defined as:

$$\delta_T = \frac{|\overline{T_i} - \overline{T_{i+1}}|}{\overline{T_i}} \cdot 100\%, \tag{7}$$

$$\delta_q = \frac{|\overline{q_i} - \overline{q_{i+1}}|}{\overline{q_i}} \cdot 100\%, \tag{8}$$

where $\overline{T_i}$, $\overline{T_{i+1}}$, $\overline{q_i}$, $\overline{q_{i+1}}$ were the average temperatures and heat fluxes on the container top wall in two subsequent steps.

4. Results and discussion

As explained in the previous section, the numerical model requires an iteration loop in order to obtain the solution. A plot of the convergence process versus the number of iterations is shown in Figure 3. The error δ_T^1 was determined considering the temperature profile obtained from the transformer with prescribed average heat transfer coefficients and the temperature profile from the first iteration. The error δ_q^1 was determined from 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 iteration process seems to be very efficient, since after nine steps the error was less than 0.01%. This fast convergence was achieved when each separate submodel had fully converged. Results were also obtained with partly-converged submodels, but many more iterations were required and the total computer time increased.

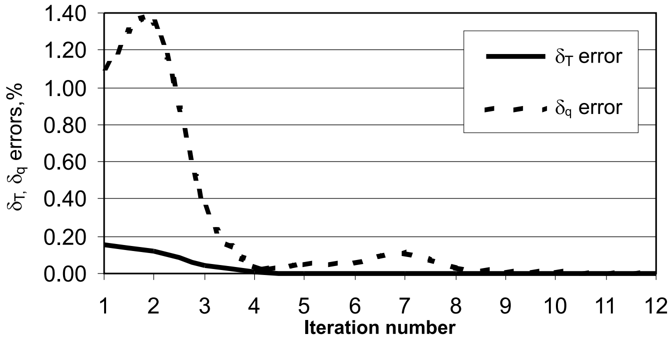

Figure 3. Convergence rate versus number of iterations

The temperature field in the prior project [7] was mainly verified based on experimental measurements at selected points (see Figure 4). Values of temperature at these points were also used to compare the efficiency of the cooling system being attached to the bottom or to the top wall of the transformer casing (column 1 and 2 in Table 3). It is clear that these values are close to each other and the only difference results from the internal transformer structure and its casing. Results presented in column 3 were obtained on the assumption of an ideal contact between the transformer's upper supporting system (the surface is shown in Figure 1) and the transformer cooler. In order to decrease the influence of thermal contact resistance if the upper cooler is applied, the metal-metal connection between the casing and cooler should be guaranteed.

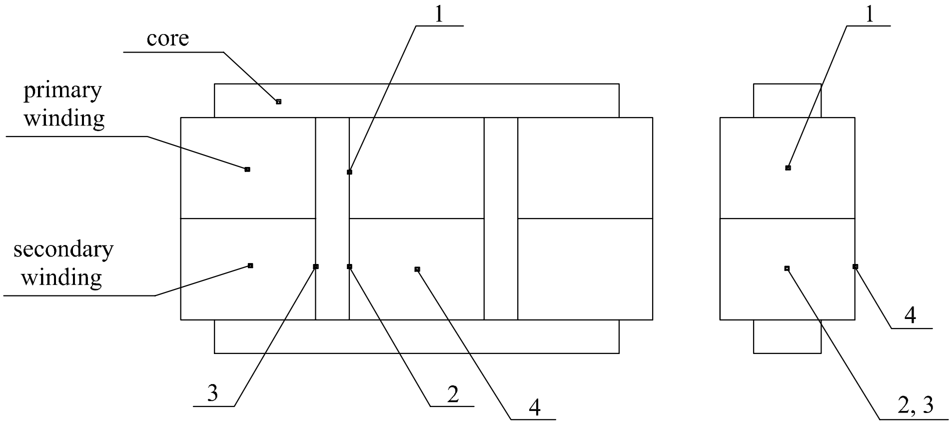

Figure 4. Schematic layout of thermocouples on the transformer coils and core

Energy balance was also calculated for the cases considered, *i.e.* for the results for the transformer with a lower and an upper cooling system. Values of the heat transfer rate on the external walls of the transformer are presented in Table 4. The energy balance confirms the importance of the water cooling system to the heat dissipation process. Heat transfer rates on solid walls have rather small values. The right-hand side walls are warmer than the corresponding left-hand side walls, consistent with the water flow direction.

Table 3. Temperature field in the transformer with cooling system: 1 – transformer with the lower cooler, 2 – transformer with the upper cooler, 3 – transformer with the upper cooler (partly ideal connection between the transformer casing and its upper cooler)

Measurement point	Measured temperature [K]	Calculated temperature [K]		
		1	2	3
Point 1	331.95	328.20	326.40	311.60
Point 2	332.35	326.85	327.65	313.30
Point 3	328.00	327.30	327.90	313.70
Point 4	323.35	326.45	327.40	312.70

Table 4. Energy balance: 1 – transformer with the lower cooler, 2 – transformer with the upper cooler

Wall no.	Wall name	Heat transfer rate [W]	
		1	2
1	Container_Back	−1.86	−0.68
2	Container_Front	−1.85	−0.67
3	Container_Left	−2.97	−0.82
4	Container_Right	−2.98	−0.85
5	Cont_Top/Cool_Top	−3.64	0.43
6	Cool_Sys_Top_Back	−0.0060	0.064
7	Cool_Sys_Top_Front	−0.0057	0.059
8	Cool_Sys_Top_Left	−0.0022	0.029
9	Cool_Sys_Top_Right	−0.0033	0.028
10	Cool_Sys_Back	0.019	0.33
11	Cool_Sys_Front	0.017	0.31
12	Cool_Sys_Left	0.036	0.47
13	Cool_Sys_Right	0.025	0.45
14	Cont_Bott/Cool_Bott	−0.04	−0.84
15	Water_Inlet	−1639.9	−1639.9
16	Water_Outlet	1539.3	1527.8
Total heat transfer rate		−113.97	−113.86

In the considered case, the air temperature was in the range 292K to 311K, as shown in Figure 5, but warmer air occurred only near the casing side walls. Obviously, in this region, the maximum velocity (0.18m/s) occurred. It seems that the dimensions of the artificial external boundaries for the air submodel were appropriately determined since the velocity field at the boundaries had small values. Namely, the average velocities at the bottom and top walls were less than 0.014m/s, and at the side walls they were less than 0.01m/s. The flow field of the air around the transformer is shown in Figure 6.

Generally, the largest amount of air flows out through the central part of the top wall. The air inlet occurs at the bottom boundary, but also partly at the top wall. The most important information concerning flow rates has been shown in Table 5.

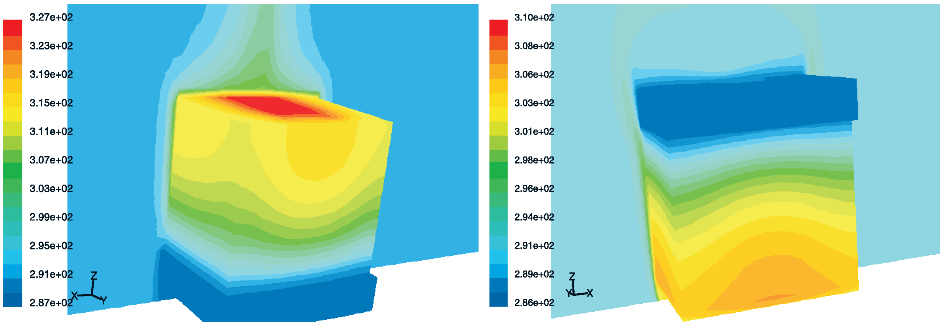

Figure 5. Temperature field within the transformer with cooling system and the surrounding air; the lower cooler is in the left, and the upper one in the right

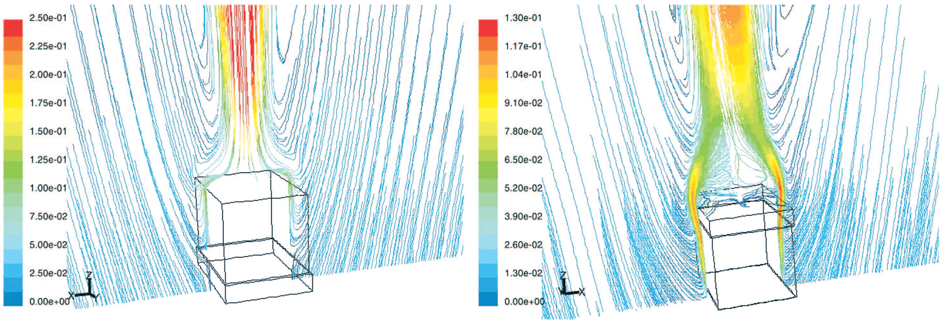

Figure 6. Path lines coloured by velocity within the surrounding air; the lower cooler is in the left, and the upper one in the right

Table 5. Flow rates in the surrounding air: 1 – transformer with the lower cooler, 2 – transformer with the upper cooler

Wall name	Mass flow rate [kg/s]		Average gauge pressure [Pa]		Velocity [m/s]			
					average		maximum	
	1	2	1	2	1	2	1	2
back	0.0095	0.0049	$-3.74\cdot10^{-5}$	$-2.27\cdot10^{-5}$	0.009	0.008	0.016	0.014
bottom	−0.1154	−0.0686	$2.18\cdot10^{-5}$	$-1.08\cdot10^{-5}$	0.022	0.012	0.038	0.025
front	0.0099	0.0048	$-4.12\cdot10^{-5}$	$-2.43\cdot10^{-5}$	0.009	0.008	0.017	0.014
left	0.0103	0.0054	$-3.80\cdot10^{-5}$	$-2.37\cdot10^{-5}$	0.008	0.008	0.016	0.015
right	0.0099	0.0064	$-3.90\cdot10^{-5}$	$-2.73\cdot10^{-5}$	0.008	0.009	0.014	0.015
top	0.0756	0.0471	$-1.55\cdot10^{-4}$	$-4.63\cdot10^{-4}$	0.021	0.014	0.594	0.178

5. Conclusions

This paper considers the heat dissipation process in an electrical transformer dipped into polymerised resin. The transformer was cooled using both natural convection (from the ambient air) and forced convection (from the water cooling system attached to the bottom or top wall). A model of the surrounding air was considered in the analysis of the natural convection problem around the transformer. The two separate submodels (*i.e.* the transformer and the surrounding air) were then solved iteratively.

The following conclusions can be drawn from this research:

- The temperature at the measurement points for both cooling systems are close. Hence, the cooler can be attached either to the bottom or top wall of the transformer casing. However, significant temperature reduction can be obtained if an ideal metal-metal connection on this surface is guaranteed.
- The energy balance indicates the significance of the applied cooler to the total heat flow. In the considered cases reverse heat transfer can occur on the external walls of the model.
- An analysis of the heat flow rates confirms that the surrounding air was adequately modelled.
- The procedure of coupling two independent subregions has been successful, and the required increase in computer power is insignificant. Moreover, the iteration process converges faster by performing less steps if each independent submodel is fully converged, rather than by performing more steps for only partly converged submodels.

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