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COMPUTER SIMULATION OF MEASURING TRANSDUCERS USED FOR DIAGNOSIS OF ICING IN SOLIDWORKS SOFTWARE PACKAGE

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Abstract: There is a number of disadvantages in existing systems of diagnosing ice formation on overhead electric power distribution lines, under the conditions of climate change. In particular, they do not meet actual precision requirements. A 3D model of a measuring traducer being the part of an improved predictive diagnostic system was designed in the SolidWorks software environment. In the Flow Simulation software module, the temperature distribution over the surface of the measuring transducer was determined as the result of the solution of hydrodynamic and thermal tasks, and the analysis of operating modes for thermoelectric cooler was conducted. It was confirmed that heat emitted by the thermoelectric module has no influence on a zone controlled by the sensor.

Key words: measuring transducer, icing, modeling of heat transfer processes, finite element method, SolidWorks, Flow Simulation.

1. Introduction

The expire of the estimated operation life of the overhead electric distribution lines, together with the intensification of ice and wind impacts caused by changes in the climate conditions of Ukraine, creates the urgent need for improvements in the methods and means of diagnosing emergency situations. It should be mentioned here that existing systems of icing diagnosis have considerable disadvantages and do not meet the actual requirements of precision [1].

For this purpose, the selection of the parameter for icing diagnosis on wires of overhead lines [1] and the design of the primary measuring transducer (PMT) [2] was justified. For the technical implementation of the proposed system of the icing diagnosis on the wires of overhead electric power distribution lines [3], it is necessary to conduct the thermal design of the measuring transducer. Considering the existence of many different kinds of wires for such sensors [2] and the possibility of creating the primary measuring transducers (PMT) of different length for one task, it is advisable to create its computer model in SolidWorks Flow Simulation software system, which can be used for designing 3D models of different complexity.

The aim of this study is to develop a computer model for simulating the processes of cooling (heating) the sensor and to carry out the evaluation of the effectiveness of heat removal from the measuring zone of a thermoelectric module (TEM) under the set climate conditions.

Fig. 1 shows a 3D model of the transducer. The thermal load of the thermoelectric module is a parallelepiped, made of the same material as the sensor, with its wider faces arranged in the same plane. The design of the primary measuring transducer allows the TEM to cool each wire separately; this solution allows neutralizing the influence of Teflon insulating gaskets between the main electrode and the additional ones.

Considering the wide assortment of wires type A (AS) [4], and thus the possibility of creating the PTM of various lengths for a given problem [2], it is advisable to develop a computer model of the measuring transducer.

Formulation of the problem. Airflow with constant velocity v and temperature t is fed to an input channel. The flow velocity around the measuring transducer conforms to the Mach number $M \ll 1$. The details of measuring transducer have certain thermal conductivity and convective heat transfer between them and the environment. The primary measuring transducer is covered with a water film.

Assumption. The air is considered incompressible, weightless, conductive, viscous liquid; fluid mode is mixed (laminar and turbulent); there is no internal heat source in liquid.

The film covering the primary measuring converter has properties of “solid” body whose thermal characteristics (thermal conductivity and heat capacity) are identical to liquid water. This approach allows the analysis of only one fluid, which is air. Heat emissions during freezing of water film on the sensor are not taken into account.

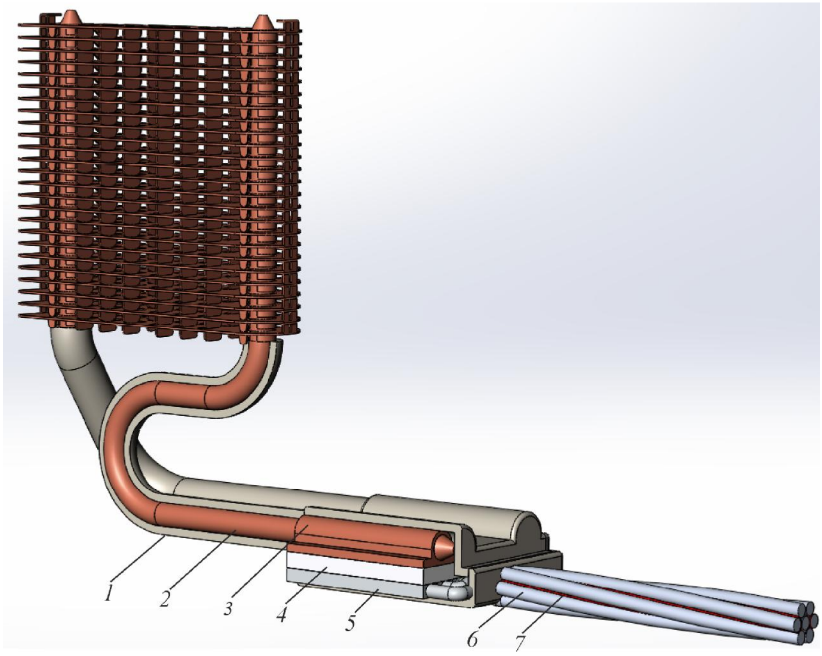


Fig. 1. Final 3D model of measuring transducer:
1 – thermo-insulation; 2 – heat pipe; 3 – heat sink; 4 – thermoelectric module (cooler);
5 – PMT cold receiver; 6 – primary measuring transducer; 7 – electrical insulation.

During the calculations, the actual insulation of measuring transducer is replaced by ideal one by setting the appropriate boundary conditions. Electrical transients in the TEM are not taken into account. All thermal contacts are assumed ideal, and the details of the measurement transducer have smooth surface. The operational mode of the measuring transducer is investigated under the most difficult weather conditions ($t_a = 2.05$ °C, $v_{a.x} = 10$ m/s) from the point of view of cooling the sensor.

Model description. Using these assumptions, the transient dimensional flow within Euler approach in the Cartesian coordinate system (x_i, i = 1, 2, 3), rotating with angular velocity Ω, around an axis passing through the origin of coordinates, is modelled with the system of equations of the laws of conservation of mass, angular momentum and energy [5, 6]

$$\left.\begin{aligned} &\frac{\partial r}{\partial t}+\frac{\partial}{\partial x_i}(r v_i)=0;\\ &\frac{\partial r v_i}{\partial t}+\frac{\partial}{\partial x_j}\left(r v_i v_j\right)+\frac{\partial p}{\partial x_i}=\\ &=\frac{\partial}{\partial x_j}\left(\mathrm{T}_{ij}+\mathrm{T}_{ij}^{R}\right)+S_i;\\ &\frac{\partial r H}{\partial t}+\frac{\partial r v_i H}{\partial x_i}=\frac{\partial}{\partial x_i}\left(u_j\left(\mathrm{T}_{ij}+\mathrm{T}_{ij}^{R}\right)+q_i\right)+\\ &+\frac{\partial p}{\partial t}-\mathrm{T}_{ij}^{R}\frac{\partial v_i}{\partial x_j}+re+S_j v_j+Q_H. \end{aligned}\right\} \qquad (1)$$

where ρ is the fluid density; x is the coordinate; τ is the time; v is the velocity of air flow; p is the pressure of fluent environment; T_{ij} is the tensor of Reynolds stress for Newtonian liquid (viscous shear)

$$\mathrm{T}_{ij}=m\left(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}-\frac{2}{3}d_{ij}\frac{\partial v_k}{\partial x_k}\right);$$

μ is the dynamic viscosity coefficient; T_{ij}^{R} is the tensor of Reynolds stress with the following Boussinesq assumption (Boussinesq approximation)

$$\mathrm{T}_{ij}^{R}=m_t\left(\frac{\partial v_i}{\partial x_j}+\frac{\partial v_j}{\partial x_i}-\frac{2}{3}d_{ij}\frac{\partial v_k}{\partial x_k}\right)-\frac{2}{3}r k d_{ij};$$

μ_t is the coefficient of turbulent viscosity

$$m_t=f_m\frac{C_m r k^2}{e};$$

f_μ is the function of turbulent viscosity

$$f_m=\left(1-\mathrm{e}^{-0{,}025R_y}\right)^2\left(1+\frac{20{,}5}{R_T}\right),$$

R_y, R_T are variables founded from equations:

$$R_y=\frac{r\sqrt{k}y}{m},\ R_T=\frac{r k^2 e}{m};$$

where y is the distance from the local average volume of fluid environment to a calculated wall; k is the turbulent kinetic energy; ε is turbulent dissipation; d_{ij} is the Kronecker delta function ($i=j \to d_{ij}=1$, $i\neq j \to d_{ij}=0$); μ is the function of dynamic viscosity.

The turbulent kinetic energy and its dissipation is founded in the result of the solution of two additional equations [6]

$$\frac{\partial r k}{\partial t}+\frac{\partial}{\partial x_i}(r v_i k)=\frac{\partial}{\partial x_i}\left(\left(m+\frac{m_t}{s_k}\right)\frac{\partial k}{\partial x_i}\right)+S_k;$$
$$\frac{\partial r e}{\partial t}+\frac{\partial}{\partial x_k}(r v_i e)=\frac{\partial}{\partial x_k}\left(\left(m+\frac{m_t}{s_e}\right)\frac{\partial e}{\partial x_i}\right)+S_e, \qquad (2)$$

where S_k, S_e are the characteristics of pulsations of kinetic energy and its dissipation

$$S_k = \mathrm{T}_{ij}^R\frac{\partial v_i}{\partial x_j} - re + m_t P_B;$$

$$S_e = C_{e1}\frac{e}{k}\left(f_1 \mathrm{T}_{ij}^R\frac{\partial u_i}{\partial x_j} + m_l C_B P_B\right) - C_{e2} f_2 \frac{re^2}{k};$$

f_1, f_2 are variables depending on the coefficients of dynamical and turbulent viscosity

$$f_1 = 1+\left(\frac{0,05}{f_m}\right)^3, \quad f_2 = 1-\mathrm{e}^{-R_T^2};$$

P_B is the turbulence caused by buoyancy forces

$$P_B = -\frac{g_i}{s_B}\frac{1}{r}\frac{\partial r}{\partial x_i};$$

g_i is the component of gravitational acceleration in direction x_i;

$C_B = 1$ at $P_B > 0$ and $C_B = 0$ at $P_B \le 0$;

$s_B = 0.9$, $s_e = 1$, $s_k = 1$, $C_{e1} = 1.44$, $C_{e2} = 1.92$, $C_m = 0.09$ are the model coefficients [6];

S_i is the external mass force, which impact on the unit mass of air flow, $S_i = S_{gravity} = -r g_i$; H is total fluid enthalpy

$$H = h + \frac{v^2}{2},$$

h is the enthalpy; λ is the thermal conductivity; q_i is the diffusional air flow

$$q_i = \left(\frac{m}{\mathrm{Pr}}+\frac{m_t}{s_c}\right)\frac{\partial h}{\partial x_i}, \quad i = 1, 2, 3; \qquad (3)$$

Pr is the Prandtl number; $s_c = 0.9$ is a model constant;

Q_H is the heat emitted by a heat source in the unit volume of fluid.

Heat transfer in solid body is modelled by an equation [5, 6]

$$\frac{\partial r e}{\partial t} = \frac{\partial}{\partial x_i}\left(l_i\frac{\partial t}{\partial x_i}\right) + Q_H, \qquad (4)$$

where e is specific internal energy, $e = ct$; c is specific heat capacity under the constant pressure conditions; λ is the thermal conductivity of solid body; Q_H is the specific (per unit of volume) release (or absorption) of heat by the source; $Q_H = -Q_{TEC}$; Q_{TEC} is the specific absorption of heat by thermoelectric cooler.

The coerced thickness of a water film is

$$l_{film} = \left(\frac{m_w^2}{r_w^2 g}\right)^{0,33};$$

where μ_w is the coefficient of dynamical viscosity of water; ρ_w is the density of water, under temperature conditions of 2 °C.

In Flow Simulation software, the Peltier element is modelled by the appropriate boundary conditions set by the catalog data: the maximal pumped heat $Q_{\max}$, maximal temperature drop $\Delta t_{\max}$, maximal current value $i_{\max}$ and maximal voltage $U_{\max}$.

The net heat transferred from the TEM "cold" surface to its "hot" surface is equal to:

$$Q_c = ait_c - \frac{Ri^2}{2} - k\Delta t;$$

and, correspondingly, on the "hot" surface of the TEM net heat calculated by the following formula is released:

$$Q_h = ait_h + \frac{Ri^2}{2} - k\Delta t,$$

where a is the Seebeck coefficient; i is current; t_c is the temperature of "cold" surface of the TEC; R is the electric resistance of the TEM; k is the coefficient of TEM thermal conductivity; Δt is the thermal drop between the "cold" and "hot" surfaces of the TEM, $\Delta t = t_h - t_c$; t_h, t_c are the temperatures of "cold" and "hot" surfaces of the TEM.

If it is necessary, the thermal influence of electric current on the sensor can be taken into account by the Joule-Lenz equation (for isotropic materials) [6]

$$Q_J = rj^2,$$

where r is the resistance per unit length; j is the electric current density.

Under the steady-state conditions, the electric current density vector

$$\mathrm{j} = -\left(\frac{1}{r_{11}}\frac{\partial j}{\partial x_1}, \frac{1}{r_{22}}\frac{\partial j}{\partial x_2}, \frac{1}{r_{33}}\frac{\partial j}{\partial x_3}\right),$$

is determined via the electric potential φ in the i-th coordinate direction from the Laplace equation

$$\frac{\partial}{\partial x_i}\left(\frac{1}{r_{ii}}\frac{\partial j}{\partial x_i}\right) = 0;$$

where r_{ii} is the temperature-dependent electrical resistivity in the i-th coordinate direction.

The calculation of the thermal conductivity of the heat pipe is based on the given value of effective thermal resistance between the cooled object and evaporation zone of the heat pipe, and on the calculated values of thermal resistance of a solid-state component. Temperature gradient of the heat pipe along its length is equal to [6]

$$\Delta t = QR ;$$

where Q is the heat flow through the heat pipe; R is the complete thermal resistance.

Boundary conditions for the system of equations (1) – (4) are formed as follows

hydrodynamic:

– input condition – *Velocity*: $v_i = 10$ m/s;

– output condition – *Environment Pressure*: $p = 101325$ Pa;

– motionless measuring transducer in the air stream: $\Omega = 0$ m/s;

– gravity force – *Gravity*: 9.81 m/s^2;

– airflow turbulence – *Turbulence Intensity*: 0.1 %;

thermal:

– initial temperature of measuring transducer – *Wall Temperature*: 2.05 °C;

– the temperature of the air flow – *Fluid Temperature*: 2.05 °C;

– thermal insulation of bodies – *Ideal Wall*, that is, they meet the Neumann condition: $\partial t/\partial \mathrm{n} = 0$, where $\boldsymbol{n}$ is a normal to respective faces;

– standard TEC, controlled parameter – *Current*, A;

– ohmic heating of the sensor – *Current*, A.

Finite element mesh. To find the numerical solution of the problem, its unsteady mathematical model (1)-(4) is digitized both by space and by time. To perform sampling for the space, the entire settlement area is covered with an estimated mesh whose cell facet planes are orthogonal to coordinate surfaces of Global coordinate system of the 3D SolidWorks model. Thus, the estimated net is described by cells that have the form of rectangular parallelepipeds.

The Flow Simulation program uses finite volumes, so the values of the independent variables are determined in the centers of the cells, and the flow of masmesh refinements, momentum and energy needed to calculate these values are determined on the faces of these cells.

Basic net is obtained by dividing the estimated domain into layers with specified number of planes. Since the calculation of flow cell faces, which are in contact with the surface of small bodies, is done without approximation, for their estimated net resolution the procedure of local mesh refinement near these surfaces is used. In addition, the special resolution procedures are used with calculated mesh for thin walls that washed over with flow and thin layers of dissimilar materials in solids without mesh refinement cells for the less wall thickness. To increase the accuracy of the model, in a group of small solids (insulating film channels between the electrodes, see. Fig. 1) the calculated local grid, with the properties described above is used.

Time sampling is made by splitting such operators as SIMPLE [7] to improve the calculation of pressure and flow rate.

The verification of the regularity of the created mesh for 3D models has been conducted by increasing its frequency to achieve convergence of the mesh and the solution of mathematical problem presented in Table 1.

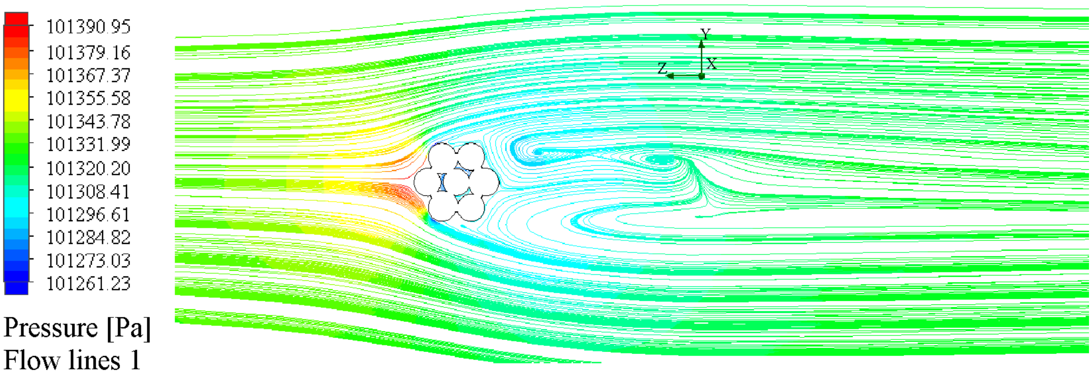
Results. The primary measuring transducer is a badly streamlined body (bluff body), because a large area of separation with reverse circulation flow is formed behind it (Fig. 2, *a*). In comparison with the circular cylinder of equal diameter and length (Fig. 2, *b*), under the identical hydrodynamic and thermal conditions, the area of separation behind the sensor has asymmetrical vortices with spiral nodes that significantly distort the lines of the main current. In the troughs between the electrodes, significant circulation zones occur. Electrodes of the sensor have the form of an oblong poled spiral surface, so flow separation behind it is shifted along a curved trajectory (Fig. 2, *a*). For a middle of the sensor ($l = 40$ mm), the low point of the separation is determined by a curvilinear coordinate $l_{sep} = 7.49$ mm, behind which the pressure does not restore and does not change (Fig. 3).

Table 1

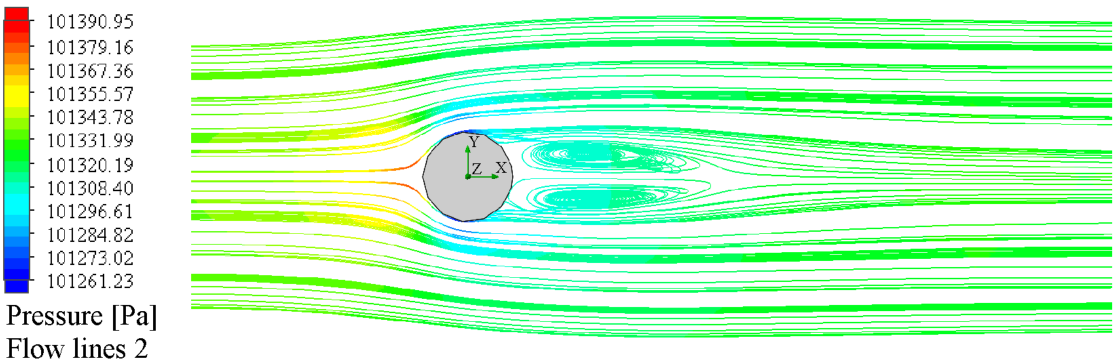
Checking the regularity of the grid of 3D model

No	Number of grid cells, pcs.			Control parameters (Fig. 5)		
	in fluid	solid state	partial	t_{c1}, °C	t_{c2}, °C	t_{c3}, °C
1	278 634	234 374	390 603	–10.07	–11.13	9.03
2	395 607	338 328	614 841	–9.18	–10.18	9.05
3	724 609	577 035	1 019 000	–9.02	–10.05	8.07
4	910 245	1 116 160	1 510 604	–9.04	–10.05	8.01

In the flow, the process of heat transfer is caused by two mechanisms: convection and conduction. In the non-separable flow the convection prevails, so thermal conductivity in this case only leads to heat transfer in the direction transverse to the direction of the flow. However, the effects of heat conduction in separation currents are very significant, especially in the area of the main flow boundaries [8]. The results shown in Fig. 4 indicate a significant impact of stream separation on the temperature distribution over the surface of the sensor t_{sen}.



a)



b)

Fig. 2. Flow lines in the plane y0z (the middle of a sensor and a cylinder): a) around the sensor; b) around a circular cylinder of an equal diameter (the external outline) and length.

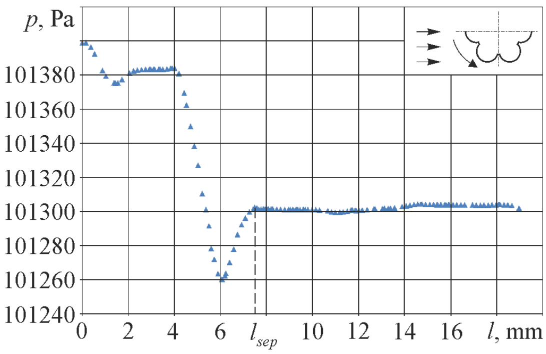


Fig. 3. Graph of distribution of excess pressure in the lower semicircle of sensor surface.

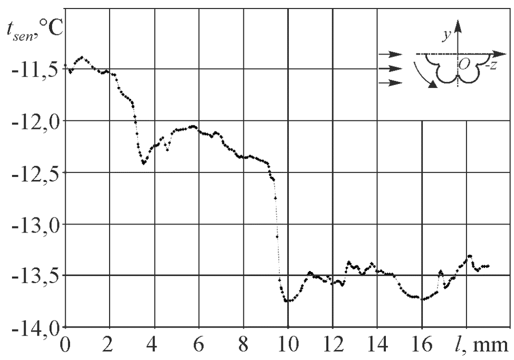


Fig. 4. Temperature distribution on the surface of the sensor (y0z plane intersects the center of the sensor).

In troughs behind the points of separation, the reverse flows of low speed (up to 1 m/s) are formed and significant air-cooling (to – 12.5 °C) occurs, so convection effects are reduced. In the rear part, liquid being on the current line of reverse circulation flow is cyclically heated by the main stream in the area of its boundaries with the reverse flow due to transversal transfer of the heat caused by heat conduction, and followed by convective heat transfer to the thermal boundary layer. Therefore, the temperature of the rear part of the sensor is reduced to – 13.7 °C.

Average temperatures on the surface of the measuring transducer is presented in Fig. 5. The coldest part of the sensor is a place of contact with TEM, along the length of the sensor temperature increases and culminates at $t_{c1} = -9\ °C$. The maximum of the radiator temperature is in the places where it contacts with the heat pipes.

Due to the heat removal from the warm side of the thermoelectric module with the use of heat pipes, its impact on the measurement area of the sensor in the most difficult sensor mode – when the flow is directed along its longitudinal axis – is eliminated (Fig. 6).

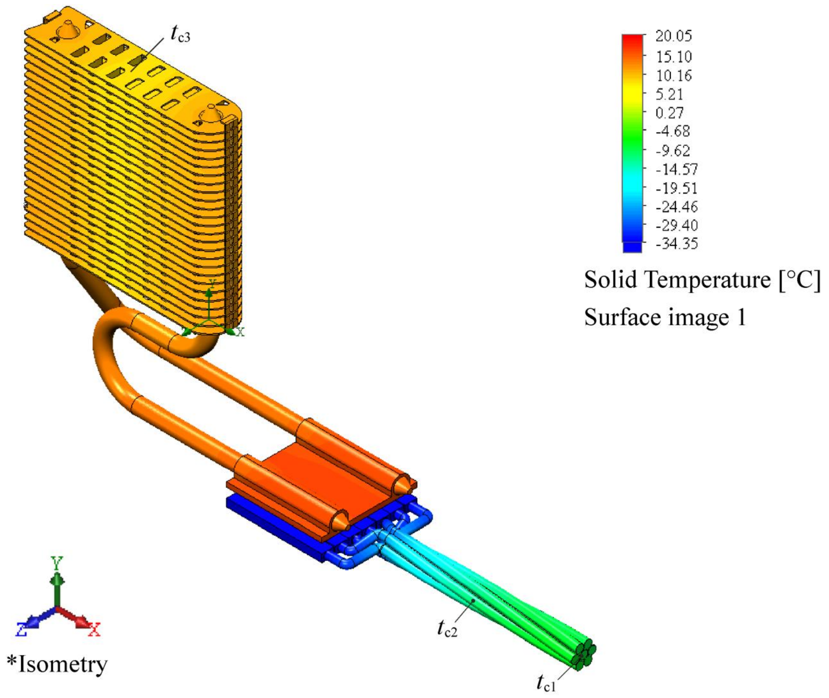


Fig. 5. Distribution of temperatures along the surface of the measuring transducer.
I_{TEC} = 4 A, t_{fl} = 2.05 °C, v_z = –10 m/s (TEM and heat sensor are not shown)

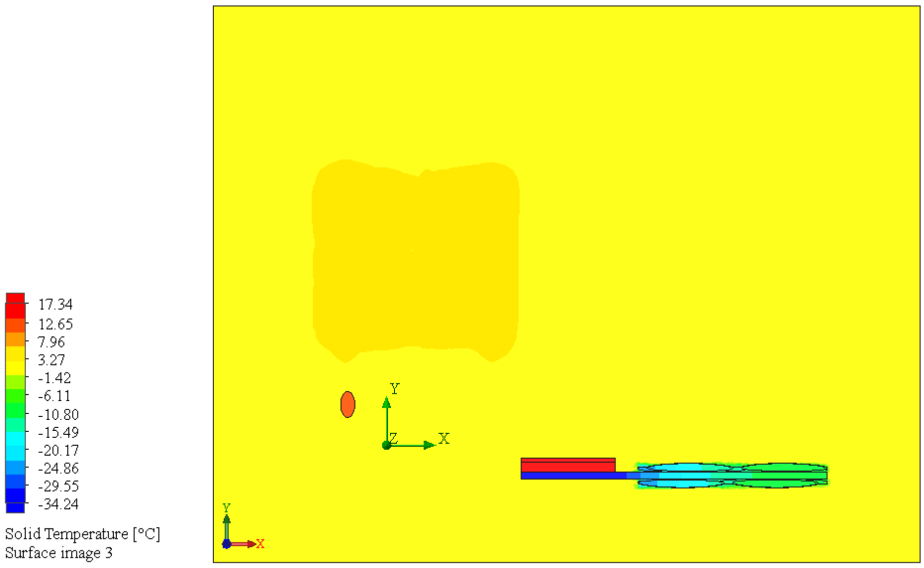


Fig. 6. Temperature distribution around the measuring transducer
in a plane at x0y I_{TEC} = 4 A, t_{fl} = 2.05 °C, $v_{a.x}$ = 10 m/s.

For a given heat load of TEM and under the most complex weather conditions, the best cooling efficiency is achieved at a current supply 4–5 A which is close to the recommended values $(0.75-0.8)I_{TEC.max}$ [9, 10].

The considered thermoelectric module has sufficient power for cooling the prime measuring transducer in modes close to optimal.

To verify the computer model having been developed for the prime measurement transducer, the convective heat transfer coefficient (surface parameter) of the sensor with the use of Flow Simulation software application and methods described in work [1] based on the film of water has been calculated. The difference in values obtained is ≈ 9 %.

Thus, the proposed computer model is possible to be implemented in the design of measuring transducers for the icing forecast via the technical diagnostic system on the wires of overhead power lines.

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КОМП'ЮТЕРНЕ МОДЕЛЮВАННЯ ВИМІРЮВАЛЬНОГО ПЕРЕТВОРЮВАЧА ОЖЕЛЕДОУТВОРЕННЯ У ПРОГРАМНОМУ КОМПЛЕКСІ SOLIDWORKS

Олександр Козловський, Дмитро Трушаков, Сергій Рендзіняк

Наявні системи діагностування ожеледоутворення на проводах повітряних ліній розподільних електромереж мають низку недоліків і в умовах зміни клімату не відповідають сучасним вимогам точності. З метою проведення теплових розрахунків удосконаленої прогнозуючої системи діагностування створено 3D-модель вимірювального перетворювача у програмному комплексі SolidWorks. У модулі Flow Simulation у результаті розв'язку гідродинамічної та теплової задач визначено розподіл температури на поверхні вимірювального перетворювача, проведено аналіз режимів роботи термоелектричного модуля. Підтверджено відсутність впливу тепла, що виділяє термоелектричний модуль на зону контролю первинного вимірювального перетворювача.

Oleksandr Kozlovskyi – graduated from Kirovograd State Technical University (major "Electrical power consumption"), Ukraine. He has been working at Kirovograd National Technical University since 2001 as Assistant Professor at the Department of Automation and Power Engineering. Area of research: systems for diagnosis of icing on overhead power lines of electrical networks.

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