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Building structures thermal calculation

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Introduction. The thermal calculation of a volumetric structure using the finite element method is considered. According to the plans of the Ministry of Energy of the Russian Federation, a powerful wind energy industry will be created in the country in the coming years. In this regard, calculations in the production of building structures of wind power plants are currently becoming a challenge. The production of such fiberglass structures is a complex thermochemical process, including the polymerization of the binder under strictly specified thermal conditions. The work objective is to develop a method for three-dimensional finite element calculation of the non-stationary heating mode of a complex-shaped composite structure.
Materials and Methods. The determination of the temperature fields of a complex-shaped structure made of inhomogeneous materials causes using numerical methods and, first of all, the finite element method. The finite element modeling of the behavior of composite materials under molding is still incomplete. For its partial solution, the well-known heat conduction equation is adapted for a specific problem based on the first law of thermodynamics. New finite element models describing the thermal fields in the structure during its manufacture are proposed. The accuracy of modeling thermal processes is specified. Numerical simulation of heating is carried out.
Results. The solution to the problem was performed in the multifunctional software complex ANSYS with the implementation of the calculation method in the parametric programming language APDL. The temperature fields of the blade elements of wind power plants at the stage of their manufacture were calculated, which made it possible to identify the characteristic features of the production process of these structures and to obtain recommendations for clarifying the process of their gluing.
Discussion and Conclusions. The results obtained can be used in thermal calculations of elements of complex layered structures made of composite materials in wind power, mechanical engineering, aircraft, shipbuilding, instrumentation, etc.

Keywords: finite element calculation, temperature field, nonmetallic structure, technological process, modeling.

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Introduction. Thermal calculations in the production of building structures of wind power plants are currently becoming a challenge. According to the plans of the Ministry of Energy of the Russian Federation[1], the wind power industry will be created in the country in the coming years. In 2016-2017, large Russian and foreign investors came to it, who committed themselves to the development of the technological and production base. The major disadvantages of blade wind power plants are eliminated through improving their design and manufacturing technique. First of all, this applies to the blades, which are the main elements of the wind turbine. They concentrate the key intellectual component of the installation. The production of a fiberglass blade is a complex thermochemical process, including the polymerization of the binder under a strictly specified thermal regime. In this regard, the exact calculation of the temperature fields in the body of the blade during its molding is of great practical importance.

[1]Renewable energetics in Russia has established itself as an industry. Ministry of Energy of the Russian Federation. URL: https://minenergo.gov.ru/node/10307/ (accessed: 04.02.2021). (In Russ.).

The determination of the temperature fields of a complex-shaped structure made of inhomogeneous materials causes the need to use numerical methods in calculations and, first of all, the finite element method (FEM). The problem of finite element modeling of composite materials under molding remains unresolved to date. This is due to complexity of the behavior of the composite as an inhomogeneous material with pronounced thermally dependent physical properties, including rheological ones, residual internal phenomena, aging, etc.

Modern models take into account the anisotropy of the material, its plastic behavior under a complex stress-strain state, etc. Thus, the temperature properties of composite materials were studied in [1, 2]. To substantiate and confirm the influence of the distribution and orientation of strengthening particles on the coefficient of thermal expansion of the material, the authors performed finite element modeling. Under the geometric construction, a real microstructure was taken as the basis. Calculations have established that the experimentally detected anisotropy of temperature properties is explained by internal stresses in the composite that depend on the filler orientation.

Many studies consider the calculations of two-dimensional models of reinforced composite materials. To analyze and optimize the properties of the composite, a calculated finite element scheme is proposed that takes into account its temperature properties [3]. With the help of FEM, the fields of residual stresses formed in the matrix as a result of thermal processing for a composite model including reinforcing fibers are calculated [4]. The effective elastic characteristics of a multilayer composite material were calculated using a finite element model, with each layer being described by its own thermomechanical properties [5]. Modeling of the behavior of anisotropic materials and other issues of thermal loading are also analyzed in [6–13].

Most of the studies based on finite element analysis were performed using the universal software system ANSYS, which provides solving linear and nonlinear, stationary and non-stationary spatial problems of heat transfer and heat exchange. For example, using ANSYS, the following tasks are solved:

— non-stationary heating of the structure with time-dependent convection coefficient[2];

— thermal expansion of the elements under intense heating[3];

— heat release during plastic deformation[4];

— heat transfer in multilayer structures through the interface of media[5], etc.

S. N. Shevtsov's works are devoted to the study of the processing of polymer composite materials, e.g., in [14]. Despite a large number of works on numerical thermal calculations, assessment of the thermal mode of forming the structures of blade units is still relevant. Increasing requirements for the quality of production of wind turbine elements necessitates further refinement of mathematical finite element models of heat transfer based on a more complete account of external and internal factors.

The work objective is to study the non-stationary temperature fields of a composite structure of a complex volumetric shape of a blade element of a wind power plant in the process of its manufacture, taking into account physical features and geometric nonlinearities. One of the structures consists of a spar and a tail section, whose parts are made of fiberglass, rubber, foamed plastic, etc. The tail section is manufactured using adhesive technology in a special device, which consists of upper and lower half-body with powerful stiffeners. A blade element is laid between them. For its high-quality gluing, it is required to strictly maintain the heating speed and the holding temperature in the glue lines. Setting the thermal mode is carried out by placing the device with a section in the heating furnace.

The task statement of the study is as follows. It is required to create a finite element model of heating a blade element during its molding, calculate the volumetric temperature fields at any moment of the process, determine the accuracy of modeling thermal processes in the body of the structure, and also form a graph of the temperature rising in the furnace, providing the required heating mode for the glue zones of the section.

Materials and Methods. The basis of thermal calculations is the statement of the first law of thermodynamics that the amount of heat received by an isolated system is spent on changing its internal energy. Applied to an elementary volume, this statement can be expressed mathematically:

$$\rho c(\partial T / \partial t + \{V\}^T \{L\} T) + \{L\}^T \{q\} = q_v , \tag{1}$$

where ρ — material density; c — specific heat capacity; T — temperature; t — time; $\{q\}$ — heat flux vector; q_v — heat release per unit volume.

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[2] Thermal Time-Transient Loading and Solution in Ansys. SimuTechGroup. simutechgroup.com — URL: https://www.simutechgroup.com/tips-and-tricks/fea-articles/97-fea-tips-tricks-thermal-transient (accessed: 04.02.2021).

[3] Extreme Thermal Expansion Modeling in Ansys Mechanical Workbench. SimuTechGroup. simutechgroup.com — URL: https://www.simutechgroup.com/tips-and-tricks/fea-articles/139-extreme-thermal-expansion-modeling-in-ansys-mechanical (accessed: 04.02.2021).

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[5] Heat Conduction Across a Contact Element Gap in Ansys Workbench Mechanical. SimuTechGroup. simutechgroup.com — URL: https://www.simutechgroup.com/tips-and-tricks/fea-articles/229-fea-tips-tricks-heat-conduction-contact-element-gap-ansys-workbench-mechanical (accessed: 04.02.2021).

Vector operator $\{L\}$ and velocity vector $\{V\}$ for heat transfer realized by mass:

$$\{L\}=\begin{Bmatrix}\dfrac{\partial}{\partial x}\\ \dfrac{\partial}{\partial y}\\ \dfrac{\partial}{\partial z}\end{Bmatrix},\quad \{V\}=\begin{Bmatrix}V_x\\ V_y\\ V_z\end{Bmatrix},$$

where x, y, z — coordinates.

According to Fourier's law, the heat flow is associated with the temperature gradient:

$$\{q\}=-[D]\{L\}T, \tag{2}$$

where $[D]$ — thermal conductivity matrix:

$$[D]=\begin{bmatrix}\lambda_x & 0 & 0\\ 0 & \lambda_y & 0\\ 0 & 0 & \lambda_z\end{bmatrix}.$$

Combining (1) and (2), we get:

$$c(\partial T/\partial t+\{V\}^T\{L\}T)=\{L\}^T([D]\{L\}T)+q_v. \tag{3}$$

Opening (3), we get:

$$\rho c(\frac{\partial T}{\partial t}+V_x\frac{\partial T}{\partial x}+V_y\frac{\partial T}{\partial y}+V_z\frac{\partial T}{\partial z})=q_v+\frac{\partial}{\partial x}\left(\lambda_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_z\frac{\partial T}{\partial z}\right).$$

The basic equation of thermal conductivity is supplemented by boundary conditions:

1. Setting the surface temperature: $T = T^*$.
2. Setting the heat flow on the surface:

$$\{q\}^T\{n\}=-q^*,$$

where $\{n\}$ — surface normal unit vector; q^* — specific heat flux.

Heat transfer corresponds to Newton's law (surface convection):

$$\{q\}^T\{n\}=\alpha_f\left(T_s-T_b\right),$$

where α_f — heat transfer coefficient, T_s — surface temperature, T_b — temperature of the bordering medium.

For the case of constant thermophysical coefficients, the studied thermal processes are described by the three-dimensional equation of non-stationary thermal conductivity (the Fourier equation):

$$\rho c\frac{\partial T}{\partial t}=\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right),$$

where λ — heat conductivity factor.

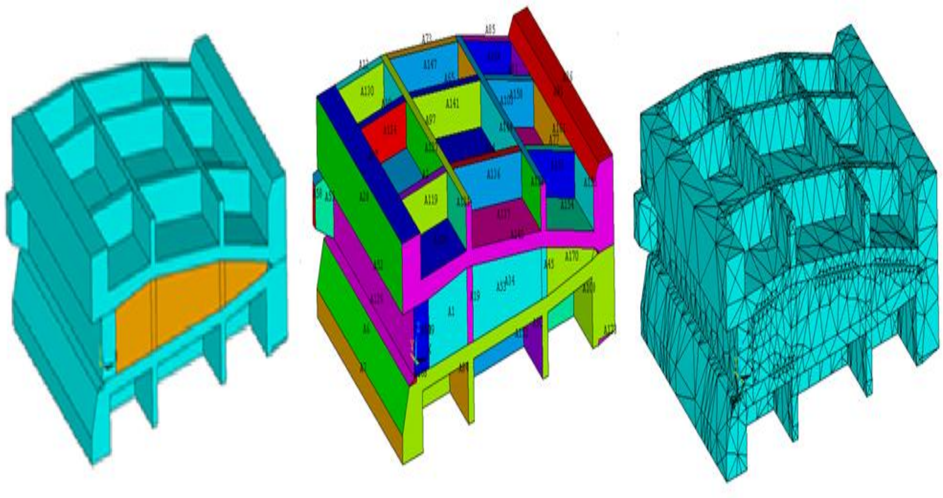
Due to the symmetry of the problem, the calculation is carried out only for half of the design. The boundary conditions for the section plane are determined from the condition: $q = 0$.

On the docking interfaces, it is assumed that there is an ideal thermal contact, the absence of thermal resistance:

$$T\big|_{-0}=T\big|_{+0}\ ;\ \lambda_1\frac{\partial T}{\partial x}\big|_{-0}=\lambda_2\frac{\partial T}{\partial x}\big|_{+0}.$$

Convective heat flows are supplied to the external surfaces of the device. Internal heat generation during heating is not taken into account. The initial conditions assume the fixation of a constant temperature over the entire area under investigation: $T = T_0$.

The problem is solved by the finite element method in the multifunctional software complex ANSYS in the parametric programming language APDL. The structure is heated from the outer surface through convection. The results of the division of the device and the section into blocks, as well as into three-dimensional tetragonal finite elements, are shown in Fig. 1.



a) *b)* *c)*

Fig. 1. Bonding device with a tail section: *a*) general view; *b*) model surfaces with their numbers; *c*) division of the analyzed area into finite elements

The thermophysical properties of the materials used in the calculations are given in Table 1.

Table 1

Thermophysical properties of the materials

Material	λ, W/(m·K)	*c*, J/(kg·K)	ρ, kg/m^3
Fiberglass	0.38	1230	1710
Al-alloy	176	798	2700

The program created to solve this problem determines the temperature values in each calculation node throughout the entire bonding process.

The calculation algorithm consists of the following steps:

— setting the initial data (geometry, thermophysical properties, initial temperature, etc.);

— division of the area into finite elements;

— application of heat sources;

— determining the temperature of the area at the end of the heating steps;

— output of calculation results (heat flows, temperature fields) to print.

To validate the program, it was tested. Figure 2 shows the experimental and calculated dependences of temperature on time in the adhesive zone (lower curves) and in the furnace itself (upper curves). The absolute error in calculating the temperature at the bonding point does not exceed 5^{o} C, the relative error for really significant temperatures is no more than 6 %.

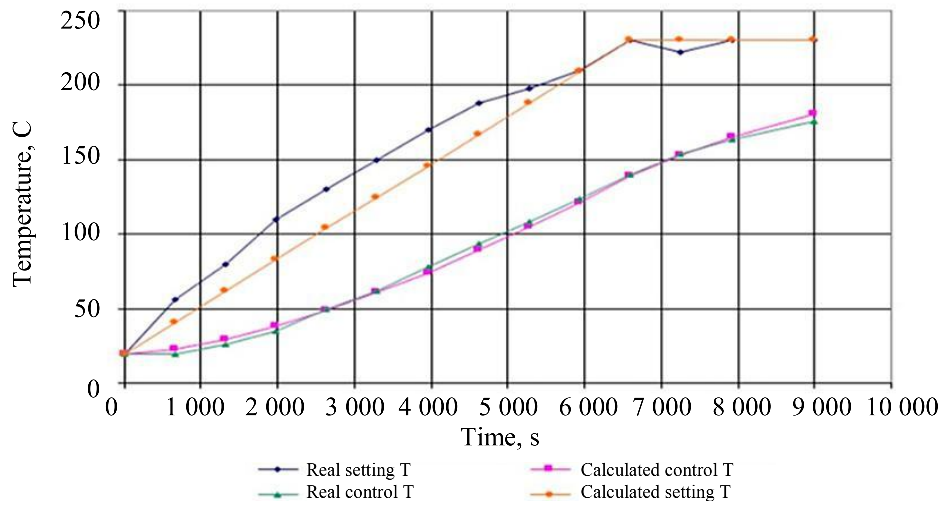
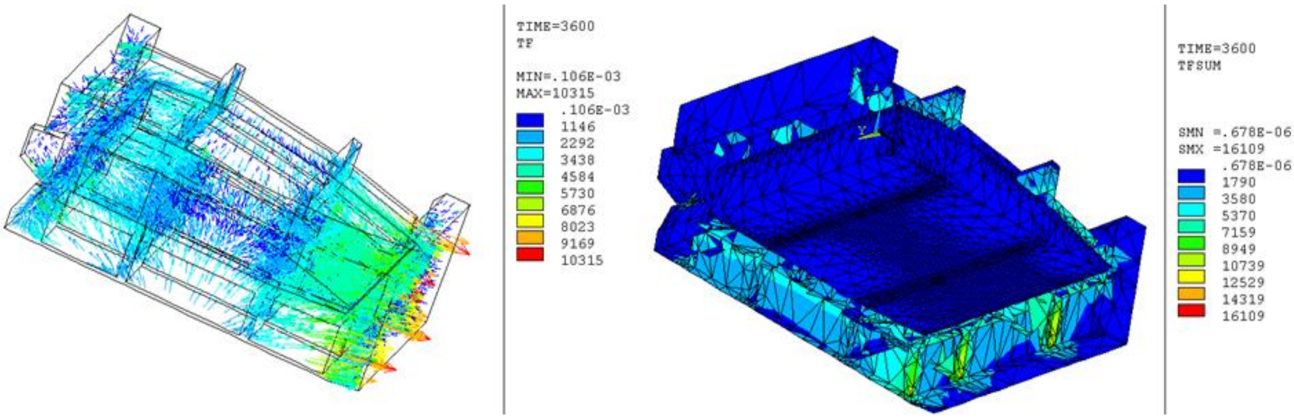


Fig. 2. Dependences of calculated and measured temperatures at the control and reference points on the time

Research Results. The processing includes a monotonous, continuous heating of the bonding device and the blade element to a certain temperature and its maintenance for a specified time. The calculation results are shown in Fig. 3−7. So, Figure 3 shows the volume distribution at a certain time of heat fluxes in vector form, and the total amount of heat in the body of the device with a section.

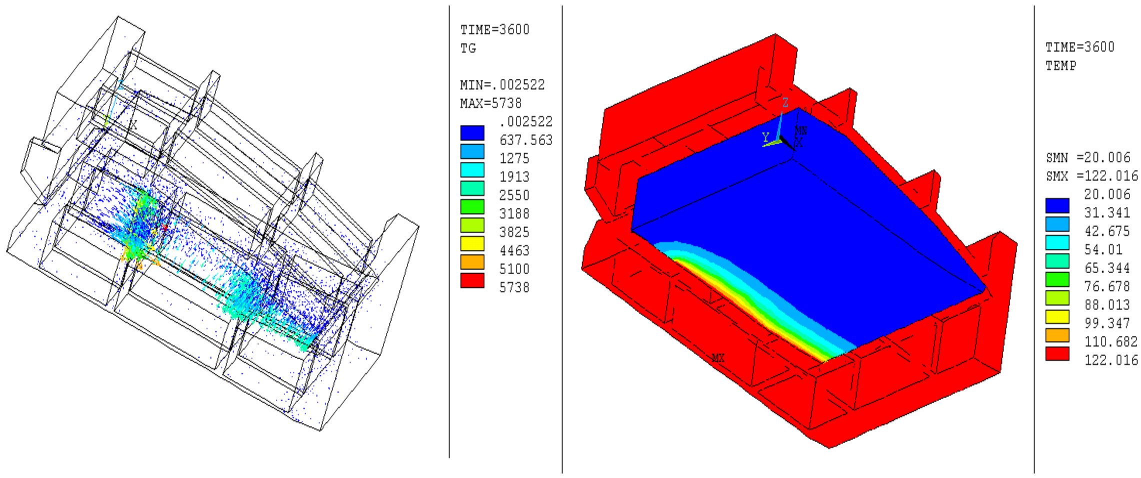


a) *b*)

Fig. 3. Heat flows (*a*) and total heating (*b*) of the device with a section

Since the heating rate of the device is relatively small, the heat flows are redistributed evenly over its volume and turn out to be approximately the same in all directions. minor exceptions apply only to the stiffeners. Convective heat flows are supplied from the sides having a large area, and are carried away by thermal conductivity into the body of the half-bodies through a narrow cross-section.

Figure 4 shows the temperature gradients in the body of the device with a section at one of the heating moments. It can be seen that the heat spreads from the outer surfaces of the device to the inner areas. Heat flows are most actively supplied in places close to the side brass and move simultaneously both from the side brass and from the upper and lower half-bodies of the device. Also, Figure 4 shows a three-dimensional view of the temperature field at the same time. Since the blade section is non-metallic, its thermal conductivity is low, and the temperature distribution is uneven.



a) *b*)

Fig. 4. Vector fields of the temperature gradient (*a*) and temperature (*b*) in the body of the device with a blade section

The temperature and time dependences at particular points of the bonding zone are shown in Fig. 5-7. It is possible to obtain maximum compliance of the schedule for setting and holding the temperature in the bonding zones with the requirements of the process through changing the values of the setting ambient temperatures and the number of their switches.

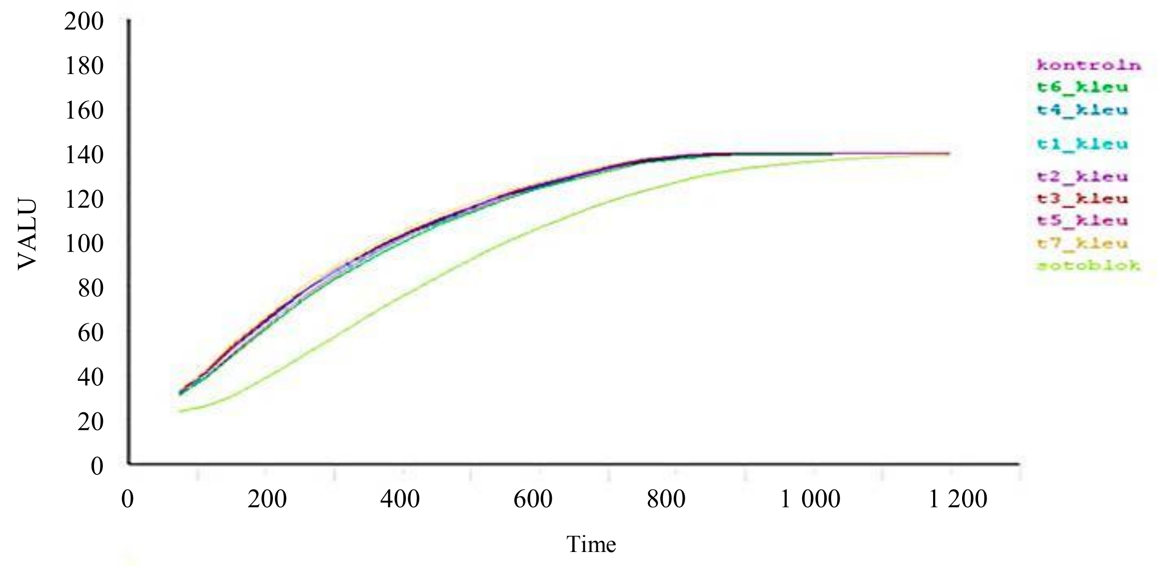


Fig. 5. Temperature versus time dependences at the characteristic points of the bonding zones and in the block (green line) for the technological mode, which includes two switches at the setting temperatures of 160 and 140 °C

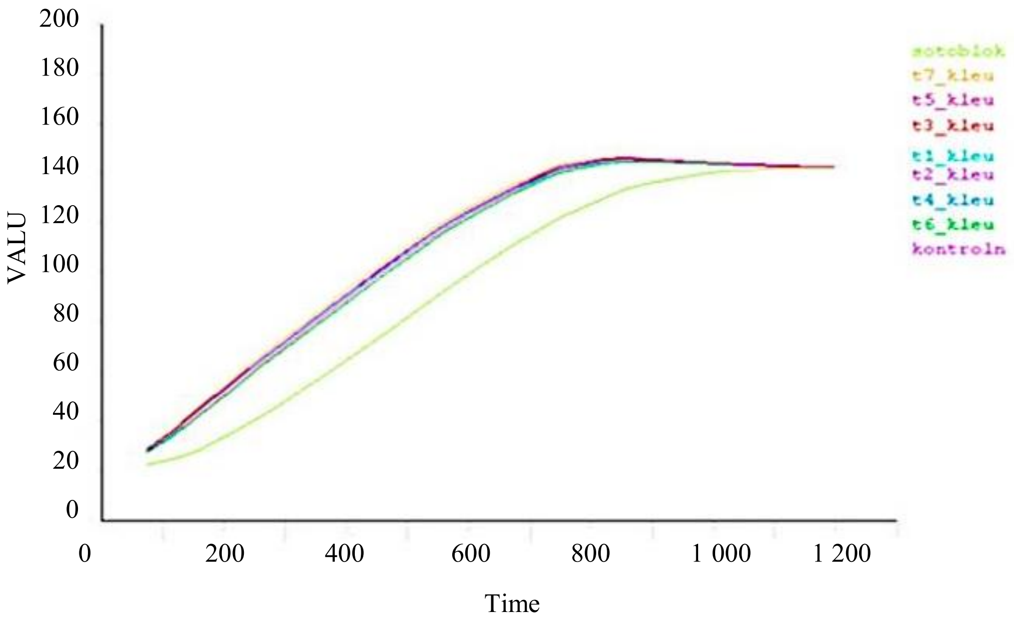


Fig. 6. Temperature versus time dependences at the characteristic points of the bonding zones and in the block (green line) for the technological mode, which includes four switches with an accuracy of setting the temperature up to 10 °C

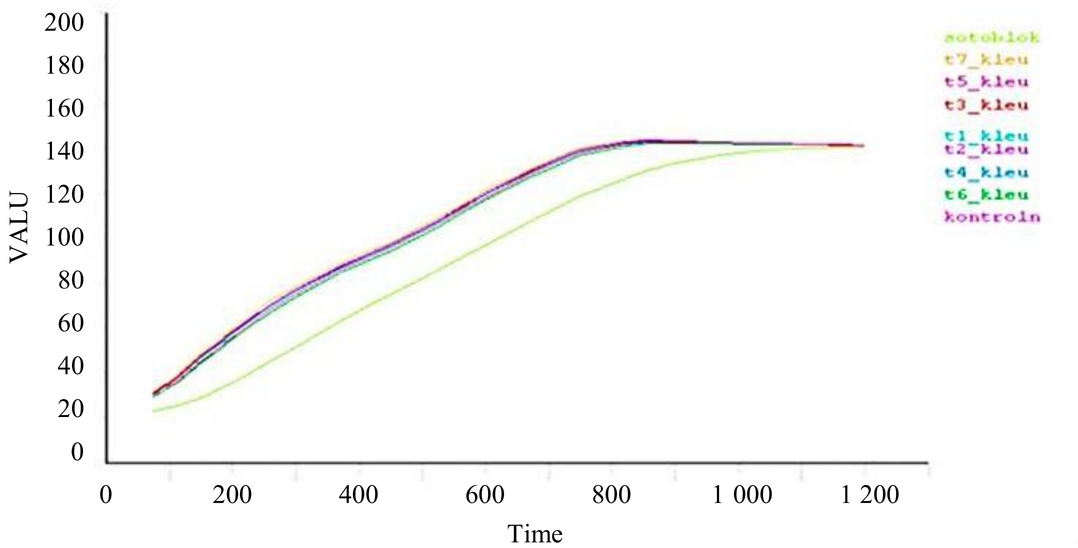


Fig. 7. Temperature versus time dependences at the characteristic points of the bonding zones and in the block (green line) for the technological mode, which includes three switches

Discussion and Conclusions. The performed thermal calculation of the elements of building structures of wind power plants at the manufacturing stage made it possible to identify the characteristic features of heating and obtain recommendations for clarifying the parameters of their bonding process.

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