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Запропонована нагрівальна система для прогнозування теплового стану, контролю та регулювання обігріву технологічно активних зон виробничих споруд. Це дає можливість забезпечити якісний рівень дотримання стандартів теплового режиму у виробничих спорудах завдяки застосування енергозберігаючих багатofункціональних систем багаторівневої системи обігріву. При цьому обігрівні прилади резисторного типу розташовані нижче рівня підлоги, при живленні їх нагрівачів від традиційних і нетрадиційних поновлювальних джерел енергії.

Проведено моделювання теплових процесів в нагрівальній системі, яке зведено до рішення задачі теплопровідності в системі плоских шарів. Складовою частиною цього рішення є визначення температури поверхні підлоги у вигляді функціонального ряду, що встановлює зв'язок між стандартами на нагрівання поверхні підлоги й потужністю енергопотоків у багаторівневій системі обігріву. Такий підхід дозволяє реалізувати структурно-функціональне керування енергопотокими й при цьому забезпечити оперативність і точність дотримання заданих стандартів теплових параметрів мікроклімату технологічно активної зони виробничих споруд різного функціонального призначення

Ключові слова: формування заданого режиму мікроклімату, електротеплові процеси, теплопровідність, грюоча підлога, трубчасті нагрівачі

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CREATING A MICROCLIMATIC THERMAL MODE BY THE MULTILEVEL SYSTEM FOR HEATING INDUSTRIAL STRUCTURES

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1. Introduction

Increasing the productivity of livestock bio-objects is an important and quite complex economic problem. Its complete or partial solution requires systematic fundamental re-

search and applied developments aimed at the construction of the theoretical foundations of automated environmentally safe and resource-saving electro-technical complexes. These complexes ensure the thermal mode of the microclimate of production premises and structures and determine optimal

geometric parameters of their multifunctional heating structures. In addition, they are based on the methods of structural and functional control of energy flows, used in hybrid power systems of special tubular electric heaters (TEH), which are a part of power heat-generating modules [1].

The improvement of the existing and the development of new effective scientifically reasonable energy-saving electric technologies and their design decisions as the means of forming the microclimate modes of industrial facilities for agricultural purposes is a relevant variant of the solution to this problem. This problem has an essential solution in terms of the use of renewable energy resources in the processes of manufacturing agricultural production.

2. Literature review and problem statement

Papers [2, 3] report the results of the search for effective means and methods of the formation of resource-saving technologies. They are based on the modern achievements of metrological support, which make it possible to combine the promptness and efficiency of using traditional and renewable energy sources, positively influencing the ecology of the environment. These solutions require functional improvement of both the control system and of design solutions of heat-generating power modules.

A characteristic indicator of the efficiency of using energy resources on the farms, specializing in the production of agricultural products on an industrial basis, can be a comparison of indicators of energy consumption per unit of production. The fact that this indicator is several times as high negatively affects the cost of a unit of the manufactured products, reducing its competitiveness in the domestic and foreign markets. At the same time, production indicators under conditions of an increase in the quality of the finished product and improvement of working conditions of the maintenance staff and animal keeping conditions are compared [4, 5].

In papers [6–8], experts emphasize that the conceptual approaches to the creation of environmentally friendly agricultural production are based on the application of energy-saving technologies, various types of power carriers, including NRES. Modern projects of buildings for different functional purposes cannot be imagined without consideration of certain natural local factors or the use of the NRES. However, we must emphasize that it is necessary to solve a series of specific scientific, technical, and economic problems.

Articles [9, 10] propose using an infrared heater. The height, at which it is mounted, depends on the air temperature in the premises and the temperature of animals. The temperature was controlled with the help of sensors. The hybrid heating system, which includes solar collectors, is proposed to save energy. But this hybrid system has a series of drawbacks, specifically, the lack of any flexible regulation of the temperature mode in the premises.

In paper [11], it is proposed to use a combined heating system based on background air supply and local heating of places for animal keeping, specifically, heating panels for a brood sow area, a heating mat and an infrared radiator for the piglets' area. The disadvantage of this system is that the microclimate system is difficult to repair, the low service life of the technological equipment, and ineffective use of the potential of non-traditional sources. In addition, the

drawbacks include ineffective use of the floor surface in the technologically active area of the premises, as well as a high level of mutual traumatism of the piglets, which are found on the rug.

At the same time, analysis of literary sources showed that in a number of well-known scientific research [12, 13] that explore electrothermal accumulator microclimate systems with heating floors, the researchers focused on the direct problems of thermal conductivity, choosing the ratio of geometric parameters and capacities, which must be connected to heating modules to ensure and maintain the set parameters of the floor surface microclimate.

But this approach complicates solving the problems of clear adherence to specified temperature modes on condition of the rational and efficient use of energy resources. This is due to the fact that it is rather difficult to introduce into the program of solving direct problems of thermal conductivity the discrete information, which reflects the given modes for the floor and air heating relative to the height of the production facilities.

Based on the conducted analysis of theoretical research, it is possible to emphasize the expediency of the development of innovative heating systems. Another approach to solving the problem other than the above is the application of a multi-level heating system and the solution of inverse problems of heat conductivity in order to determine the energy components connected to the heaters of M-tier units of the heating system. Only inverse problems of thermal conductivity make it possible to bring into the own problem statement the specified temperature modes of certain production facilities taking into consideration the changes in the environment.

3. The aim and objectives of the study

The aim of this study is to form the thermal mode of the microclimate by the multilevel heating system (HS) to ensure the set modes of the uniform floor surface heating in the technologically active areas to improve the efficiency of heating floors of production facilities.

To achieve the aim, the following tasks were set:

- to perform modeling of thermal processes in the HS;
- to model the heating system for heating the floor of specialized premises.

4. Materials and methods to study the modeling of thermal processes in a multilevel heating system

The heating system was proposed in order to predict the thermal state, control and regulate the heating of technological active areas of production facilities (PF). This system ensures a high-quality level of compliance with the thermal mode standards in the PF due to the use of energy-saving multifunctional systems of a multilevel heating system as heating resistor-type devices. Such heating devices are located below the floor level with powering their heaters from traditional and non-traditional renewable energy sources.

The heating system is a multilayer structure, in a series of layers of which the special heating elements (SHE) in the form of pipes are mounted along the system. Three active layers (tiers), each containing a certain number of heating pipes, are applied.

Modeling of thermal processes in the HS is reduced to solving the problem of thermal conductivity in the system of flat layers.

$$\frac{\partial^2 u_i}{\partial x^2} + \frac{\partial^2 u_i}{\partial y^2} = -\frac{1}{\lambda_i} p_i(x, y), \quad i = 1, \dots, N, \quad (1)$$

$$0 \leq x \leq A, \quad 0 \leq y \leq B. \quad (1)$$

$$u_i(x, y)|_{x=0} = t_0. \quad (2)$$

$$-\lambda_N \frac{\partial u_N}{\partial x} \Big|_{x=x_N} = \alpha(u_N - t_c) \Big|_{x=x_N}. \quad (3)$$

$$\frac{\partial u_i}{\partial y} \Big|_{y=0} = 0, \quad 0 \leq x \leq x_N. \quad (4)$$

$$\left(u_i + h \frac{\partial u_i}{\partial y} \right) \Big|_{y=B} = T_{soil.i}, \quad (5)$$

$$x_{i-1} \leq x \leq x_i, \quad i = 1, \dots, N. \quad (5)$$

$$\lambda_i \frac{\partial u_i}{\partial x} \Big|_{x=x_N} = \lambda_{i+1} \frac{\partial u_{i+1}}{\partial x} \Big|_{x=x_i}, \quad i = 1, \dots, N-1. \quad (6)$$

$$u_i \Big|_{x=x_N} = \left(u_{i+1} - r_i^* \cdot \lambda_{i+1} \frac{\partial u_{i+1}}{\partial x} \right) \Big|_{x=x_i}, \quad i = 1, \dots, N-1, \quad (7)$$

where i is the number of a layer (counted upwards to the floor surface);

$u_i = u_i(x, y)$, $i = 1, 2, \dots, N$ is the temperature distribution around the partial area of the i -th layer;

$p_i = p_i(x, y)$ is the assigned function of the density of heat sources, distributed around the i -th layer, W/m^3 ;

λ_i is the coefficient of thermal conductivity of the material of the i -th layer;

$x_{i-1} \leq x \leq x_i$ is the area of localization of the i -th layer along the depth of the HS;

$d_i = x_i - x_{i-1}$ is the thickness of the i -th layer;

t_c is the ambient temperature at some distance from the floor surface; T_{soil} is the soil temperature outside the HS along its thickness (height), accepted as constant within each layer;

r_i^* is the thermal contact resistance between layers;

A is the height of the HS; B is the limiting HS surfaces by the width;

α is the coefficient of thermal transfer from the floor surface of the HS into the air environment;

$h = \lambda^* / \alpha_s$ is the parameters of thermal conductivity from the HS unit into the soil, accepted as a constant magnitude along the entire depth of the HS, in this case λ^* is a certain mean value of the coefficient of thermal conductivity of the HS along its thickness, α_s is the coefficient of thermal transfer in the conditions of the 3rd kind.

Under real conditions of the heated premises, the convection heat exchange from the floor surface has a nonlinear nature, due to the air mobility (for example, through the ventilation) and other factors. However, in order to obtain analytical solutions to the formulated mathematical model, we will consider the heat transfer coefficient α to be a constant magnitude, which within the theoretical-experimental

approach can be corrected during diagnosing the thermal mode of the HS in the actual time scale.

The solution to the problem is represented in the form of functional superposition that takes into consideration all types of heat sources – air environment over the technologically active areas, deep soil and the soil outside the side wall of the HS, as well as of each individual heating element of the HS. An integral part of this solution is to determine the floor surface temperature $t_n = u(x_N, y)$ in the form of a functional series that establishes the relationship between the floor surface heating standards and the power of energy flows in a multilevel heating system. This approach makes it possible to realize the structural and functional control of energy flows and at the same time ensure high efficiency and accuracy in adherence of the floor heating standards in the technologically active areas (TAA).

The analytical solution to the boundary problem of thermal conductivity (1)–(7) was constructed using the method of finite integrated transformations (FIT). The linearity of the original problem makes it possible to apply the principle of functional superposition of two functions when constructing the solution for each layer:

$$u_i(x, y) = v_{0i}(x, y) + v_i(x, y) = [T_{soil.i} + v_{00i}(x, y)] + v_i(x, y), \quad (8)$$

where $v_{0i}(x, y)$ is the solution of a uniform equation (1) with the assigned boundary conditions (2)–(5); $v_{00i}(x, y)$ is the uniform equation (1) with mixed boundary conditions (uniform boundary conditions of the 3rd kind on the side wall and non-uniform boundary conditions of the 1st and 3rd kind on the lower and the upper surfaces of the HS, respectively); $v_i(x, y)$ is the partial solution of the non-uniform equation with uniform boundary conditions.

Function $v_{0i}(x, y)$ determines the contribution of external influences to the temperature field of the i -th layer, and $v_i(x, y)$ is the contribution to the temperature field of the i -th layer only from the set of the concentrated sources in the form of the system of heating elements under non-uniform boundary conditions on the parts of the HS surface. Functions $v_{0i}(x, y)$ and $v_i(x, y)$, in addition to the boundary conditions, must satisfy the conditions of connection on the inner inter-layer conditions (6), (7), which meet the conditions of harmonizing the temperatures and the heat flows through them, taking into consideration the final thermal contact resistance between layers.

The solution to the problems of thermal conductivity in the FIT image area for desired functions $v_{0i}(x, y)$ and $v_i(x, y)$ and $p_i(x, y) = p_i(y)$ in equation (1) takes the form:

$$\overline{v_{00i}}(x, \mu) = \frac{1}{B} \int_0^B K(y, \mu) \cdot v_{00i}(x, y) dy, \quad (9)$$

$$\overline{v_i}(x, \mu) = \frac{1}{B} \int_0^B K(y, \mu) \cdot v_i(x, y) dy,$$

where $K(y, \mu)$ is the core of the FIT, common for all layers, which is the solution to the problem for $0 \leq y \leq B$:

$$\frac{\partial^2 K}{\partial y^2} + \mu^2 K = 0, \quad \frac{\partial K}{\partial y} \Big|_{y=0} = 0, \quad (10)$$

$$\left(K + h \frac{\partial K}{\partial y} \right) \Big|_{y=B} = 0.$$

A solution to problem (10) is the function $\cos(\mu \cdot y)$, where the parameter μ is the root of equation: $\text{ctg}(\mu_q B) = h \cdot \mu_q$, $q = 1, 2, \dots$. Thus, the transformation core takes the form:

$$K(\mu_q y) = \cos(\mu_q y), \quad q = 1, 2, \dots \tag{11}$$

Solutions of the problem (1)–(7) for each layer separately are represented in the form of

$$u_i(x, y) = v_{0,i}(x, y) + v_i(x, y),$$

where

$$v_{0,i}(x, y) = T_{\text{soil},i} + \sum_{q=1}^{\infty} \frac{\cos(\mu_q y)}{N_q} v_{00,i}(x, \mu_q), \tag{12}$$

$$v_i(x, y) = \sum_{q=1}^{\infty} \frac{\cos(\mu_q y)}{N_q} \bar{v}_i(x, \mu_q),$$

$$N_q = \frac{1}{2} \left[1 + \frac{(h/B)}{1 + (\mu_q h)^2} \right]. \tag{13}$$

Determining functions $\bar{v}_i(x, \mu_q)$ and $v_{00,i}(x, \mu_q)$ into the display area comes down to the integration of ordinary differential equations for each layer ($i = 1, 2, \dots, N$):

$$\begin{aligned} \frac{\partial^2 \bar{v}_i}{\partial x^2} + \mu_q^2 \bar{v}_i &= -\frac{\cos(\mu_q B)}{hB} T_{\text{soil},i}, \\ \frac{\partial^2 v_{00,i}}{\partial x^2} + \mu_q^2 v_{00,i} &= 0. \end{aligned} \tag{14}$$

A solution to the corresponding problems for each layer in the display area was obtained as a combination of hyperbolic functions:

$$\begin{aligned} \bar{v}_i(x, \mu_q) &= \frac{W_{i,q}}{\mu_q^2} + \alpha_{i,q} \cdot \text{ch}[\mu_q(x - x_i)] + \\ &+ b_{i,q} \cdot \text{sh}[\mu_q(x - x_i)], \end{aligned} \tag{15}$$

$$\begin{aligned} v_{00,i}(x, \mu_q) &= c_{i,q} \cdot \text{ch}[\mu_q(x - x_i)] + \\ &+ d_{i,q} \cdot \text{sh}[\mu_q(x - x_i)], \end{aligned} \tag{16}$$

where

$$W_{i,q} = -\frac{1}{\lambda_i B_0} \int_0^B K(y, \mu_q) \cdot p_i(y) dy$$

is the integrated transformation of the function of distribution of sources in the band.

This approach makes it possible to assign in the layers the arbitrary distribution of sources, both continuous and discrete, it is only necessary that integral should exist.

Numerical values $2N$ of coefficients $a_{i,q}$, $b_{i,q}$ ($i = 1, 2, \dots, N$) for each value of index q are determined from the solution of the system of the linear non-uniform equation of the $2N$ order of the following form:

$$\alpha_{i,q} \cdot \text{ch}(\mu_q h_i) - b_{i,q} \cdot \text{sh}(\mu_q h_i) = -\frac{W_{1,q}}{\mu_q^2},$$

$$\alpha_{1,q} + b_{1,q} \frac{\lambda_N}{\alpha} = -\frac{W_{N,q}}{\mu_q^2},$$

$$\begin{aligned} \alpha_{1,q} &= \frac{W_{i+1,q} - W_{i,q}}{\mu_q^2} + \\ &+ \alpha_{i+1,q} [\text{ch}(\mu_q h_{i+1}) + \mu_q r_i^* \lambda_{i+1} \text{ch}(\mu_q h_{i+1})] - \\ &- b_{i+1,q} [\text{ch}(\mu_q h_{i+1}) + \mu_q r_i^* \lambda_{i+1} \text{ch}(\mu_q h_{i+1})], \\ b_{i,q} &= \frac{\lambda_{i+1}}{\lambda_i} \left[\frac{-\alpha_{i+1,q} \text{ch}(\mu_q h_{i+1}) +}{+ b_{i+1,q} \text{ch}(\mu_q h_{i+1})} \right], \quad i = 1, \dots, N-1, \end{aligned} \tag{17}$$

which are formed when conditions of connection on the inter-layer are met taking into consideration the thermal contact resistances r_i^* (6), (7) and boundary conditions on surfaces $x = 0$, $x = x_N$ (2), (3).

Numerical values $2N$ of coefficients $c_{i,q}$, $d_{i,q}$ ($i = 1, 2, \dots, N$) for each value of index q are determined from the solution of the system of linear non-uniform equations of the $2N$ order of a similar form, where instead of spectral coefficients $W_{i,q}/\mu_q^2$, the equation includes spectral coefficients of external temperatures $t_0, t_c, T_{\text{soil},i}$.

The sets of functions $\bar{v}_i(x, \mu_q)$ and $v_{00,i}(x, \mu_q)$, determined in this way, enable us with the help of transformations (12), (13) to obtain the solution of the stated problem. The number of terms in series (12) and (13) is established through the computational experiment by the result convergence (for the explored configuration, the number of terms of the corresponding series is equal to 50...80).

5. Results of studying the modeling of a floor heating system for specialized premises

The computational experiment was conducted for a multilevel heating system with the 9-layer structure, three of which are active, that is, the layers containing TH (tubular heating element).

During modeling heat transfer processes in such HS, five options of energy supply to the HS tiers, which are hereinafter called the modes of a multilevel heating system, are separated:

- mode I – energy supply to the upper (from the floor surface) tier;
- mode II – energy supply simultaneously to the upper and to the middle tiers;
- mode III – energy supply only to the middle tier;
- mode IV – energy supply simultaneously to the middle and lower tiers;
- mode V – energy supply only to the lower tier.

The transverse cross-section of a multi-level heating system is a rectangular multi-layer area. By the HS height, we orient axis OX, the beginning of which $x=0$ is in the middle of the plane of the bottom part of the HS, which is in contact with deep soil. The “height” of the HS is equal to A, plane $x=A$ coincides with the floor surface, washed by the air of the premises. Axis OY is oriented across the HS section so that plane $y=0$ is its symmetry plane. Vertical surfaces $y=\pm B$ limit the HS by width, forming the HS heated surface band $-B \leq y \leq B$ on the surface, contact the soil array through the side walls. The OZ axis is oriented along the band. Assuming the length of the actual HS significantly exceeds its width $2B$, we neglect the heat transfer processes in the direction of axis OZ.

Fig. 1 schematically shows the location of the HS layers and the options of energy distribution by active tiers. The operating modes of the HS are implemented by the automatic control system, which uses the information from the sensors, determines the amount of electricity supplied to the electric heaters of a certain tier of a multilevel heating system. The structure of the studied HS meets a number of technical requirements that ensure its application for heating specialized premises. The temperature and power operation modes of one particular structural implementation of the heating system, which contains three active (heating) layers-tiers, are explored.

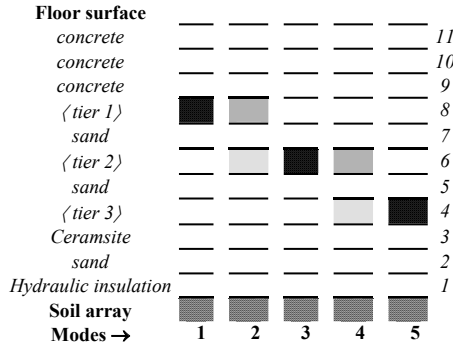


Fig. 1. Schematic image of the multilayer HS and distribution of energy supplied to the HS by layers of location of heating elements (tiers), which corresponds to different HS operation modes; energy re-distribution among the HS layers are shown by the layers painted in half-tones; the content of the layers is shown on the left, the numbers of the HS layers, starting from the trench bottom, is shown on the right

The accepted characteristics of the layers one by one from bottom to top correspond to the heating system. The lower layer is the hydraulic insulation (ruberoïd) of the thickness of $d_1 = 0.01$ m, $\lambda = 0.017$ W/m·K. The sand layer is next $d_2 = 0.04$ m, $\lambda_2 = 0.58$ W/m·K, the heat insulation layer is foam concrete $d_3 = 0.20$ m, $\lambda_3 = 0.41$ W/m·K. The active layer (tier No. 3) is the layer of TEH, filled with sand – $d_4 = 0.15$ m, $\lambda_4 = \lambda_4^{eff}$, the sand layer – $d_5 = 0.15$ m, $\lambda_5 = 0.58$ W/m·K. The active layer (tier No. 2) is the layer of TEH, filled with sand – $d_6 = 0.15$ m, $\lambda_6 = \lambda_6^{eff}$, sand layer – $d_7 = 0.15$ m. The active layer (tier No. 1) is the layer of TEN, filled with sand – $d_8 = 0.15$ m, $\lambda_8 = \lambda_8^{eff}$, the layer of monolithic concrete – $d_9 = 0.30$ m, $\lambda_9 = 0.87$ W/m·K. The effective coefficient of thermal conductivity of the active layers λ_i^{eff} depends on the number of TEH. For the pipes of the square $d \times d$ crossing, the side of which d coincides with the height of the layer:

$$\lambda_i^{eff} = \lambda_{fill} \left[1 - \left(\frac{d \cdot M}{2M} \right) \cdot \left(1 - \frac{\lambda_{coz}}{\lambda_{fill}} \right) \right],$$

where λ_{fill} is the coefficient of thermal conductivity of the filled layer (sand), M is the number of the HS in the active layer. The assigned conditions of non-ideal thermal contact, in which contact thermal resistances were accepted equal to $r_i^* = 0.15$ m²·K/W, were set on the boundaries of the layers that contain heating elements. The number of TEH in each of the three active tiers were selected by performing the structural and functional control of the electric drive to heating elements of the HS with the view to ensuring the set standards for the floor surface heating.

The following results were obtained: upper-tier No. 1 – $M_1=9$, middle tier – $M_2=7$, lower tier No. 3 – $M_3=5$. The TEHs are located in the layers symmetrically in relation to plane $y=0$ and evenly (with the same pitch), the distance of extreme pipes from the side walls is the same and equals to $l_s = 0.2$ m. Taking into account the assigned odd number M_i of the heating elements, located in the electric insulation pipes by cross-section $d \times d$, distribution of power density of sources in the active layers is assigned in the form:

$$p_i(y) = \sum_{j=-(M_i-1)/2}^{(M_i-1)/2} p_{i,j} f(y - y_{i,j}^c), \quad (18)$$

where $p_{i,j}$ is the density of power of distributed sources in a pipe, W/m³; $f(y - y_{i,j}^c)$ is the function of distribution of thermal power in the area of HS localization with the coordinate center $y_{i,j}^c$, the acceptable distribution of thermal power of the trapezoidal form.

Owing to the conducted computational experiment, it was proved that the structure of the considered multilevel heating system will ensure the uniformity of floor heating with the accuracy of not less than 0.5 C.

The uniform heating of the floor surface can be ensured by the distribution of the level of heat generation power in the special tubular heating elements in a two-dimensional system specific for each mode (I–V). The contribution of each heating element in the resultant temperature field on the floor surface of the TAA depends on its location in the HS array, heat exchange conditions on the boundary surfaces of the heat generating modules, as well as the power supplied to the heaters.

Fig. 2–4 show the relevant expected energograms (linear powers of the TEH) for heating levels of $t_n=18$ °C and $t_n=38$ °C for heating modes I (Fig. 2), III (Fig. 3), V (Fig. 4), at different values of thermal losses through the side wall of the multilevel heating system.

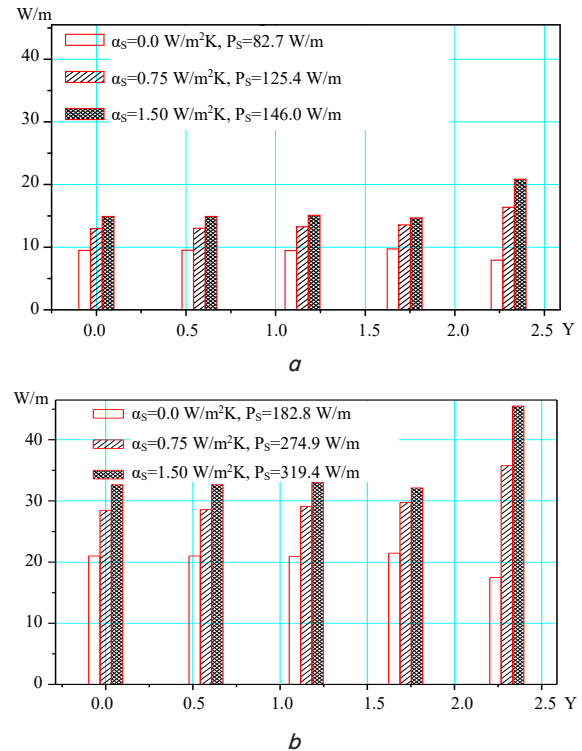


Fig. 2. Energograms of HS for mode I: a – tier 1, $t_n=18$ °C; b – tier 1, $t_n=38$ °C

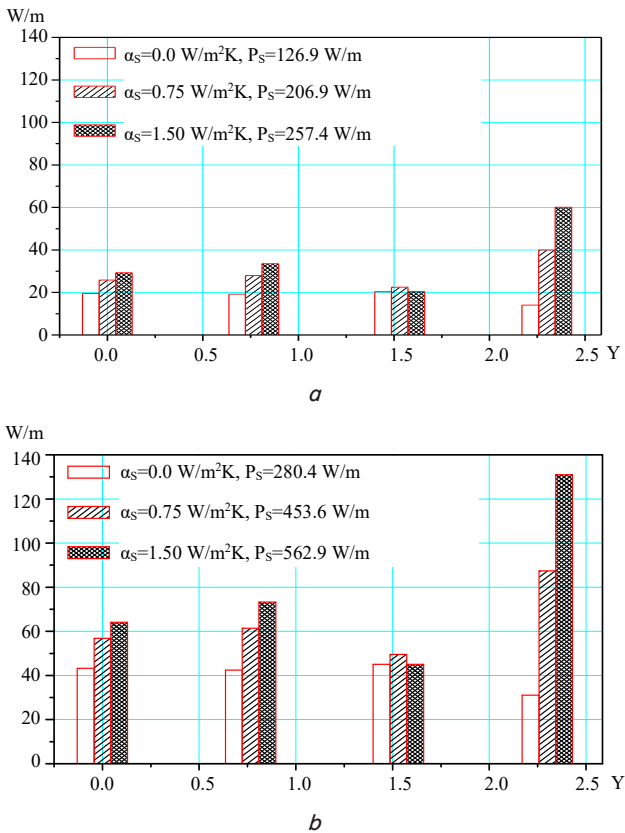


Fig. 3. Energograms of the HS for mode III: a – tier 2, $t_n=18\text{ }^\circ\text{C}$; b – tier 2, $t_n=38\text{ }^\circ\text{C}$

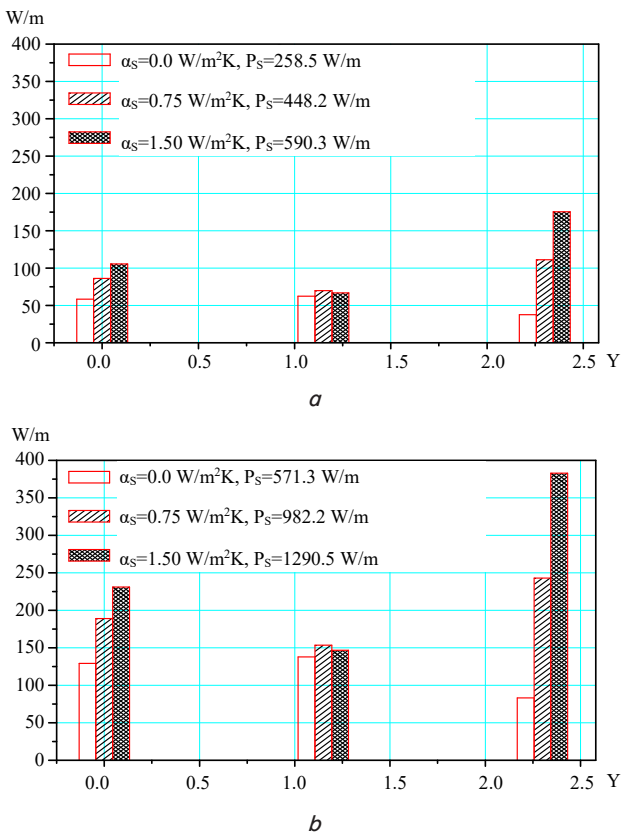


Fig. 4. Energograms of HS for mode V: a – tier 3, $t_n=18\text{ }^\circ\text{C}$; b – tier 3, $t_n=38\text{ }^\circ\text{C}$

6. Discussion of results of studying the multilevel heating system

The essence of the operation of the multilevel HS is the ability to perform the main function – to maintain the specified thermal mode of the TAA at supplying the power to any tier (TEH unit) separately, or by powering any combination of the TEH units. The degree of uniformity of temperature distribution on the width of the heated floor (the degree of deviation from the specified standard) depends on the number of heating elements in the active layer and the size of the HS.

Modeling of the multilevel heating system involves optimizing the distribution of power components to ensure the assigned temperature mode (standard floor heating surface) on the floor surface. Visual information about the results of this optimization is shown in a series of complex figures. Fig. 2–4 show the energograms (linear powers of the TEH, localized on the band of a multilevel heating system) for heating levels $t_n=18\text{ }^\circ\text{C}$ and $t_n=38\text{ }^\circ\text{C}$ and for heating modes I, III, V at different values of heat losses through the side wall of the heating system. Ideal thermal insulation $\alpha_s=0\text{ W/m}^2\cdot\text{K}$, $\alpha_s=0.75\text{ W/m}^2\cdot\text{K}$ and $\alpha_s=1.5\text{ W/m}^2\cdot\text{K}$. Power is supplied, accordingly, to tiers 1, 2 or 3, in this case, energy flows come to the TEH units, located by the floor width in layers 8, 6 or 4 of the heating system. At the same time, in accordance with the mode, 9, 7 or 5 of the TEH are connected. The figures show only the right half of the heating system ($0 < y < 2.5\text{ m}$), where the relative levels of linear power of the TEH are shown by columns in the relevant points of axis OY.

Based on solving the inverse problems of heat conductivity for a multilevel heating system, it is possible to develop the procedure of the structural-functional control of energy flows in the heating elements of the TEH based on the pre-calculated database. It allows ensuring the standards of the TAA heating with a precision of up to $1\text{ }^\circ\text{C}$ using the information from the limited number of thermal sensors.

The optimization of energy flows distribution allows a noticeable decrease on average by 13.8 W/m in power consumption for heating a multilevel heating system in comparison with the case of uniform heating.

The multilevel heating system makes it possible to predict the desired redistribution of energy flows between the TEH in the tiers and between the sides of the TEH in the tiers to ensure a predetermined level of floor surface heating under certain conditions of heat exchange of the heating system with the environment. The totality of such calculations for discrete datasets (temperature values, characteristic of heat exchange indicators, levels of existing energy resource from traditional energy sources and the NRES) can be brought to a typical system – a database for the control and measurement system (CMS) when it comes to structural and functional control. This will make it possible to compare in real time the results of the calculation prediction with the information about the temperature mode of the TAA coming from the CMS sensors, and, in the case of inconsistency caused by abrupt changes in external and internal factors, to correct purposefully energy flows, maintaining a predetermined level of floor surface heating.

To analyze the temperature modes of the floor of livestock premises, their optimization by differentiated energy supply to the heating elements of a multilevel heating system, we developed the methodology of modeling the

process of heat transfer of the N-layer heating system and a corresponding computer model. The analytical solutions of inverse problems of heat conductivity for the heating system unlimited by width were implemented in computer modeling, which enables determining specific heating power (for layers) that provide the predetermined level of floor surface heating. These values of power are used to determine the power of the energy components corresponding to separate heating elements in the multilevel heating system that is limited by width, taking into consideration the heat exchange through the side walls. In addition, the computer modeling of the multilevel heating system implies the optimization of the distribution of power components among the heating elements so as to provide the assigned temperature mode (standard of floor surface heating) on the floor surface. This can be done in a limited number of points, which does not exceed the number of heating elements in the active layer. At the same time, the uniformity of temperature distribution by the width of the heated floor (degree of deviation from the specified standard) essentially depends on the number of HP in the active layer and the dimensions of the heating system.

7. Conclusions

1. Modeling thermal processes in the HS is reduced to solving the problem of thermal conductivity in a system of flat layers. It was established that a part of this solution is to determine the floor surface temperature $t_n = u(x_N, y)$ in the form of a functional series, which made it possible to assess the relations between the standards for floor surface heating and the power of energy flows in a multilevel heating system. This made it possible to implement the structural and functional control of energy flows and at the same time ensure high efficiency and accuracy in adherence to the standards of floor heating in technologically active areas, taking into consideration a change in ambient temperature.

2. The modeled heating system for heating the floor of specialized premises makes it possible to ensure the maximum energy-saving mode, the mode of thermal stabilization of the floor surface, the heat accumulation mode, and the alignment of schedules of electrical network loading.

Owing to the conducted computational experiment, it was proved that the structure of the studied multilevel heating system will ensure uniformity of floor surface heating with the precision of not less than 0.5 C.

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