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Mathematical modeling of the temperature regime in industrial premises

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Abstract. Comfortable temperature conditions in any room are provided by heating systems, thermal insulation properties of enclosing structures, external environmental conditions. Practical experience, literature analysis show that the existing temperature control systems in industrial premises have disadvantages. Eliminating is possible by using a multi-circuit functional control structure, allowing to reduce the inertia of the temperature control system by taking into account the outdoor temperature, the influence of natural light on the temperature inside the production facility. For its operation, a practically oriented mathematical model is needed, which allows taking into account the influence of a large number of external factors on the temperature regime with minimal delay. A mathematical model has been developed for use as a program in industrial electronics devices for predicting, correcting the temperature field, regulating the temperature regime in the production areas of a room at any point. Based on experimental data, the analysis of the results of the adequacy of the mathematical model shows that the temperature values obtained by the mathematical model of forecasting, correction of the temperature regime fall within the confidence interval and are within the standard deviation. The mechanism of technical implementation is proposed and the prospects of its use are shown.

1 Introduction

Ensuring a comfortable temperature regime in industrial premises allows you to increase labor productivity. A lot of research is devoted to the search for optimal temperature values under certain working conditions. The results of these studies form the basis of regulatory and technical documentation in accordance with which the employer is obliged to ensure the temperature regime in the production premises [1-8]. Comfortable temperature conditions in any room are provided by the heating system, thermal insulation properties of enclosing structures, as well as external environmental conditions (Figure 1).

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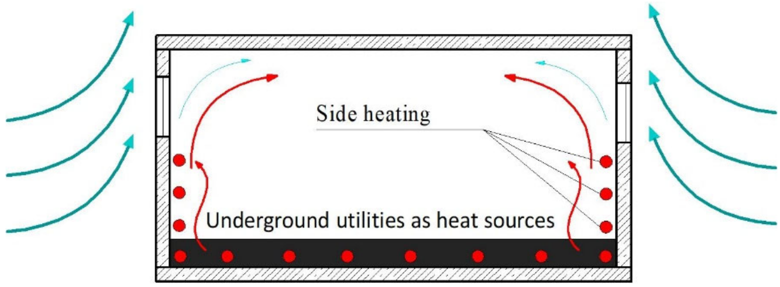

Fig. 1. Conditions ensuring the temperature regime: — – warm air flows in the room; — – cold air flows of the environment.

Temperature control in production facilities is carried out using automatic control systems. These systems include: a heat source, a heating network that provides the supply of coolant from the source to the structure, a frequency-controlled electric drive of circulation pumps and a control device. Programmable logic controllers are used as a control device. These industrial electronics devices, based on the data of the ambient temperature t_{ext} the temperature in the forward and return pipelines, regulate the temperature inside the room t_{int}. [1]

Practical experience and literature analysis show that the existing temperature control systems in industrial premises have the following disadvantages. Firstly, the single-circuit temperature control structure is inertial. This is due to the fact that production facilities have a large working volume and with a sharp change in external environmental conditions: a sharp decrease in outdoor air temperature, high values of natural solar irradiation, the real temperature values in production facilities do not correspond to the required for a long time. This has a negative impact on the safety of working conditions. Secondly, the temperature control of the coolant is carried out by changing the cross section of the supply pipeline. [2]

To date, many unified systems for automatic control of microclimate parameters have been developed, the main of which are temperature, illumination and humidity. Of course, there is a mutual relationship between these microclimate parameters, both inside the production premises and in the external environment, which must be taken into account when calculating. Unfortunately, in the methodological recommendations for the calculation of microclimate parameters, this factor is not paid attention to.

2 Mathematics and methods

It is possible to eliminate the shortcomings noted above by using a multi-circuit functional control structure (Figure 2). This structure makes it possible to reduce the inertia of the temperature control system by taking into account the outdoor temperature, the influence of natural light on the temperature inside the production facility. The main element of such systems is the control device. For its operation, a practically oriented mathematical model is needed, which allows taking into account the influence of a large number of external factors on the temperature regime with minimal delay. Also, this model should be a software adaptive product implemented by modern programming languages in industrial electronics devices.

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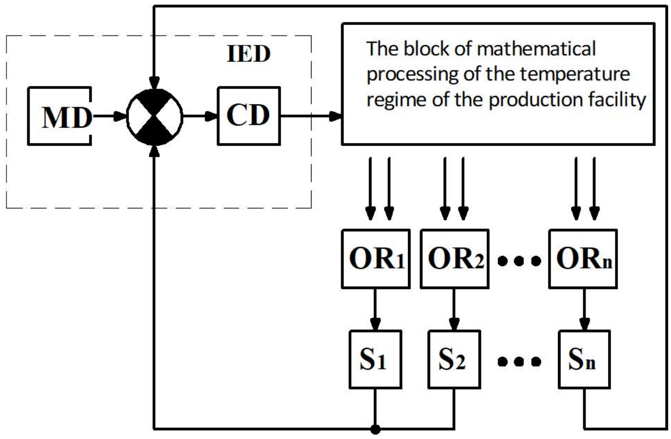

Fig. 2. Multi-circuit functional structure of temperature control: MD - the master device; CD - control device; IED - industrial electronics device; OR - objects of regulation (microclimate parameters); S - sensors that take into account the parameters of the microclimate.

It is impossible to reflect reality with a mathematical model taking into account all the factors affecting the temperature in the production room. Based on this fact, we will make the following assumptions: the enclosing structures are made of a material having one thermal insulation ability, their surfaces are assumed to be absolutely flat

In Euclidean space, the temperature change can be represented as the product of mutually perpendicular gradients of temperature vectors (1):

$$\acute{\mathrm{T}} = \acute{\mathrm{T}}_{\boldsymbol{x}}\acute{\mathrm{T}}_{\boldsymbol{y}}\acute{\mathrm{T}}_{\boldsymbol{z}}. \quad (1)$$

The analysis of scientific works devoted to safety and labor productivity [1, 2] shows that up to 70% of the cost of any goods and services produced in temperate climatic conditions is the cost of heating production facilities. Thus, industrial buildings in these territories are in cooling conditions.

All production facilities are in cooling conditions, because the ambient temperature, $\boldsymbol{t_{ext}}$, °C,, will be lower than the temperature inside the building, $\boldsymbol{t_{int}}$, °C, the temperature field along any spatial axis can be described as follows, for example, along the x axis by the expression (2):

$$\acute{T}_x = \left[\frac{t_{\boldsymbol{int}}-t(x,\tau)}{t_{\boldsymbol{int}}-t_{\boldsymbol{ext}}}\right] = f\left(\acute{X}, Bi_x, F_{0_x}\right), \quad (2)$$

where $\boldsymbol{t_{int}}$ – the air temperature in production facilities measured by a thermocouple at the initial time, °C; t_{ext} – ambient temperature; $t(x,\tau)$ – the temperature at the spatial coordinate x and at the time τ.

At the same time, the temperature field is a function depending on dimensionless quantities: the spatial coordinate $\acute{X}$, the Bio number and the Fourier number. A dimensionless spatial coordinate $\acute{X}$ is defined by the expression (3):

$$\acute{X} = \frac{x}{L}, \quad (3)$$

where x – the spatial coordinate, i.e. the distance from the origin to the point at which it is necessary to determine the temperature, m; L – linear size of the production facility, i.e. width, m. The Bio number characterizes the relationship between body temperature and heat transfer conditions on its surface. We define by the expression (4):

$$Bi = \frac{\alpha \cdot L}{\lambda_w}, \quad (4)$$

where α – the coefficient of convective return of air, is equal to 500 W/m^2·°C; λ_w – the coefficient of thermal conductivity, for air is equal to 0,027 W/m·°C. the Fourier number, which characterizes the relationship between the physical properties and dimensions of the body and the rate of change of temperature fields in it, is calculated by the formula (5):

$$F_0 = \frac{a \cdot \tau}{L^2}, \tag{5}$$

where a – the coefficient of isobaric thermal conductivity, which is for air $18{,}88 \cdot 10^6$, m^2/s.

If, in the x-axis section, the construction of protected soil is represented as part of an unlimited flat plate under cooling conditions, then the one-dimensional temperature field, using the differential equation of non-stationary thermal conductivity, can be described as follows, according to equality (6):

$$\frac{\partial t_{int}}{\partial \tau} = a_v \cdot \frac{\partial^2 t_{int}}{\partial x^2} + \frac{Q_v}{\rho \cdot c_v}, \tag{6}$$

where a_v – coefficient of thermal conductivity, m^2/s; x – coordinate, м; Q_V – volumetric density of heat sources, W/m^3; c – heat capacity, J/(kg·°C); ρ – density, kg/m^3. The second term of the right part of the expression (6) for air is insignificant, therefore the equation of non-stationary thermal conductivity for the construction of protected soil has the form of equality (7):

$$\frac{\partial t_{int}}{\partial \tau} = a_v \cdot \frac{\partial^2 t_{int}}{\partial x^2}. \tag{7}$$

The temperature and wind speed of the environment over time affect the temperature field in the production premises. Therefore, to describe the temperature field in them and to solve equation (7), it is possible to use non-stationary heat transfer with boundary conditions of the third kind. In the general solution for this case, it is advisable to use the method of separating variables [1]. It is important that cooling has a significant effect on the temperature field and, consequently, the temperature field under the greenhouse ridge is limited to a truncated half-cylinder.

In this case, the temperature $t_в$ is represented as the product of two functions:

$$t_{int} = L^* \cdot T^*, \tag{8}$$

where $L^*=f(x)$ depends only on x, $T^*=f(\tau)$ depends only on τ.

Consequently:

$$\frac{\partial t_{int}}{\partial \tau} = L^* \cdot \frac{dT^*}{d\tau}; \qquad \frac{\partial t_{int}}{\partial x} = T^* \cdot \frac{dL^*}{dx}; \qquad \frac{\partial^2 t_{int}}{\partial x^2} = T^* \cdot \frac{d^2 L^*}{dx^2}.$$

Substituting these values into expression (7) we get:

$$\frac{1}{a \cdot T^*} \cdot \frac{dT^*}{d\tau} = \frac{1}{L^*} \cdot \frac{d^2 L^*}{dx^2}. \tag{9}$$

The left side of equation (9) is a function of time τ, and the right function by spatial coordinate x. These functions can be equal when they are a constant. In the other case, there can be no equality:

$$\frac{1}{a \cdot T^*} \cdot \frac{dT^*}{d\tau} \neq \frac{1}{L^*} \cdot \frac{d^2 L^*}{dx^2}.$$

Denote this function as $-\beta^2$, we get:

$$\frac{1}{a \cdot T^*} \cdot \frac{dT^*}{d\tau} = -\beta^2; \tag{10}$$

$$\frac{1}{L^*} \cdot \frac{d^2 L^*}{dx^2} = -\beta^2. \tag{11}$$

The solution of the equation will take the form:

$$T^* = A \cdot e^{-a \cdot \beta^2 \cdot \tau}. \tag{12}$$

A negative value of β^2 corresponds to the cooling conditions of the protected ground structure during the time.

When applied to partial differential equations, the method of separating variables leads to finding a solution in the form of a series or Fourier integral, which allows solving the heat equation in the form of trigonometric series. If, according to the spatial coordinate x, the structure is bounded by an unlimited flat plate with temperature $t_в$ and placed at time $\tau=0$ in a medium with temperature t_{oc}, the solution of equation (7) has the form:

$$L^* = B \cdot cos\beta_x + D \cdot sin\beta_x. \quad (13)$$

On the enclosing structures of industrial structures, heat exchange occurs according to Newton's law. Since the problem is symmetric, we take the width of the structure *L* and place the *z* axis in its center.

Given the symmetry of *cos* as a function, expression (13) will take the form $L^*=B\cdot cos\beta_x$, and the air temperature in the protected ground structure $t_{int}=L^*\cdot T^*$:

$$t_{int} = C \cdot e^{-a\cdot\beta^2\cdot\tau} \cdot cos(\beta_x). \quad (14)$$

Given the expressions (10), (11) and (12) we get:

$$t_{int} = C \cdot e^{-(L\cdot\beta)^2\cdot F_0} \cdot cos(L \cdot \beta \cdot \overline{x}), \quad (15)$$

where the value $L\cdot\beta=\mu^*$ can be found from the characteristic equation:

$$ctg\mu^* = \frac{\mu^*}{Bi}. \quad (16)$$

Equation (16) is solved graphically, and has countless roots μ_i^* nd is given in several publications devoted to theoretical heat engineering and mathematics [3-9].

The sum of particular solutions gives the total in the following form:

$$\acute{T}_x = \left[\frac{t_{int}-t(x,\tau)}{t_{int}-t_{ext}}\right] = \sum_{i=1}^{\infty} C_i \cdot cos(\mu_i^* \cdot \overline{x}) \cdot e^{-\mu_i^{*2}\cdot F_0}. \quad (17)$$

The values of the constant C_i are determined from the initial conditions ($\tau=0$; $t_{int}=t_0$):

$$C_i = (t_{ext} - t_0) \cdot \frac{2\cdot sin\mu_i^*}{\mu_i^*+sin\mu_i^*\cdot cos\mu_i^*}. \quad (18)$$

Substituting the values of the constant C_i into equation (18), we obtain the final expression for the temperature field in the spatial coordinate *x:*

$$\acute{T}_x = \left[\frac{t_{int}-t(x,\tau)}{t_{int}-t_{ext}}\right] = \sum_{i=1}^{\infty} \frac{2\cdot sin\mu_i^*\cdot cos(\mu_i^*\cdot\overline{x})}{\mu_i^*+sin\mu_i^*\cdot cos\mu_i^*} \cdot e^{-\mu_i^{*2}\cdot F_0}. \quad (19)$$

A production facility in cross-section according to the spatial coordinate *x* can be considered an unlimited plate with boundary conditions of the third kind.

To determine the limits of technological temperature change in width *x*, it is necessary to take into account that the series is convergent. Therefore, at$F_0 \geq 0{,}3$we can limited to only the first member of the series. We get:

$$\acute{T}_x = \left[\frac{t_{int}-t(x,\tau)}{t_{int}-t_{ext}}\right] = \frac{2\cdot sin\mu_i^*\cdot cos(\mu_i^*\cdot\overline{x})}{\mu_i^*+sin\mu_i^*\cdot cos\mu_i^*} \cdot e^{-\mu_i^{*2}\cdot F_0}. \quad (20)$$

At each point of the production room along the width *x,* its temperature depends on the Bio number and the Fourier number, expressions (4) and (5).

The internal thermal resistance of production facilities in comparison with the external thermal resistance of the environment is high, i.e. $Bi \to \infty$, therefore, the boundary conditions of the third kind pass into the boundary conditions of the first kind. Under these conditions ($Bi \to \infty$ and $F_0 \geq 0{,}3$) from equation (20) we obtain ($\mu_1^* = \frac{\pi}{2}$; $cos\mu_1^* = 0$; $sin\mu_1^* = 1$):

$$\acute{T}_x = \left[\frac{t_{int}-t(x,\tau)}{t_{int}-t_{ext}}\right] = \frac{4}{\pi} \cdot cos\left(\frac{\pi}{2} \cdot \acute{x}\right) \cdot e^{\frac{-\pi^2}{4}F_0}. \quad (21)$$

Such mathematical operations make it possible to determine the temperature field in production facilities by the y coordinate can be represented as follows:

$$\acute{T}_y = \left[\frac{t_{int}-t(y,\tau)}{t_{int}-t_{ext}}\right] = \frac{4}{\pi} \cdot cos\left(\frac{\pi}{2} \cdot \acute{y}\right) \cdot e^{\frac{-\pi^2}{4}F_0}. \quad (22)$$

Along the *z* axis, the temperature field can be described similarly to the heating processes in half of the cylinder, i.e. by the analytical expression (23)

$$\acute{T}_z = \left[\frac{t_{int}-t(z,\tau)}{t_{int}-t_{ext}}\right] = 1 - \frac{2\cdot a\cdot\alpha\cdot\tau}{\lambda_w\cdot r} \cdot e^{\frac{-1}{4\cdot F_0}}, \quad (23)$$

where *r* - the radius of the cylinder equal to the height *z* from the floor surface to the point where it is necessary to determine the temperature, m. The calculation of the temperature field by the spatial coordinate *z,* i.e. by height, it is necessary to take into account the geometric features of the production facility.

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It is advisable to introduce into formula (23) a coefficient that takes into account how many times the height of the production facility is less than its length, *d,* m:

$$k_r = \frac{2\cdot z}{d}. \quad (24)$$

Given the expressions (1), (21), (22), (23) and (24), we get:

$$\frac{t_{int}-t}{t_{int}-t_{ext}} = \left[\frac{4}{\pi}\cdot cos\left(\frac{\pi}{2}\cdot \acute{X}\right)\cdot e^{\frac{-\pi^2}{4}\cdot F_0}\right]\cdot\left[\frac{4}{\pi}\cdot cos\left(\frac{\pi}{2}\cdot \acute{Y}\right)\cdot e^{\frac{-\pi^2}{4}\cdot F_0}\right]\cdot\left[\frac{2\cdot z}{d}-\frac{4\cdot z\cdot a\cdot \alpha\cdot\tau}{d\cdot\lambda_w\cdot z}\cdot e^{\frac{-1}{4\cdot F_0}}\right],$$

where $\acute{Y} = y/d$ – spatial coordinate; t – this is the temperature in the spatial coordinate system x,y,z, ytaking into account the overall dimensions of the production facility at the time τ. We express t, and we get the final expression for determining the temperature at any point of the working volume of the structure:

$$t = t_{int} - \left[\frac{16}{\pi^2}\cdot cos\left(\frac{\pi}{2}\cdot\frac{x}{L}\right)\cdot cos\left(\frac{\pi}{2}\cdot\frac{y}{d}\right)\cdot e^{\frac{-\pi^2}{2}\cdot F_0}\right]\cdot\left[\frac{2\cdot z}{d}-\frac{4\cdot a\cdot\alpha\cdot\tau}{d\cdot\lambda_w}\cdot e^{\frac{-1}{4\cdot F_0}}\right]\cdot[t_{int}-t_{ext}]. \quad (25)$$

Expression (25) can be used in practice as a program in industrial electronics devices for predicting and correcting the temperature field and regulating the temperature regime in the production areas of a room at any point.

Results and discussions

The construction of enclosing structures of industrial, residential and agricultural structures is necessary to reduce the influence of such external climate parameters as temperature, humidity and natural solar radiation. To analyze the average outdoor temperature values in large industrial centers of Russia, we used archival data and conducted our own experiments [10-18]. The analysis of the average temperature data, as well as data on the number of sunny days and natural solar radiation in the middle latitude of Russia allows us to draw the following conclusion. The application of the mathematical model proposed by expression (25) as a program in industrial electronics devices for regulating the temperature regime in production facilities will be very relevant for creating safe working conditions.

In addition, we have experimentally confirmed the mutual influence of climate parameters. For example, the analysis of temperature indicators in several production facilities showed its dependence on natural solar illumination. The results are shown in Figure 3.

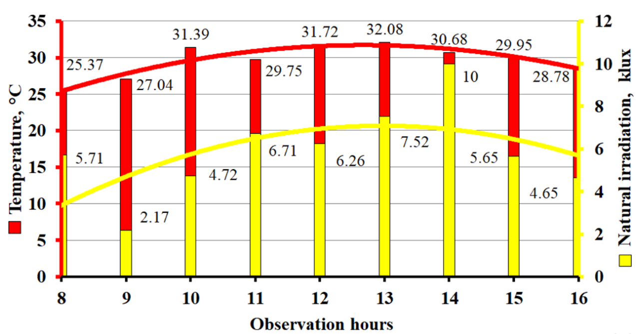

Fig. 3. Average values of temperature and natural solar illumination.

The analysis of Figure 3, which shows the average temperature values at the control points of industrial premises in the summer without the use of an air conditioning system, shows that on a bright sunny day, the temperature in industrial premises increases regardless of the operation of heating sources due to the greenhouse effect. The influence of the outdoor air temperature and the temperature regime of the production room has been well studied and is presented in the temperature charts of boiler rooms. Our experiments also confirmed the effect of temperature on humidity. To measure temperature, humidity, and the level of natural illumination, we used a universal device of the brand "TKA-PKM" 41 series. As a control device, we used a digital anemometer-thermometer of the ISP-MG4 brand. All instruments at the time of the experimental data were checked.

We used the obtained experimental values of microclimate parameters to prove the adequacy of the mathematical model of forecasting and correction of temperature regulation in industrial premises. Using the least squares method, the determination of the standard error of the experiment and the standard deviation of the experimental values of the microclimate parameters in the working volume of production facilities, we obtained the result shown in Figure 4.

The analysis of the results of the adequacy of the mathematical model (Figure 4) shows that the temperature values obtained by the mathematical model of forecasting and correction of the temperature regime fall within the confidence interval and are within the standard deviation. Therefore, our proposed model is adequate and can be used to calculate temperature values at any point of the working volume of industrial buildings and structures.

The existing systems for creating a temperature regime in industrial premises are quite simple. Their principle of operation is to maintain the required value of the temperature of the coolant in the heating system, depending on the outdoor temperature values, i.e. according to the temperature schedule, which is recorded as a program in an industrial electronics device, for example, a thermostat. The operation of such systems is well described in the catalogs of organizations of suppliers of heating equipment and does not reveal their potential for energy saving of fuel and energy resources completely. This equipment has long and firmly taken its place on the market, but most of the control principles in them are built according to a simple single-circuit structural scheme for regulating any microclimate parameter without taking into account the influence of other parameters on it and does not predict changes in these parameters over time due to their mutual influence. The operation of such equipment is based on the control system receiving indicators from one sensor of a certain parameter. It is obvious that the operation of such control systems for the safe provision of temperature conditions in production facilities is not perfect and must be modernized.

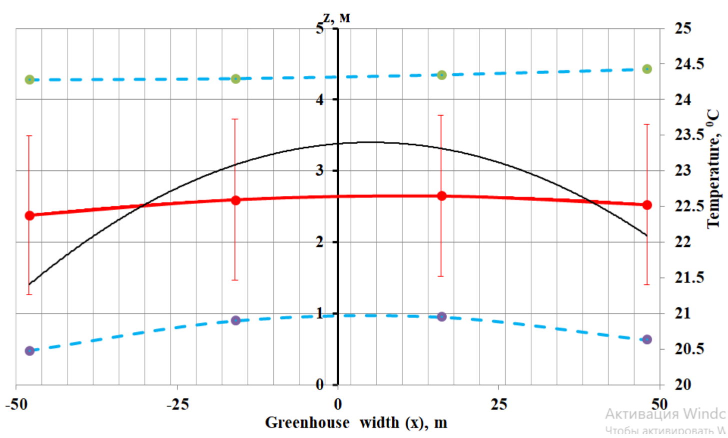

Fig. 4. Determination of the adequacy of the mathematical model: • – experimental temperature values; I – confidence interval; ▬ – temperature values calculated by the least squares method; ▬ – temperature values obtained by mathematical model; - - - – standard deviation.

Experiments on the effect of natural sunlight on the temperature of industrial premises, presented in Figure 3, allows us to conclude that, as in the environment, and in industrial facilities, the main parameter that has a noticeable effect on all others is natural irradiation. It should also be borne in mind that this parameter is not regulated in industrial premises. It is possible to eliminate this disadvantage in existing equipment control devices for creating a microclimate in production facilities by using a mathematical model of safe forecasting and correction of the temperature regime within the technological range in the algorithm of operation, since temperature is one of the main parameters of the microclimate on which the safe working conditions of personnel depend. To do this, the single-circuit control block diagram in programmable logic controllers must be converted to the one shown in Figure 2. As can be seen here, a block of mathematical processing of the temperature regime is mounted in the feedback link. Also, this block forms a database of interrelated microclimate parameters: natural solar illumination and temperature. In addition, it will be advisable to provide for a constant survey of light and temperature sensors in the control system with the synchronization frequency of the microprocessor, which is the main element of the programmable logic controller. With an increase in natural illumination, the microcontroller supplies control actions to the electric drive of the circulation pumps in the heating system to reduce their rotation speed and calculates the temperature increase in the working volume of the production facility due to the greenhouse effect.

3 Conclusion

The vital activity of any biological object, which can include a person, depends on the processes of heat exchange with the environment, therefore, the safe provision of temperature conditions in industrial premises, where people spend up to 8 hours a day, has a significant impact on labor productivity and, ultimately, on the cost of production [11]. At the same time, from an economic point of view, it is important to systematically reduce energy costs to ensure the required temperature regime throughout the year when the values of outdoor air temperature and natural solar radiation vary in a wide range. In scientific works devoted to the influence of air temperature in the production room on the human body, it is indicated that a decrease in temperature by 4 °C is considered sharp for the human body [19-30], but at the same time it can significantly reduce heating costs. In addition, a decrease in temperature from the normalized values during vaccination and the fight against viral seasonal diseases can lead to a decrease in workers' immunity.

In the future, it will be advisable to develop with the help of a mathematical apparatus and determine the target function of the influence of temperature in the production room on labor productivity and health of workers in order to determine from an economic point of view the balance of costs for fuel and energy resources and safe regulation of the temperature regime in industrial premises.

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