Mathematical model of temperature mode for protected ground

I. Vladykin, N. Kondrateva, and O. Riabova

Abstract— Electro technology for protected ground is currently being developed as an energy-efficient and science-based branch of an agricultural sector. World tendencies of vegetable cultivation development for protected ground show almost universal switch to intensive energy-saving technologies for vegetable growing.

The reduction of energy consumption is particularly topical as energy usage takes a significant percentage of the cost of vegetable output from greenhouses. The analysis of scientific publications, reports from greenhouse complexes and our own studies has shown that expenditure of energy on vegetable production in greenhouse complexes is around 40%.

The analysis of specialist literature reveals that vegetable production in protected ground cannot always be profitable due to the influence of various economical, technological and also natural factors. So the reduction of costs on fuel-and power resources in the cost of output from protected ground is of current interest.

Increased production in protected ground is connected with maintenance of required microclimate parameters by various electrical facilities for greenhouses. The operation of technological electrical facility that provides required microclimate parameters is impossible without programmable logic controllers which need the development of special operating model and program.

With reference to the above mentioned the research task is to work outa mathematical model of temperature field which describes temperature change in the working volume of structures for protected ground according to external environmental conditions and allows managing the operation of installed equipment effectively in energy saving mode to maintain the required parameters of microclimate.

Development of the mathematical model describing the change of temperature mode in greenhouses will allow to work out a program for electrical equipment operation under conditions of protected ground and reduce the consumption of fuel -and -energy resources by means of a system of microclimate maintenance.

Keywords— mathematical model, temperature field, greenhouse, energy saving, electro technologies.

Information about the authors

Ivan Vladykin, FSBEI of HE “Izhevsk State Agricultural Academy”, Associate Professor, Ph.D. in Engineering Science,

Nadezda Kondrateva, FSBEI of HE “Izhevsk State Agricultural Academy”, Associate Professor, Ph.D. in Engineering Science,

Olga Riabova, FSBEI of HE “Izhevsk State Agricultural Academy”, Senior Instructor

I. The Relevance of Reserch

The global market has been developing under the influence of worsening of food security in many countries. This situation increases attention to vegetables being a staple of a diet and causes the globalization of agriculture due to easing of trade barriers, strengthening the role of a consumer and vegetable market competition, increasing requirements of consumers to the quality of a final product [1].

Vegetables are not an exchange commodity, but they play an important role in production and consumption in countries of different location and economic status.

The increase of population and intention of some countries to be protected from negative world market conditions contributes the increase of vegetable production. Thus, for example, the countries of Europe and central Asia produced 136 millions of tones of vegetables in 2010. There are four main producers in this area: Turkey, Italy, Spain and the Russian Federation. All together they produce half of the total volume of regional vegetable production. Globally the production of vegetables in the period from 2001 to 2010 increased by 54% in comparison with the previous decade [2].

Vegetables are sources of vitamins that have a positive effect on metabolism, physiological functions and protective properties of a body. A complex set of chemical compounds of vegetables allows considering them a valuable medical dietary product. These factors lead to a tendency of constant increasing of volumes of vegetable production which is of great importance. Improvement of social welfare and information campaigns which are done to improve nutrition contribute to increased consumption of vegetables.

Taking into consideration that production of vegetables in the northern hemisphere is concentrated in the structures for protected ground and that one of the main parameters of microclimate influencing the productivity is temperature, the task of mathematical modeling is relevant.

The practical value of mathematical modeling of temperature mode in conditions of structures for protected ground is to select the most suitable regulating devices for the purpose of increasing the productivity of cultivated biological objects.

II. The Analysis of Mathematical Model of Temperature Mode

In modern scientific periodicals there are many works devoted to mathematical modeling of temperature modes in different research fields [3], [4] etc. Generally they are the publications devoted to modeling of temperature modes for devices, parts and operating procedure in industry. There is not large number of research works devoted to the study of temperature modes in structures for protected ground.

There are several ways of modeling temperature fields in structures for protected ground. The most common of them is the method of electro thermal analogy.

This work presents a mathematical model of the temperature field in the soil of a greenhouse taking into account influence of air steams speed. The mathematical model of temperature modes regulation can be presented as the equation of convecting heat transfer without internal heat sources which has the following form:

$$T = T_0 \cdot e^{\left(\ln\left(\frac{T_2}{T_0}\right)\cdot\frac{z^2}{b^2}+\ln\left(\frac{T_1}{T_0}\right)\cdot\frac{(x-a)^2}{a^2}\right)}$$

where T_0, T_1, T_2 – is temperature in characteristic points of elliptic;
a and ***в*** –are parameters of the ellipse which is described by an isotherm curve;
x and ***z***- are width and height of a greenhouse.

The following mathematical model describes elliptic curves in cross-section of a greenhouse and can be presented as a temperature field in cross-section of a greenhouse taking into account only width and height. The length is not considered in this mathematical model.

We suggest considering developing the mathematical model of temperature mode in structures for protected ground taking into account the influence of other microclimate parameters. It is useful to use the finite elements method for this purpose. It will allow discretizing the range of spatial variables by decomposing with some inaccuracy into the number of no overlapping domains of a plain shape, for example elementary geometric configurations. Within each of them the function of an object state can be approximately described of the same type by the linear combination of a finite number of pre-selected basic functions.

III. The Mathematical Model of a Temperature Mode

A relevant task for the conditions of biological objects production in protected ground is the mathematical modeling of a temperature mode so that with minimum number of temperature sensors the operating system is able to control this physical quantity over the whole working volume of the protected ground.

The relation of any mathematical model and reality is arranged by the chain of hypothesizes, idealizations and simplifications. An ideal object constructed at the stage of conceptual modeling is described with the use of mathematical methods. As a rule the details that may considerably and out of control influence the result are neglected in mathematical models. The same equations can be models of different types depending on a phenomenon and the model [6] is used to study it.

Taking into consideration traditional approaches to mathematical regulation for the description of temperature field in working volume of structures for protected ground, some assumptions are made:

- The soil surface is perfectly smooth and has the same temperature in all points; the heat flow is directed only from the soil into the air space of the greenhouse. So soil surface can be considered as an isothermal plane.
- Side cladding structures have a single layer structure with perfect thermal insulation. Side and hipped heating does not affect the temperature field in a greenhouse.
- Motion path of heat flows of air masses in cross section of a greenhouse is close to elliptic shape. Kinematics of process is considered without searching for reasons that determine the motion of heat masses along elliptic paths.
- The working volume of protected ground is considered as a space bounded by planes at sides, and by cylinder at the top because it is the closest geometric configuration that can be used to describe a greenhouse, it has smooth boundary which results in continuous first order derivatives.

There is no doubt that modern structure for protected ground represents a shape of finite dimensions of regular geometric shape, constructed by mutual intersection of unlimited plates (figure 1):

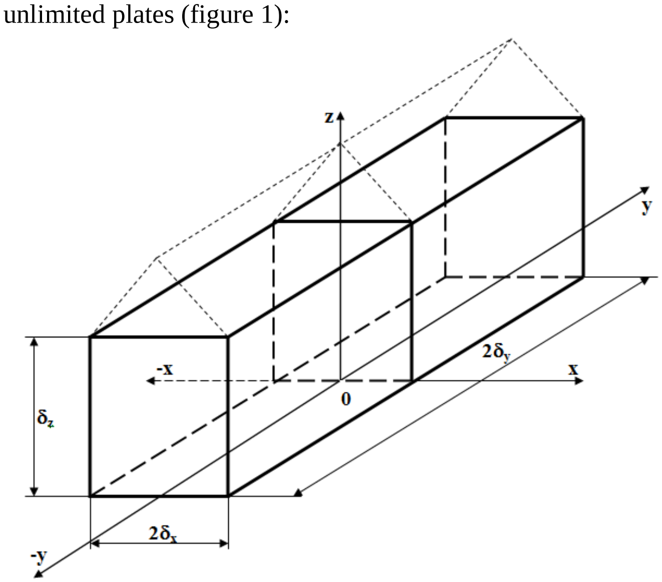


Fig. 1 The structure for protected ground as a shape of finite dimensions.

Taking into consideration that in most modern greenhouses a ridge pole is separated from the mail volume by screening system for the purpose of reducing heat losses in winter and to protect biological objects from extremely strong solar radiation in summer, then a greenhouse is a parallelepiped with finite dimensions along the Cartesian axial ***x***, ***y***, ***z***.

If a shape is formed by intersection of two flat planes having thickness of $2\delta_x$ on the axis and $2\delta_y$ on the axis, then temperature pattern equals:

$$\bar{\theta} = \bar{\theta}_x \cdot \bar{\theta}_y \quad (1)$$

Consequently for parallelepiped (figure 1):

$$\bar{\theta} = \bar{\theta}_x \cdot \bar{\theta}_y \cdot \bar{\theta}_z \quad (2)$$

Based on the results of other researches we take into account the fact that cooling affects temperature field and therefore temperature field under a ridge pole is limited by a trimmed semi cylinder (figure 2).

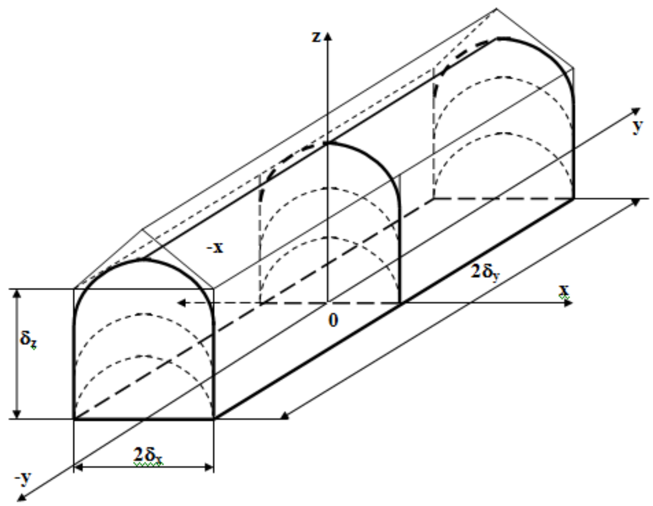


Fig. 2 The greenhouse in the shape of a trimmed semi cylinder

So temperature field in protected ground can be described as intersection of two unlimited plate son axis ***x*** and ***y***, and as a cylinder on the axis ***z***. On the basis of that the formula (2) can be converted:

$$\bar{\theta} = \bar{\theta}_x \cdot \bar{\theta}_y \cdot \bar{\theta}_z = \left[\frac{t_{ea} - t(x,\tau)}{t_{ea} - t_g}\right] \cdot \left[\frac{t_{ea} - t(y,\tau)}{t_{ea} - t_g}\right] \cdot \left[\frac{t_{ea} - t(z,\tau)}{t_{ea} - t_g}\right] \quad (3)$$

where t_{ea} is the temperature of external air, i.e. environment temperature;
t_g is the temperature of air in greenhouse at the moment $\tau = 0$, which can be measured by a sensor installed in the warmest place.

Taking into account that a greenhouse is in the condition of cooling, i.e. $t_{ea} < t_g$ the formula (3) can be converted:

$$\bar{\theta} = \bar{\theta}_x \cdot \bar{\theta}_y \cdot \bar{\theta}_z = \left[\frac{t_g - t(x,\tau)}{t_g - t_{ea}}\right] \cdot \left[\frac{t_g - t(y,\tau)}{t_g - t_{ea}}\right] \cdot \left[\frac{t_g - t(z,\tau)}{t_g - t_{ea}}\right] \quad (4)$$

Thus, for definition of the general temperature pattern in protected ground we need to determine temperature pattern on each axis. The description of temperature fields on axises x and ***y*** can be made the same way, i. e. as in unlimited plates and on the axis ***z*** as a cylinder.

Temperature field in the unlimited flat plate situated in cooling conditions:

$$\bar{\theta}_x = \left[\frac{t_g - t(x,\tau)}{t_g - t_{ea}}\right] \quad (5)$$

Can be determined with the use of the differential equation of non-stationary heat conductivity that has the form:

$$a \cdot \Delta t + \frac{Q_V}{c \cdot \rho} = \frac{\partial t}{\partial \tau} \quad (6)$$

where ***a*** is a temperature conductivity coefficient, m^2/s;
Δt – is temperature difference, ^0C;
Q_V – is volume density of the sources of heat, W/m^3;
c – is heat capacity, Joule/(kg·K);
ρ – is density, kg/m^3.

The solution of equation (6) is carried out by methods of mathematical physics. The simplest way to solve this equation is the method of one-dimensional non-stationary heat conductivity without internal heat sources; therefore the expression (6) is transformed into:

$$\frac{\partial t}{\partial \tau} = a \cdot \frac{\partial^2 t}{\partial x^2} \quad (7)$$

To solve the equation (7) the method of separation of variables is commonly used. In this case the temperature ***t*** is presented as two functions:

$$t = L^* \cdot T^* \quad (8)$$

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

So:

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

Substituting these values in expression (7) we have:

$$\frac{1}{a \cdot T^*} \cdot \frac{dT^*}{d\tau} = \frac{1}{L^*} \cdot \frac{d^2 L^*}{dx^2} \quad (9)$$

The left side of equation (9) is the function of time, i.e. only τ, and the right side function of the geometrical size on axis ***x***. These functions can be equal only when they are constant. In any other case, as τ and x are independent, there can be no equality.

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

If we define this function as $-\beta^2$, then we have:

$$\frac{1}{a \cdot T^*} \cdot \frac{dT^*}{d\tau} = -\beta^2 \quad (10)$$

$$\frac{1}{L^*} \cdot \frac{d^2 L^*}{dx^2} = -\beta^2 \quad (11)$$

The solution of equation (10) has the form of:

$$T^* = A \cdot e^{-a \cdot \beta^2 \cdot \tau} \quad (12)$$

The minus sign in the value of β^2 corresponds to cooling conditions, which can be applied for greenhouses because during time τ there will certainly be a temperature drop ***t***.

If a green house is limited on an axis ***x*** by an unlimited flat plate which has initial temperature t_g and placed in time point

τ=0 into environment with temperature t_{ea}, then the solution of equation (11) has the form of:

$$L^* = B \cdot cos\beta_x + D \cdot sin\beta_x \tag{13}$$

Heat exchange occurs according to a Newton`s law on the borders of plates. The problem is symmetric so let the thickness of plate be $2\delta$and place an axis x in the center of the plate (figure3).

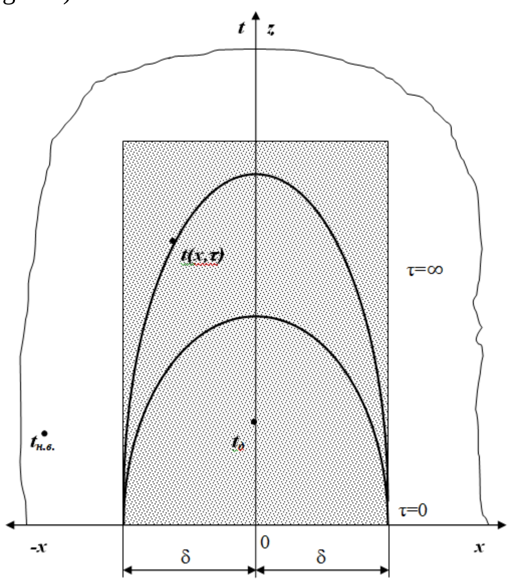


Fig. 3 Non-stationary temperature field

By the symmetry of the function ***cos*** we write the expression (13) in the form of $L^*=B \cdot cos\ \beta_x$ and equation of temperature field $t=L^* \cdot T^*$:

$$t = C \cdot e^{-a \cdot \beta^2 \cdot \tau} \cdot cos(\beta_x) \tag{14}$$

Entering the criteria of similarity:

$$Bi = \frac{\alpha \cdot \delta}{\lambda_w}, F_0 = \frac{\alpha \cdot \tau}{\delta^2}, \overline{x} = \frac{x}{\delta},$$

we have:

$$t = C \cdot e^{-(\delta \cdot \beta)^2 \cdot F_0} \cdot cos(\delta \cdot \beta \cdot \overline{x}) \tag{15}$$

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

$$\cot \mu^* = \frac{\mu^*}{Bi} \tag{16}$$

Equation (16) is solved graphically, it has out of number equation root sμ_i^* and it is mentioned in several publications devoted to theoretical heat-process engineering and mathematics [8].

The sum of particular solutions gives an overview in the following form:

$$\bar{\theta} = \left[\frac{t_g - t(x,\tau)}{t_g - t_{ea}}\right] = \sum_{i=1}^{\infty} C_i \cdot \cos(\mu_i^* \cdot \bar{x}) \cdot e^{-\mu_i^{*2} \cdot F_0} \tag{17}$$

Values of constants of C_i are determined from the initial conditions ($\tau=0$; $t_\partial=t_0$):

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

Substituting values of constants of C_i into the equation (17), we can get the final expression for temperature pattern on ***x-*** axis:

$$\bar{\theta}_x = \left[\frac{t_g - t(x,\tau)}{t_g - t_{ea}}\right] = \sum_{i=1}^{\infty} \frac{2 \cdot \sin \mu_i^* \cdot \cos(\mu_i^* \cdot \bar{x})}{\mu_i^* + \sin \mu_i^* \cdot \cos \mu_i^*} \cdot e^{-\mu_i^{*2} \cdot F_0} \tag{19}$$

Green house section of the ***x***–axis is reasonable to consider as an unlimited plate with boundary conditions of the third sort (figure3).

Series to determine temperature field on ***x-*** axis is convergent. It means that starting from particular value$F_0 \geq$ 0,3 all the following values of series are negligibly small in comparison with the first one. So, at$F_0 \geq 0{,}3$ it is possible to take only the first value of series, and then we have:

$$\bar{\theta}_x = \left[\frac{t_g - t(x,\tau)}{t_g - t_{ea}}\right] = \frac{2 \cdot \sin \mu_i^* \cdot \cos(\mu_i^* \cdot \bar{x})}{\mu_i^* + \sin \mu_i^* \cdot \cos \mu_i^*} \cdot e^{-\mu_i^{*2} \cdot F_0} \tag{20}$$

In a particular point of the plate and it means also a greenhouse on ***x***-axis, it`s temperature depends only on similarity criteria accepted above, ***Bi*** and F_0.

As the internal thermal resistance of a greenhouse is great in comparison with external thermal resistance of environment i.e.$Bi \to \infty$, then in this matter boundary conditions of the third series turn into boundary conditions of the first series. Under these conditions from the equation (20) we have: ($\mu_1^* = \frac{\pi}{2}, \cos \mu_1^* = 0, \sin \mu_1^* = 1$):

$$\bar{\theta}_x = \left[\frac{t_g - t(x,\tau)}{t_g - t_{ea}}\right] = \frac{4}{\pi} \cdot \cos\left(\frac{\pi}{2} \cdot \bar{x}\right) \cdot e^{-\frac{\pi^2}{4} F_0} \tag{21}$$

Performing similar calculations, temperature pattern in a greenhouse on ***y***–axis can be determined as:

$$\bar{\theta}_y = \left[\frac{t_g - t(y,\tau)}{t_g - t_{ea}}\right] = \frac{4}{\pi} \cdot \cos\left(\frac{\pi}{2} \cdot \bar{y}\right) \cdot e^{-\frac{\pi^2}{4} F_0} \tag{22}$$

On ***z*** – ax is temperature pattern can be described similar to the heating processes of a half cylinder r, i.e. by an analytic expression:

$$\bar{\theta}_z = \left[\frac{t_g - t(z,\tau)}{t_g - t_{ea}}\right] = 1 - \frac{2 \cdot a \cdot \alpha \cdot \tau}{\lambda_w \cdot r} \cdot e^{-\frac{1}{4 \cdot F_0}} \tag{23}$$

where ***a*** is a coefficient of isobaric thermal conductivity, for air it is 18,88·10$^6\left[\frac{m^2}{s}\right]$;

$\boldsymbol{\lambda_w} = 0{,}027\ \left[\frac{\mathrm{W}}{\mathrm{m \cdot K}}\right]$ –is air thermal conductivity;

$\boldsymbol{\alpha}$–is a coefficient of convective return, it is equal to 500 $\left[\frac{\mathrm{W}}{\mathrm{m^2 \cdot K}}\right]$;

$\boldsymbol{\tau}$ – is current time, s;

r – is a radius of cylinder equal to altitude $\boldsymbol{z}$ from the surface of ground to the point where it is necessary to define temperature.

Also we cannot ignore the fact that width and length of a greenhouse are several times bigger than height of structures for protected ground, i. e. $l \gg z$ or $\delta \gg z$ (figure4). Therefore we consider it necessary to add to the expression (23) a geometrical constant of structures for protected ground $\boldsymbol{k_\Gamma}$, that in actual fact is ratio of compression inscribed in a half of ellipse cross section of a greenhouse. So, $k_\Gamma = \frac{2 \cdot z}{l}$.

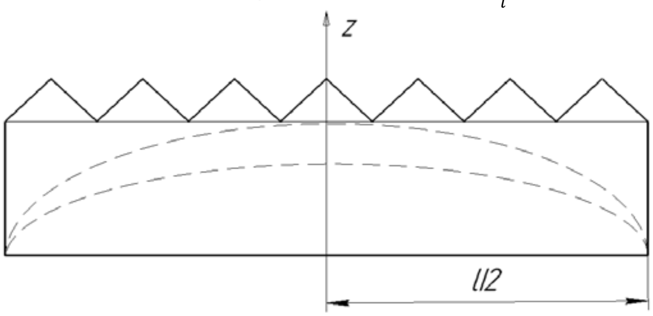


Fig. 4 Cross section of a greenhouse.

Then, from dimensionless sizes of temperature field we can turn to specific values of temperature in some point of working value of protected soil:

$$\frac{(t_g - \boldsymbol{t})}{(t_g - \boldsymbol{t_{ea}})} = \bar{\theta} \qquad (24)$$

Multiplying both left and right parts of the expression (24) by $\left(\boldsymbol{t_g} - \boldsymbol{t_{ea}}\right)$ we get:

$$\left(t_g - t\right) = \bar{\theta} \cdot \left(t_g - t_{ea}\right).$$

So, $\boldsymbol{t}$ equals to:

$$t = t_g - \bar{\theta} \cdot \left(t_g - t_{ea}\right).$$

Taking into consideration that $\bar{\theta} = \bar{\theta}_x \cdot \bar{\theta}_y \cdot \theta_z$, we get:

$$t = t_g - \left[\frac{4}{\pi} \cdot \cos\left(\frac{\pi}{2} \cdot \bar{x}\right) \cdot e^{-\frac{\pi^2}{4} \cdot F_0}\right] \cdot \left[\frac{4}{\pi} \cdot \cos\left(\frac{\pi}{2} \cdot \bar{y}\right) \cdot e^{-\frac{\pi^2}{4} \cdot F_0}\right] \cdot \left[1 - \frac{2 \cdot a \cdot \alpha \cdot \tau}{\lambda_w \cdot z} \cdot e^{-\frac{1}{4 \cdot F_0}}\right] \cdot \left(t_g - t_{ea}\right) \qquad (25)$$

Having carried out mathematical transformations and having transformed relevant values $\overline{x} = \frac{x}{\delta}$ and $\overline{y} = \frac{y}{l}$ into real ones, from the expression (25) we have the following:

$$t = t_g - \left[\frac{16}{\pi^2} \cdot \cos\left(\frac{\pi \cdot x}{2 \cdot \delta}\right) \cdot \cos\left(\frac{\pi \cdot y}{2 \cdot l}\right) \cdot e^{-\frac{\pi^2}{2} \cdot F_0}\right] \cdot \left[\frac{2 \cdot z}{l} - \frac{4 \cdot a \cdot \alpha \cdot \tau}{\lambda_w \cdot l} \cdot e^{-\frac{1}{4 \cdot F_0}}\right] \cdot \left(t_g - t_{ea}\right) \qquad (26)$$

where $\boldsymbol{l}, \delta, z$ – are length, width and height of a greenhouse, m.

IV. EXPERIMENTS

For examining microclimatic mode in protected ground and also for the purpose of study of factors which influence the mode we have conducted experimental researches of microclimatic parameters in several structures. We have been studying microclimatic parameters for two years in equal structures for protected ground of five replications.

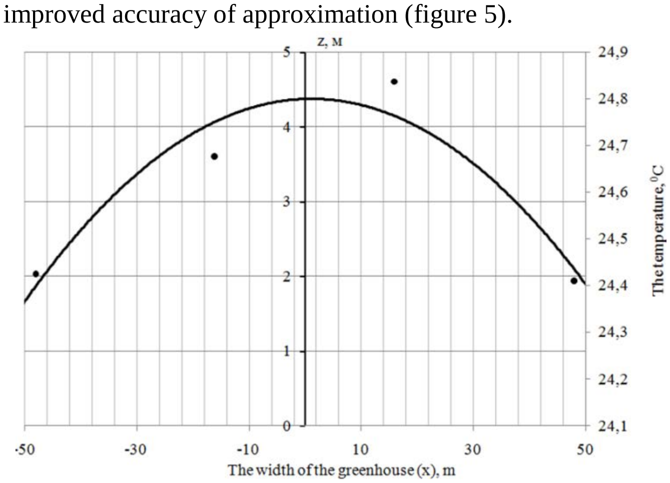
Making observations of temperature values in structures for protected greenhouses we have noticed that an approximating curve of experimental data can be described by polynominal second-order function with rather high accuracy of approximation R^2=0,862 (27).

$$\mathrm{t} = -0{,}288 \cdot \tau^2 + 7{,}321 \cdot \tau - 14{,}69 \qquad (27)$$

where $\boldsymbol{t}$ – is the temperature in a greenhouse, ^{0}C;

$\boldsymbol{\tau}$–is the time of observation.

Further increasing of order of polynominal function has not improved accuracy of approximation (figure 5).



● the experimental data — the approximating curve

Fig. 5 Temperature in cross section on axis x of a greenhouse

The research allows to make conclusion that temperature field in structures for protected ground can be described as a rotation body of a polynominal second-order curve which is ellipsoid inscribed in geometrical dimensions of the object of protected ground, i.e. parallelepiped (figure 6).

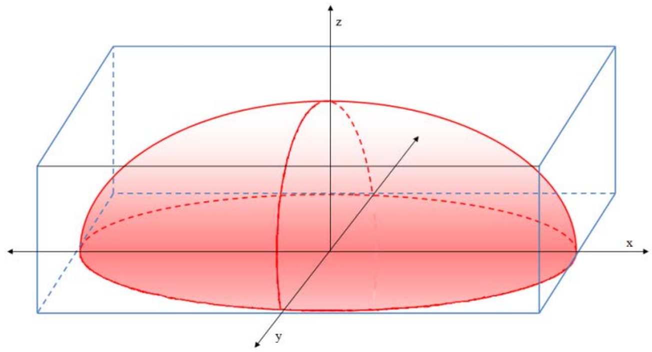


Fig. 6 The shape of temperature field in a greenhouse.

Processing of experimental and calculated values of temperature shows that suggested mathematical model adequately describes temperature change over entire working volume of a structure for protected ground taking into account all disturbing and regulated influences on temperature mode.

V. CONCLUSION

1. The analysis of electrical equipment operation in structures for protected ground has shown that there is the possibility to reduce the consumption of energy resources due to coordinated work of the existing equipment which is carried out by programmable logic controllers under changing external conditions. The proposed mathematical model of temperature mode allows to reduce energy expenditureon heating the structures for protected ground up to 10%.
2. The mathematical model of temperature field is developed. It describes temperature change in working volume of structures for protected ground taking into consideration environmental conditions and allows managing work of the existing power equipment by programmable logic controllers in order to maintain required microclimate parameters.
3. Operation algorithm and program for programmable logic controllers are developed on the basis of proposed mathematical model. They allow increasing the efficiency of work of existing power equipment for the systems of maintaining microclimate conditions in greenhouses due to coordinated work mode. It has allowed to decrease the consumption of heat energy by 10...12% in the structures for protected ground with the area of $15m^2$.
4. We have carried out field tests on efficiency upgrading of work of the existing power equipment in coordinated mode and they reveal the following. The developed mathematical model can further be used as a program for logic controllers with flexible hierarchy structure that switches over in real time mode. It is also possible to save 10...12% costs offuel and energy resources and due to the stability of temperature mode the cropping capacity of cucumber can be increased by 8%.

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