MATHEMATICAL MODEL OF ENERGY CONSUMPTION IN GREENHOUSES

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The temperature modeling results in greenhouse, which are based on heat and mass transfer equations using MATLAB are synthesized. Coefficients of multiparameter mathematical models for Netherlands greenhouses are determined.

Mathematical model, greenhouse, climate, temperature, humidity.

It is known that the optimum temperature in the greenhouse, especially in winter, is the most energy-consuming factor in the production of vegetables. Besides temperature significantly affects photosynthesis in plants and is associated with the intensity of solar radiation, which depends on the length of daylight and external weather conditions. Some solar radiation is photosynthetically active (PAR), which is involved in the process of photosynthesis, and the rest turned into heat, increasing the temperature in the greenhouse, and the disturbing influences climate biotechnical object. Thus, an important task is the synthesis of a mathematical model of biotechnical object, which takes into account the main parameters of microclimate and allow it to analyze such elements that have the greatest weight in use of energy resources.

The purpose of research is making a simulation mathematical model of energy in the greenhouse during a winter based on the equations of heat and mass transfer, which will determine the amount of energy required to maintain optimum parameters of microclimate for growing tomatoes.

Materials and methods of the research. During the studies winter type g+reenhouse, installed in "Combinat " Teplychniy "area 3,6 ha was considered.

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In order to facilitate microclimate control the greenhouse was divided into technological areas. In terms of modeling one zone can be considered as an object with lumped parameters.

Constructive and thermal characteristics of the greenhouse zone:

1. Sections sizes – 4,5 x 8 m. = 36 m^2.
2. Number of sections – 180.
3. Greenhouse area – 6480 m^2 (90 x 72 m)
4. Column height in the center – 4,5 m, the edges – 4 m.
5. Glazed surface area F_{ck} = 6480·1,008 + 2·4·72 = 7108 m^2.
6. Thickness of glass – 4 mm = 0,004 m.
7. Volume of the section – 6480 x 4,25 = 27540 m^3.
8. Length of rails heating pipes 10·4,5·180 = 8100 m.
9. Length of side walls heating pipes 4·2·72 = 576 m.
10. Length of distribution lines – 142 m, average diameter 0,127 m.
11. Heating pipes surface 3,14·0,051 · (8100 + 576) = 1389 m^2.
12. Distribution lines surface 3,14·0,127·142 = 57 m^2.
13. Pipe wall thickness 2,25 mm = 0,00225 m.
14. Internal volume of heating pipes – $3{,}14 \cdot 0{,}0465^2/4 \cdot 8676 = 14{,}73$ m^3.
15. Internal volume of distribution lines – $3{,}14 \cdot 0{,}12^2/4 \cdot 142 = 1{,}61$ m^3.
16. Temperature of hot water 95 °C.
17. Air temperature in the greenhouse 19 °C.
18. Greenhouse fence coefficient 1,097 m^2/m^2.

For the synthesis of a mathematical model of heating greenhouses one zone was used (Fig. 1), it consists of 180 sections and it was assumed to be the object with lumped parameters. The air temperature in the greenhouse t_p is equal in the total volume of greenhouse and water temperature in the heating tubes t_v is the arithmetic mean value between the inlet hot water temperature t_g and water temperature at the outlet of the greenhouse t_y.

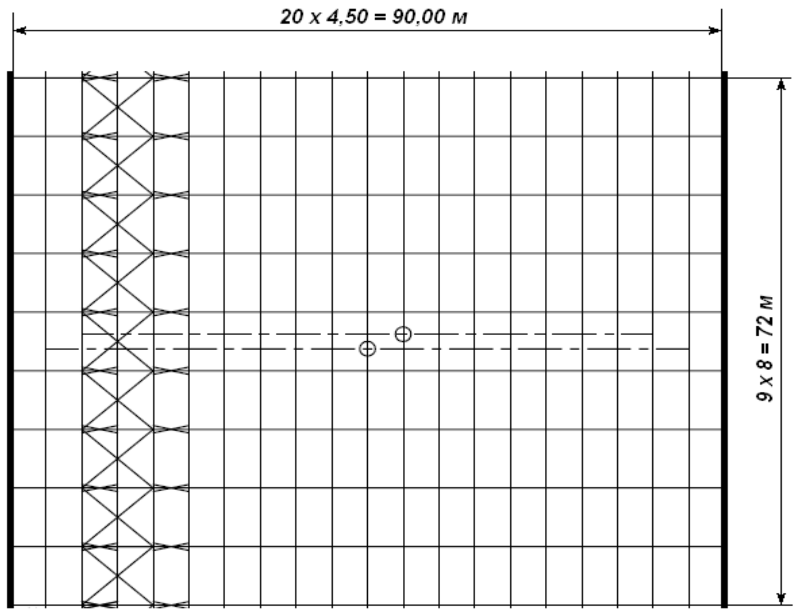

Fig. 1. The scheme of the greenhouse zone

The static model of technological object via temperature was constructed. It was represented as the object in two parts that accumulate energy - heated water link and greenhouse air that is heated link (Fig. 2).

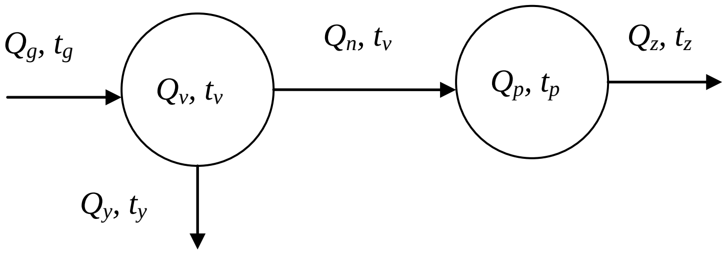

Fig.2. The scheme of heat flow in the greenhouse

In static mode, quantity of heat in the water Q_v and heat in greenhouse air Q_p remains unchanged and therefore we can write two equations of thermal balance for water:

$$Q_g - Q_y - Q_n = 0$$

and for greenhouse air: $Q_n - Q_z = 0$, (1)

where Q_g – quantity of heat that received by the water, J.; Q_y – the heat, that was withdrawn with water, J.; Q_n – heat that transferred to the air, J.; Q_z – the heat that was lost into the surrounding space, J. The heat amount received by the greenhouse heating system during a second and that came out of it, depends on water heat capacity C_v, pump productivity G_n, water density ρ_v and water temperature, and the heat amount stored in the heating system also depends on the water volume in the system V_v. In accordance with this:

$$Q_g = C_v G_n \rho_v t_g;$$

$$Q_y = C_v G_n \rho_v t_y; \tag{2}$$

$$Q_v = C_v V_v \rho_v t_v.$$

Heat amount stored in the greenhouse depends on the air heat capacity C_P , air density ρ_v, temperature t_p and volume of the greenhouse V_p:

$$Q_p = C_p V_p \rho_p t_p. \tag{3}$$

Heat is transferred from the water through the pipe wall to the air and from the air through the greenhouse glass to ambient air is determined by the Fourier law:

$$Q_n = k_1 F_t (t_v - t_p), \tag{4}$$

where k_1 – heat transfer coefficient through the pipe; F_t – area of the heating pipe, m^2. Heat transfer coefficient determined by the formula:

$$k_1 = Nu_p \frac{\lambda_p}{D_{mp}}. \tag{5}$$

Air features values found depending on the air temperature in the range from -50 to 60 °C on the basis of the method of least squares equations.

Air density, kg/m^3:

$$\rho_p = 1{,}2934 - 4{,}8735 \cdot 10^{-3} \cdot t_p + 1{,}7287 \cdot 10^{-5} \cdot t_p^2. \tag{6}$$

Kinematic coefficient of air viscosity , m^2/sec:

$$\nu_p = (13{,}3154 + 0{,}08647 \cdot t_p + 1{,}1144 \cdot 10^{-4} \cdot t_p^2) \cdot 10^{-6}. \tag{7}$$

Coefficient of air thermal conductivity , W/(m ·°C):

$$\lambda_p = (2{,}4373 + 7{,}8736 \cdot 10^{-3} \cdot t_p - 1{,}3487 \cdot 10^{-6} \cdot t_p^2) \cdot 10^{-2}. \qquad (8)$$

The Prandtl number for air:

$$\Pr_p = 0{,}70876 - 3{,}3487 \cdot 10^{-4} \cdot t_p - 2{,}1179 \cdot 10^{-6} \cdot t_p^2. \qquad (9)$$

Coefficient of volume expansion of air, 1/°K:

$$\beta_p = \frac{1}{t_p + 273}. \qquad (10)$$

To find the Nusselt criterion for heat transfer from a horizontal pipe to the air we use the formula of [1]:

$$Nu_p = C \cdot (Gr_p \, Pr_p)^n, \qquad (11)$$

where for $1000 < Gr_p \, Pr_p < 1 \cdot 10^9$ $C = 0{,}5$ a $n = 0{,}25$.

The value of $Gr_p \, Pr_p$ determined by the expression:

$$Gr_p \Pr_p = 9{,}81 \cdot \beta_p \frac{(t_v - t_p) D_{mp}{}^3}{\nu_p^2} \Pr_p. \qquad (12)$$

The heat that is lost through the greenhouse glass, we get using the expression:

$$Q_z = k_z F_c (t_p - t_z) \eta_o, \qquad (13)$$

where k_z – coefficient of heat transfer through the glass surface of the greenhouse; F_c – glazed surface area of the greenhouse, m^2; η_o – greenhouse fence coefficient, which is equal to F_c/F. Heat transfer coefficient is determined by the expression:

$$k_z = \frac{1}{\frac{1}{\alpha_1} + \frac{\delta_c}{\lambda_c} + \frac{1}{\alpha_2}}, \qquad (14)$$

where α_1, α_2, – appropriate coefficients of heat transfer from air to glass walls of the greenhouse and from the greenhouse glass to the outside air; λ_c – coefficient of thermal conductivity of glass walls; δ_c – glass thickness, mm.

The heat transfer coefficient from air to greenhouse glass walls accept permanent α_1 = 6.4 W/m^2·°C.

The heat transfer coefficient from glass to the outside air is based on [2]:

$$\alpha_2 = Nu_z \frac{\lambda_z}{L_0}, \tag{15}$$

where L_0 is the linear dimension of the greenhouse section, which is half of the section width 2,25 m, and the value of the Nusselt number for outside air get considering the rate of outdoor air (climate):

$$Nu_z = 0{,}67\,\mathrm{Re}_z^{1/2} \cdot \mathrm{Pr}_p^{1/3}, \tag{16}$$

where the Reynolds number is found from the equation:

$$\mathrm{Re}_z = \frac{V_z L_0}{\nu_z} \tag{17}$$

and V_z - air velocity (wind) on the street, m/s.

Thermophysical properties of water are found from the obtained equations depending on water temperature.

The density of water, kg / m^3:

$$\rho_v = 1000{,}6 - 0{,}0719 \cdot t_v - 3{,}5501 \cdot 10^{-3} \cdot t_v^{\,2}. \tag{18}$$

Heat capacity of water, J / kg °C:

$$\lambda_p = (4{,}2074 - 1{,}4878 \cdot 10^{-3} \cdot t_v + 1{,}64695 \cdot 10^{-5} \cdot t_v^2) \cdot 1000. \tag{19}$$

From a static model move to a dynamic . Taking into account equations of statics and equation we obtain the system of differential equations of heat changes during time in the water and in the greenhouse air. Given the parameters that we consider the same, namely environment volumes, air and water densities derivatives will be determined at temperatures (average) t_v of water and air temperatures t_p of the greenhouse:

$$\begin{aligned} C_v V_v \rho_v \frac{dt_v}{d\tau} &= C_g G_g \rho_g t_g - C_y G_y \rho_y t_y - \alpha_p F_t (t_v - t_p); \\ C_p V_p \rho_p \frac{dt_p}{d\tau} &= \alpha_p F_t (t_v - t_p) - k_z F_c (t_p - t_z). \end{aligned} \tag{20}$$

Assuming that $t_v = (t_g + t_y)/2$, the above equation we find the temperature of chilled water and substitute in equation (20). After simplification will result equation (20) to the Cauchy form :

$$\frac{dt_v}{d\tau} = \frac{C_g G_g \rho_g t_g - C_y G_y \rho_y (2t_v - t_g) - \alpha_p F_t (t_v - t_p)}{C_v V_v \rho_v};$$
$$\frac{dt_p}{d\tau} = \frac{\alpha_p F_t (t_v - t_p) - k_z F_c (t_p - t_z)}{C_p V_p \rho_p}. \quad (21)$$

Research results. To calculate the value of heat that loss to the environment based on [2] obtained the dependence of the heat loss the wind speed (m/s) and external temperature (error is δ_q = *3,84*), which is an alternative equation to calculate the heat loss through the greenhouse fence:

$$Q1_z / \eta_o = 41{,}42143 + 20{,}1357\, V_z - 4{,}2552\, t_z - 0{,}5952\, V_z t_z - 1{,}6623\, V_z^2 + 0{,}08893\, t_z^2. \quad (22)$$

Determine the flow of coolant. When the coolant temperature difference = 95 - 70 = 25 °C and the heat loss of the greenhouse tent $Q_ш$ = 504,62 W/m^2 on schedule (Fig. 4), we find flow of coolant G_T = 7.2 kg/ hr-m^2 or using the formula :

$$G_T = \frac{Q_ш}{C_v \Delta t} = \frac{504{,}62 \cdot 3600}{4{,}215 \cdot 10^3 \cdot 25} = 17{,}2 \text{ kg/hr} \cdot \text{m}^2.$$

Determine the parameters of heating the entire section area F_T = 6480 m ^{2}.

$$\mathrm{Q}_ш^\mathrm{C} = \mathrm{Q}_ш \cdot 6480 = 504{,}62 \cdot 6480 = 3270 \text{ kW}.$$

Coolant flow in the heating system:

$$\mathrm{G}_\mathrm{T}^\mathrm{C} = G_T \cdot 6480 = 17{,}2 \cdot 6480 = 111{,}5 \cdot 10^3 \text{ kg/hr}.$$

Check the mode of movement of coolant in the heating system. Coolant flow in the heating system:

$$G_T^C = 111{,}5 \cdot 10^3 / \rho_в = 111{,}5 \cdot 10^3 / 970{,}5 = 114{,}9 \text{ m}^3\text{/hr},$$

where ρ_v = 970,5 kg/m^3 — coolant density at t_{cp} = 82,5 °C.

When heating from its own boiler for heating tents coolant is water at temperature 95 °C. For greenhouses ground heating systems - the water at temperature in the direct conduit 40 °C.

In the MATLAB environment simulation mathematical model of the dynamics of change hot water average temperature and air temperature in the greenhouse was synthesized (Fig. 3) .

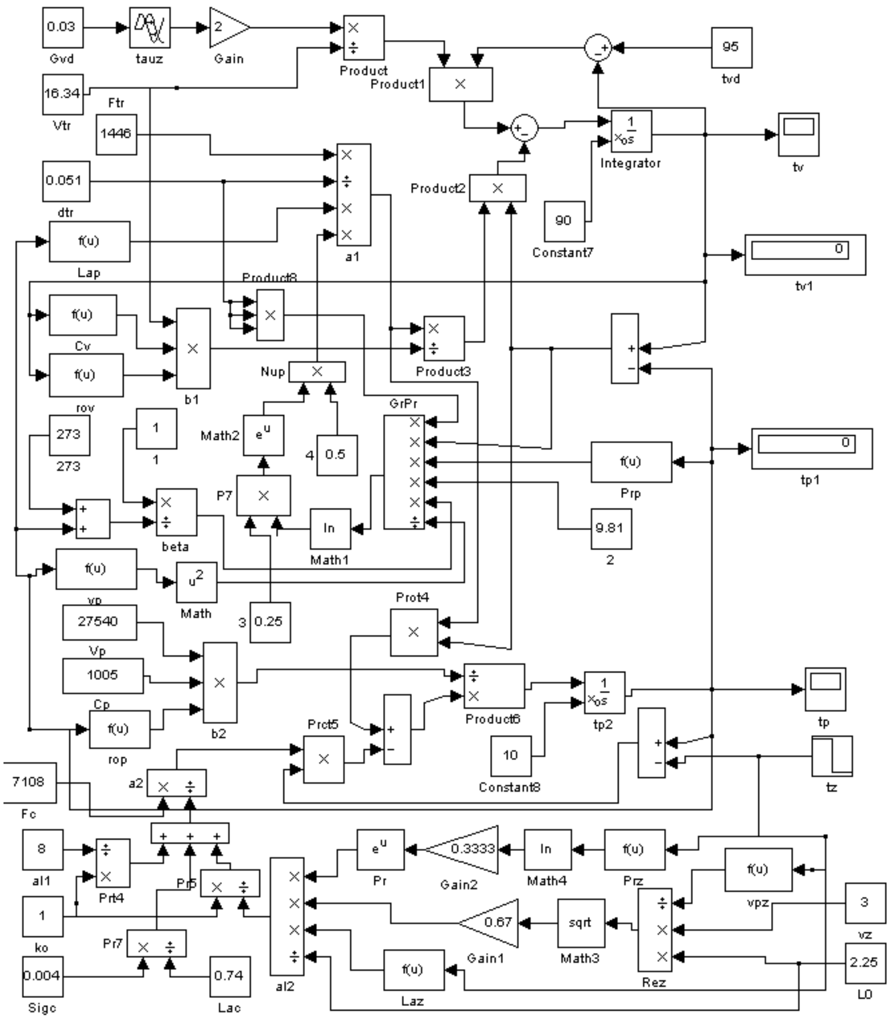

Fig. 3. Block diagram of energy consumption model in the greenhouse using Simulink

The study of the simulation model showed that to achieve the desired temperature in the greenhouse at 19 ^oC hot water temperature will be about 95 ^{o} C. Temperature water leaving the system - at 88 ^oC, with an average water temperature of 91,5 ^oC. In reality, the system is stabilized by water temperature during the period 500 s, and the air temperature in the greenhouse in 1250 s. In the acceleration curve can be seen object time delay 100 s. (Fig. 4).

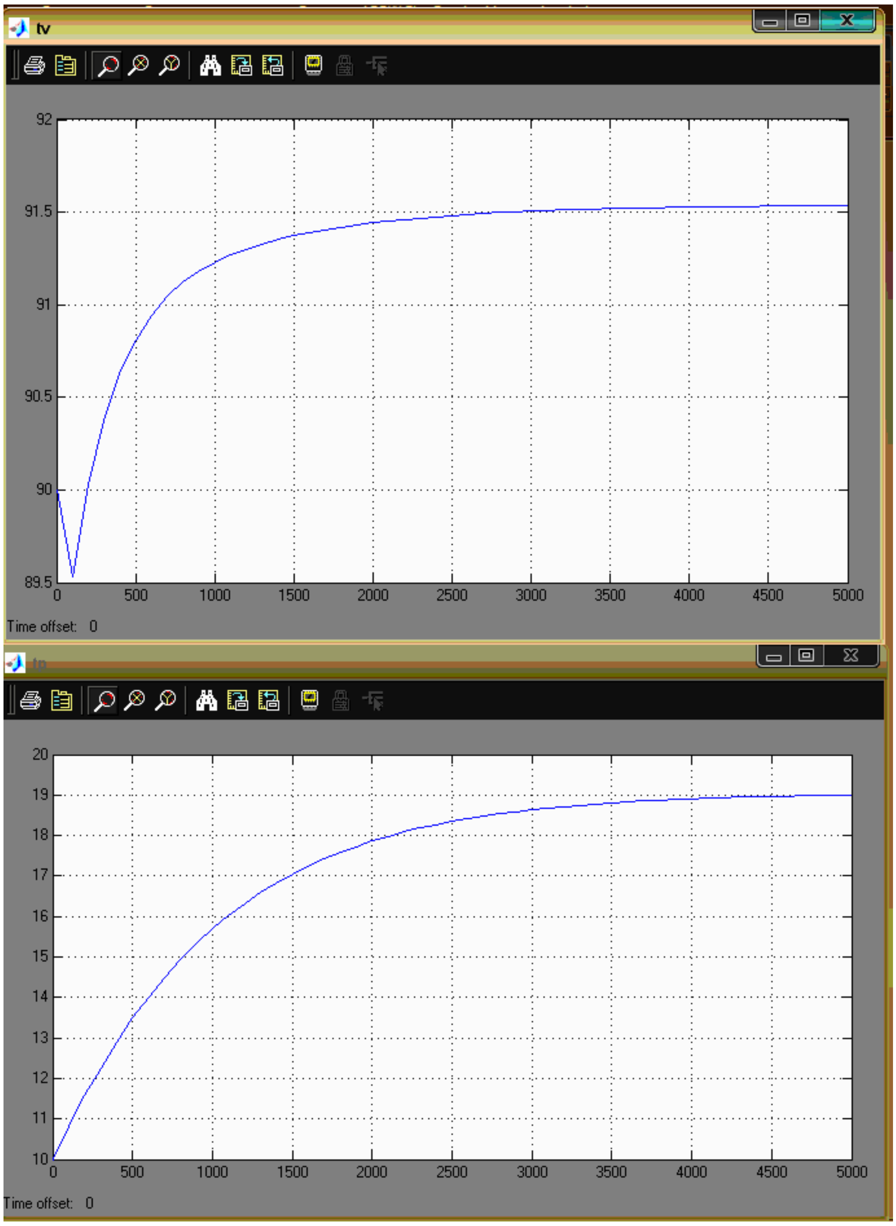

Fig. 4. Dynamics of change in the average temperature of hot water (upper graph) and air temperature (lower graph) in the greenhouse

The result of calculation of heat balance at the air temperature in the greenhouse 18 ˚C, external temperature -15 ˚C, the average temperature of water in the heating system 82,5 ˚C, the schedule of heat in the greenhouse during the day was obtained .

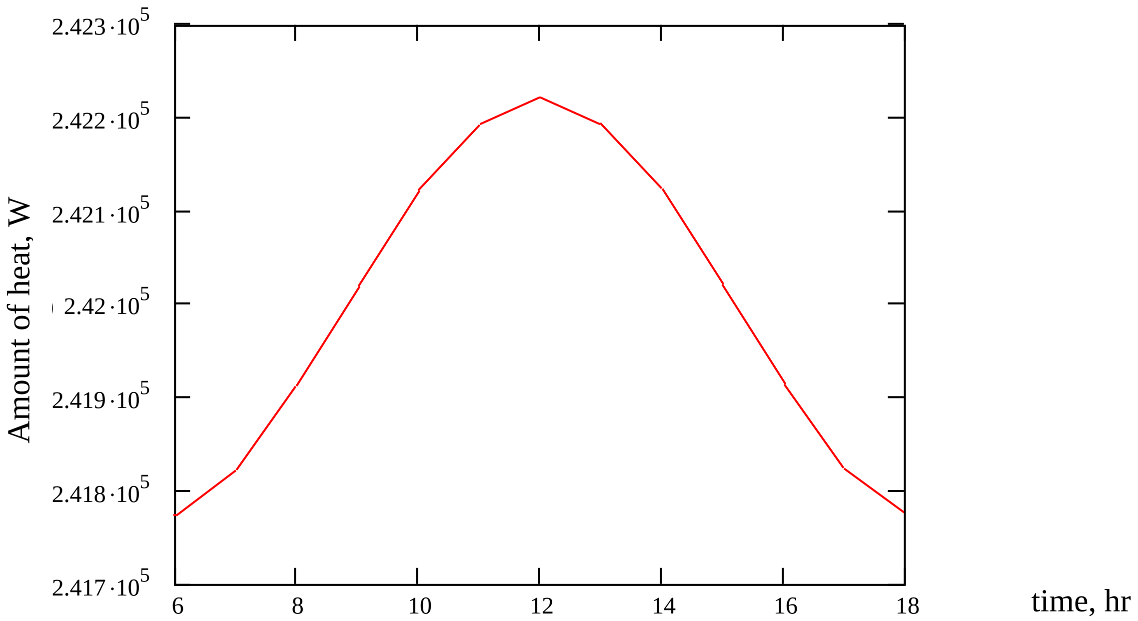

Fig. 5. The amount of heat changing in the greenhouse during the day

Using boiler regime map installed in the greenhouse № 9 of "Combinat "Teplichniy" it is possible to determine the cost of natural gas for heating greenhouses (consider that in winter the boiler operates at full capacity).

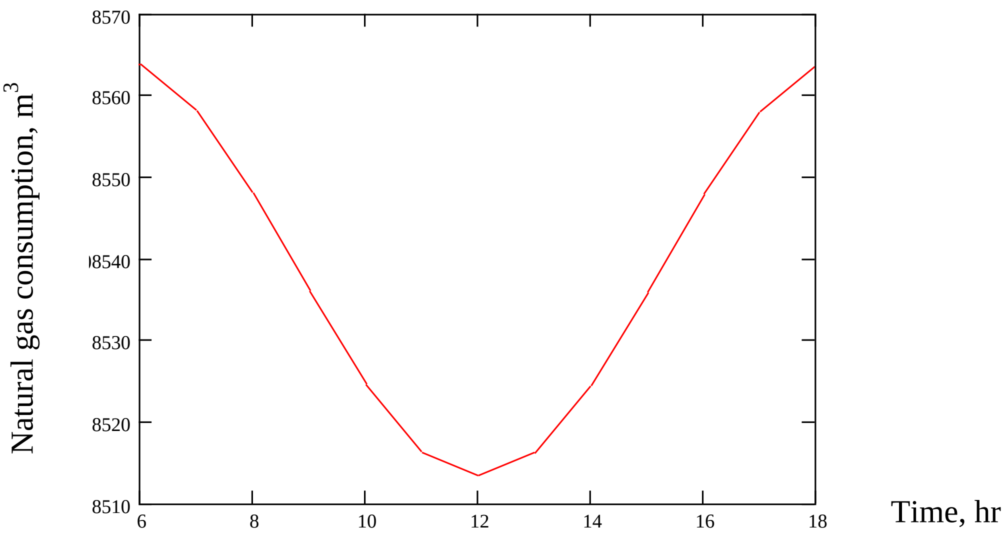

Fig 6. Natural gas consumption for heating greenhouses in winter

Thus, the amount of natural gas required to maintain the desired temperature in the greenhouse during the day decreases closer to daylight hours and increased at night. This is due to the influence of solar radiation on heat balance in the greenhouse.

Improving the heat transfer model in the greenhouse may with counting on heat from solar radiation for heating air and heat loss from ventilation air. Also model could include the equation of photosynthesis process of plants depending on the greenhouse temperature, lighting and feeding carbon dioxide CO_2, which is knitted with ventilation regime .

The final stage of model synthesis is optimization of the greenhouse using multiobjective decision. An example of such a solution is to bring the many local criteria into one objective function by using the method of generalized desirability function proposed by E. Harrinhton, which can be described by the equation:

$$F(x) = \prod_{k=1}^{s} f_k(x)^{\lambda_k} \to \max , \quad (23)$$

where f_k is local criteria that could be the mass of plants increase through photosynthesis, energy consumption for heating the air in the greenhouse and ventilation, the cost of CO_2 on plant nutrition and λ_k - weighting factor that

$$\lambda_k \geq 0, \quad \sum_{k=1}^{s} \lambda_k = 1$$

Conclusions

The imitation mathematical model of energy costs in the greenhouses due to heat transfer was obtained, heat transfer coefficients and the hot water temperature required to maintain the desired temperature in the greenhouse, were determined . These calculations were performed for the modern winter type greenhouse, which is constructed by Holland technology and installed in “Kobinat “Teplichniy” Brovary district Kyiv region.

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Приведены результаты моделирования температурного режима в теплице на основе уравнений тепло-массообмена с использованием среды MATLAB. Определены коэффициенты многопараметрической модели для теплицы зимнего типа, построенной по современным голландским типовым проектам

Математическая модель, теплица, микроклимат, температура, влажность.

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