Green Technologies in Agriculture: Optimization of Heat Balance and Increasing Energy Efficiency of Greenhouses

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Abstract. In the context of the growing need for environmentally friendly and sustainable technologies, solar greenhouses represent an important element of green technologies aimed at reducing the environmental impact and increasing energy efficiency in agriculture. This paper presents an analysis of the coefficient of natural heat accumulation of solar radiation in the soil of translucent film fencing of hemispherical solar greenhouses. The study covers the dynamics of daily heat accumulation and identifies key factors affecting the efficiency of heat exchange inside the greenhouses. The method of heat engineering calculation of solar heating solar greenhouses, compiled balance equations for individual volumes, parts and in general greenhouses with their subsequent solution, the calculated expressions of solar greenhouses in autumn and spring during which heating in film solar greenhouses of semi-cylindrical shape, depending on the number of layers and orientation to the cardinal points of their translucent fencing and can be illuminated only through the use of solar energy. Based on the analysis of graphical dependencies constructed with the proposed calculation expressions, the degrees of influence of the orientation of the semi-cylindrical translucent film enclosure to the cardinal points, the presence or absence of vegetation in solar greenhouses, the number of layers of the translucent enclosure and external meteorological conditions on the formation of the daily cycle of air and soil surface temperature inside solar greenhouses are established. The obtained results contribute to the optimization of solar greenhouse parameters and the development of efficient methods for using solar energy, which is important for sustainable development and the introduction of green technologies in the agricultural sector.

Key Words: Green technologies; Solar greenhouses; Heat exchange; Energy efficiency.

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1 Introduction

In the context of the need to move towards sustainable development, green technologies are becoming a key element of the strategy to mitigate the impact on the environment. Solar greenhouses that use renewable solar energy to maintain optimal conditions for growing crops are one of the effective practices in the field of green technologies. Their use allows not only reducing greenhouse gas emissions associated with traditional heating methods, but also significantly increasing the energy independence of the agricultural sector.

This study is aimed at determining the coefficient of natural accumulation of solar radiation heat in the soil of translucent film fences of hemispherical solar greenhouses and analyzing its daily dynamics. This issue is of key importance for optimizing the design parameters of solar greenhouses and developing additional heat accumulators that will allow more efficient use of excess solar heat accumulated during the daytime to maintain the thermal regime at night.

The determining initial factors of the formation of the thermal regime in solar greenhouses are the arrival of solar radiation (the main energy source) and the ambient temperature. Consequently, the reliability of calculations for determining the temperature regimes of solar greenhouses in this case will completely depend on the correct accounting of the arrival of solar radiation, ambient temperature and their changes during the day.

Methods of analytical thermal engineering calculation of solar cultivation facilities, taking into account the daily and annual non-stationarity of their operating modes, which are reduced to the compilation of systems of balance equations for individual surfaces, volumes, parts and the whole structure, followed by a decision regarding the desired parameters based on the frequency of arrival of solar radiation and ambient temperature.

The daily (in clear weather) and annual changes in the arrival of solar radiation and ambient temperature are presented in the form of a harmonic function (sinusoids) and in calculations are limited only to the first harmonic. In contrast to the annual, the natural course of total solar radiation in the daily cycle is intermittent: changing almost sinusoidally during the day (only in clear weather), it is broken by night pauses. Therefore, for the entire daily period, the change in the arrival of solar radiation cannot be described by a purely harmonic function for all calculated periods and cases.

Taking into account the above circumstances, in order to study the thermal regimes of solar greenhouses, taking into account the daily non-stationarity of the arrival of total solar radiation and changes in ambient temperature, we proposed and experimentally tested a method based on the joint use of numerical and analytical methods for calculating the daily course of the air temperature of solar greenhouses [12-15].

The soil of the solar greenhouse is represented as a semi-bounded massive, protected from above by a translucent fence, and the vegetation cover is like a solid screen with zero thermal resistance. In this case, the internal volume of the solar cell can be located as a buffer zone located between a semi-bounded massive and a translucent fence.

In greenhouses, the heating of which is mainly based on the direct use of solar energy, i.e. on insolation heating, in clear weather during daytime hours, a significant amount of heat is naturally accumulated in the soil, as the most heat-intensive environment of the structure, which is spent at night to compensate for heat losses. In the case of heat inflow from solar radiation in an amount greater than the amount of heat accumulated naturally in the soil and heat losses to the environment, overheating occurs in greenhouses.

In order to avoid overheating of solar cells, various types of additional short-term heat accumulators are usually used [1-8], which make it possible to rationally use at night and during the following days the excess heat of the total solar radiation that passed through the translucent insulation during the day and absorbed by plant leaves and the interior of the structure and thereby smooth out the daily course of the air temperature inside the solar cell.

It follows from the above that the optimal capacity of short-term additional heat accumulators in solar greenhouses, other things being equal (meaning the thermal engineering qualities of the enclosing elements) depends on the daily course (pace) of natural heat accumulation of solar energy in the soil of structures.

It should be noted that, despite numerous studies in the field of development and creation of solar greenhouses and thermal accumulators for them, the issues of natural accumulation of solar heat in the soil and its effect on the parameters of a short-term additional battery have not been sufficiently studied. The analytical method of thermal calculation of solar greenhouses [9-11], which takes into account the daily non-stationarity of the arrival of total solar radiation and ambient temperature, gives significant errors when determining the flow of solar heat accumulated in the soil of structures. The reason for this, as already noted above, is the incorrectness of the representation of the daily arrival of solar radiation in the form of a harmonic series due to the presence of discontinuities (discontinuity of the function) from the moment of sunset to sunrise and the limitation of the first harmonic. In addition, due to the predominance of semi–clear and cloudy weather in winter, it is almost impossible to imagine the daily arrival of total solar radiation in the form of a harmonic series.

For a detailed analysis of the processes of natural accumulation of solar radiation heat in the soil and optimization of the capacity of short-term additional batteries, we introduce the concept of the coefficient of natural accumulation of solar radiation heat in the soil of solar cells. This is the ratio of the flow of heat accumulated naturally in the soil to the flow of solar radiation absorbed by the surfaces of plant leaves (in the presence of vegetation cover) or soil (in the absence of such) inside the solar greenhouse.

2 Objects and Methods of the Research

The objects of research are small-sized solar greenhouses with one- and two-layer translucent film fences of semi-cylindrical shape and additional short-term accumulators of daytime excess heat of solar radiation. If we denote $q_F(x=0,z)$ by the flow of heat accumulated in the soil in a natural way $q_{abs_{pla}}(z);q_{abs_{bl}}(z)$ is the heat flows of solar radiation absorbed by the surface of plant leaves and soil, then, according to the definition, the coefficient of natural heat accumulation of solar radiation in the soil of solar heats

$$k_{ak}^{wvc} = \frac{q_F(x=0,z)}{q_{abs_w}(z)};$$

(1)

$$k_{ak}^{Nwvc} = \frac{q_F(x=0,z)}{q_{abs_s}(z)},$$

(1a)

(wvc, Nwvc is respectively, with and without vegetation cover). In the conditions of non-stationary thermal processes caused by the daily unevenness of the arrival of solar radiation and changes in ambient temperature, from Fourier's law

$$q_F(x=0,z) = -\lambda \frac{\partial t_s(x,z)}{\partial x}\Big|_{x=0}.$$

(2)

Representing the differential in the right part (2) in the difference form for calculating the heat flow of solar radiation accumulated in the soil of the solar greenhouse, we have

$$q_{F,z} = \frac{\lambda_s}{\Delta x}\left(t_{s_{1,z}} - t_{s_{0,z}}\right).$$

(3)

In accordance with [12-14], the values in the absence and presence of vegetation cover inside solar greenhouses are determined from formulas (4) and (5)

$$t_{s_{0,z}} = \frac{q_{abs_{s,z}}\left(1+\frac{K_{ad}^{fen}}{\alpha_{ad_s}}\right)+K_{ad}^{fen}t_{0,z}+\frac{\lambda_s}{\Delta x}\left(1+\frac{K_{ad}^{fen}}{\alpha_{ad_s}}\right)t_{s_{1,z}}}{\frac{\lambda}{\Delta x}\left(1+\frac{K_{ad}^{fen}}{\alpha_{ad_s}}\right)+K_{ad}^{fen}}, \quad (4)$$

and respectively

$$t_{s_{0,z}} = \frac{q_{abs_{w,z}}+K_{ad}^{fen}t_{0,z}+\frac{\lambda_s}{\Delta x}\left(1+\frac{K_{ad}^{fen}}{\alpha_{ad_s}}\right)t_{s_{1,z}}}{\frac{\lambda}{\Delta x}\left(1+\frac{K_{ad}^{fen}}{\alpha_{ad_s}}\right)+K_{ad}^{fen}}, \quad (5)$$

Substituting (4) and (5) into (3), after some simplifications, we obtain expressions for calculating the solar heat flows accumulated in the soil of solar greenhouses in the presence and absence of vegetation cover in them,

$$q_{F,z}^{wvc} = (q_{abc_{p,z}} - k_{ad}\left(t_{s_{1},z} - t_{0,z}\right)/(1+k_{ad}\left(1/\alpha_{ad_s}+\Delta x/\lambda\right)); \quad (6)$$

$$q_{F,z}^{Nwvc} = (q_{abc_{s,z}} - (\alpha_{ad_s}k_{ad}/\alpha_{ad_s}+k_{ad})\left(t_{1,z}-t_{0,z}\right))/(1+(\alpha_{ad_s}k_{ad}/\alpha_{ad_s}+k_{ad}))(\lambda/\Delta x)) . \quad (7)$$

Substituting (6) and (7), respectively, in (1) and (1a), we find

$$k_{ak}^{wvc} = (1-k_{ad}\left(t_{s_1,z}-t_{0,z}\right)/q_{abc_{s,z}})/(1+k_{abc}\left(1/\alpha_{abc_s}+\Delta x/\lambda\right)); \quad (8)$$

$$k_{ak,z}^{Nwvc} = (1-\alpha_{ad_s}k_{ad}\left(t_{1,z}-t_{0,z}\right)/(\alpha_{ad_s}+k_{ad})/q_{abc_s})/(1+k_{ad}\alpha_{ad_s}\Delta x/(\alpha_{ad_s}+k_{ad})\lambda). \quad (9)$$

Note that the coefficients of natural heat accumulation of solar radiation in the soil of solar greenhouses, respectively, in the presence and absence of vegetation cover k_{ak}^{wvc} and k_{ak}^{Nwvc}, determined from the relations (8) and (9) have a physical meaning when $q_{abc_{p,z+1}>0}$ and $q_{abc_{s,z+1}>0}$.

As can be seen from (8) and (9) k_{ak}^{wvc} and k_{ak}^{Nwvc} other things being equal, they are directly proportional, respectively, to the solar radiation flows (q_{abc_p} and q_{abc_s}) absorbed by the surfaces of plant leaves and soil inside the solar greenhouses, and the ambient temperature t_0, inversely proportional to the reduced coefficient of heat loss through translucent insulation K_{ad}^{fen}.

2.1 Thermal optimization of the capacity of an additional short-term heat accumulator in solar greenhouses

As noted above, the main essence of the use of additional short-term heat accumulators in solar greenhouses is the rational use at night of the excess heat of the total solar radiation that passed through the translucent fence during the day and absorbed by plant leaves, soil and the interior of the structure.

Thus, the capacity of short-term heat accumulators in solar greenhouses is determined from the possibility of accumulating the daily amount of excess solar heat in it.

The daily course of excess solar heat in solar greenhouses is usually determined from the equation of the thermal balance of the greenhouse, taking into account the daytime non-stationarity of the arrival of total solar radiation and changes in ambient temperature:

$$q_{abs_p}(\tau) - q_{hl}(\tau) - q_{ak}^{nat}(\tau) - q_{sur}(\tau) = 0, \tag{10}$$

$q_{abs_p}(\tau)$ is the flow of total solar radiation absorbed by the surface of plant leaves; $q_{hl}(\tau)$ is greenhouse heat losses attributed to a unit of soil surface area; $q_{ak}^{nat}(\tau)$ is solar radiation heat accumulated naturally in the soil of the solar greenhouse; $q_{sur}(\tau)$ is daytime excess solar heat attributed to a unit of soil surface.

From the analysis (10) it should be noted that in order to avoid overheating of the greenhouse $q_{sur}(\tau)$, it should be accumulated on an additional short-term heat accumulator.

The values $q_{hl}(\tau)$, $q_{ak}^{nat}(\tau)$ and $q_{sur}(\tau)$ and (10), respectively, are determined from the expressions

$$q_{hl}(\tau) = k_{ad}(t_{i_{nor}} - t_0(\tau)), \tag{11}$$

$$q_{ak}^{nat}(\tau) = k_{ak}^{nat}(\tau) q_{abs_p}(\tau), \tag{12}$$

$$q_{sur}(\tau) = k_{ak}^{add}(\tau) q_{abs_p}(\tau), \tag{13}$$

where t_{inor} is the normalized air temperature inside the greenhouse during daylight hours. By supplying (11)-(13) to (10), we get

$$k_{ak}^{add}(\tau) = 1 - k_{ak}^{nat}(\tau) - \frac{k_{ad}\left[\left(t_{i_{nor}} - t_0(\tau)\right)\right]}{q_{abs_p}(\tau)}. \tag{14}$$

As follows from (14), the use of an additional short-term heat accumulator in solar greenhouses makes sense only when

$$k_{ak}^{nat}(\tau) < 1 - \frac{k_{ad}\left[\left(t_{i_{nor}} - t_0(\tau)\right)\right]}{q_{abs_p}(\tau)}. \tag{15}$$

The optimal heat capacity of an additional short-term heat accumulator in solar greenhouses (C_{ak}^{add}) is determined from the condition of the possibility of accumulating in it the daily amount of excess solar heat, i.e.

$$C_{ak}^{add} = \frac{F_S}{\Delta t_{ak}} \int_{(\tau)} q_{sur}(\tau) d\tau, \tag{16}$$

where F_S is the surface area of the soil in the solar greenhouses; Δt_{ak} is the temperature difference in the thermal accumulator at the beginning and end of the charging process.

The volume of heat accumulating material in an additional short-term heat accumulator is determined from

$$V_{ak,M} = \frac{c_{ak}\Delta t_{ak}}{(\rho c_p)_{ak}} = F_s \int_{(\tau)} q_{sur}(\tau) d\tau / (\rho c_p \Delta t)_{ak}, \tag{17}$$

where ρ and c_P is the density and specific heat capacity of the accumulating material.

The volume of the chamber of an additional short-term heat accumulator in solar greenhouses, assigned to a unit of soil surface area, for the general case is determined from (17) taking into account the porosity coefficient (ε), i.e.,

$$V_{ak}^{sp} = \frac{V_{ak\,M}}{F_s(1-\varepsilon)} = \int_{(\tau)} q_{sur}(\tau) d\tau / (1-\varepsilon_0)\ (\rho c_{p\Delta t})_{ak} \tag{18}$$

Naturally for water thermal accumulators ε_0=0. Replacing the integral with the sum in (18) and taking into account (13) we have

$$V_{ak}^{sp} = \frac{\sum_{i=1}^{n} q_{abs_{pi}} k_{ak}^{sp}}{(1-\varepsilon)(\rho c_p \Delta t)_{ak}}. \tag{19}$$

Substituting (14) into (19), for the optimal specific volume of the chamber of an additional short-term heat accumulator in solar greenhouses, we have

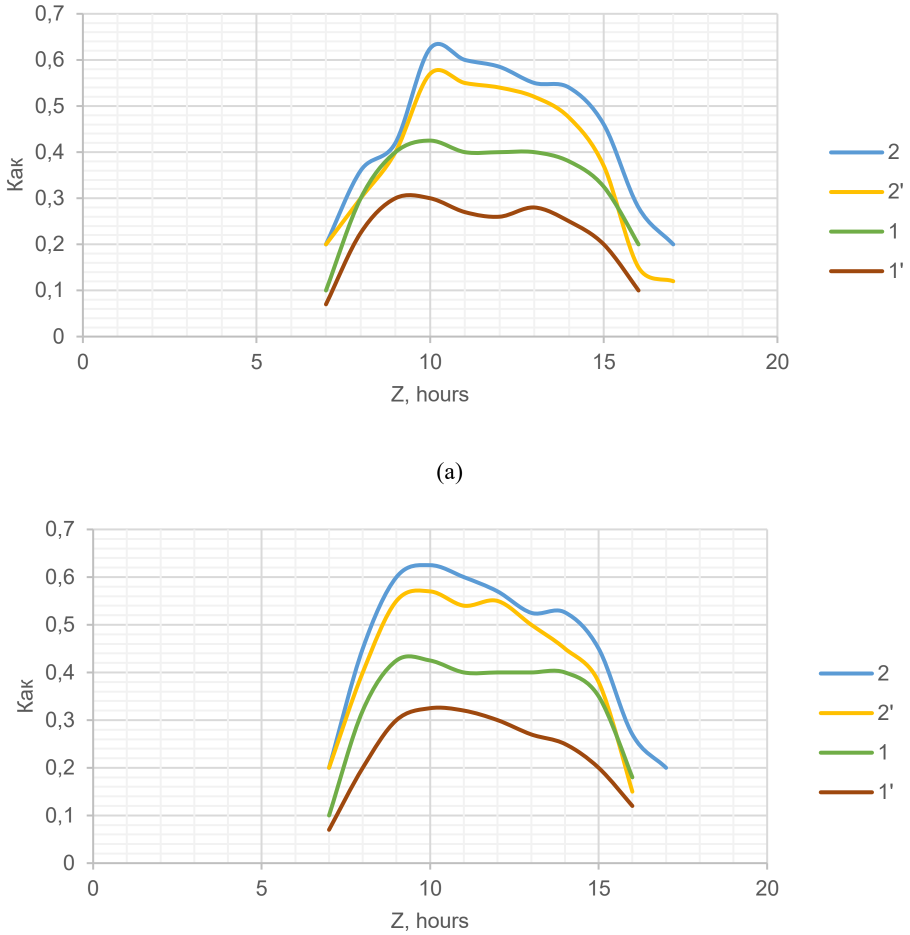
$$V_{ak}^{sp} = \frac{\sum_{i=1}^{n} [(1-k_{ak}^{nat}) q_{abs_{pi}} - k_{ad}(t_{i_{nor}} - t_0)]_i}{(1-\varepsilon)(\rho c_p \Delta t)_{ak}}. \tag{20}$$

As can be seen (20), the optimal specific volume of the chamber of an additional short-term heat accumulator in solar greenhouses, other things being equal (meaning the thermal engineering qualities of the enclosing elements, the porosity coefficient of the battery chamber, the density and specific heat capacity of the accumulating material, the temperature difference at the beginning and end of the battery charging process) depends on the daily courses of solar energy naturally accumulated in the soil of the solar greenhouse ($k_{ak}q_{absp}$), the total solar radiation absorbed by the surface of plant leaves or soil (q_{absp}) and the ambient temperature (t_0).

For clarity, we give an example of a calculation to determine the optimal volume of heat storage material in solar greenhouses with one– and two-layer translucent film fences of semi-cylindrical shape, having an equatorial orientation to the cardinal directions, respectively, in the presence and absence of vegetation cover inside the greenhouses under consideration. The calculation is made for the middle of March, when in solar heats due to the accumulation of the daily excess of solar heat in additional short-term heat accumulators, it is possible to fully cover the daily heat demand for heating, i.e. turn off the traditional heating system.

3 Results and Discussion

Fig. 1 and Fig. 2 show the daily moves of the coefficients of natural heat accumulation of solar radiation in the soil of solar greenhouses with one- and two-layer translucent film fences of semi-cylindrical shape, having equatorial and meridional orientations to the cardinal directions and March months, in clear weather and in the presence or absence of vegetation cover inside for mid-December of the considered solar greenhouses. As follows from Fig. 1, a and b, in December, the process of natural accumulation of heat from solar radiation in the soil of solar greenhouses with one- and two-layer translucent fences begins at 8.30 am and ends at 15.00 pm. The value of $k_{ak,}$ mainly depends on the presence or absence of vegetation in the solar heats and slightly depends on their orientation to the cardinal directions. Thus, the maximum values of k_{ak} in solar greenhouses with two-layer translucent fences and equatorial orientation, in the presence and absence of vegetation cover in them, are, respectively, 0.4549 and 0.6645 (at 11:00), and in helioteplices with meridional orientation- 0.4405 (at 11:00) and 0.6459 (at 10:30), which is on average more than 3.2%. In the absence of vegetation cover inside the solar greenhouses, the values k_{ak} are higher than in the presence and at their maximum, the difference is on average 46%.



(a)

(b)

Fig. 1. Daily courses of the coefficients of natural heat accumulation of solar radiation in the soil of the solar greenhouse for equatorial (a) and meridional (b) locations with single-(dotted) and two-layer (solid) translucent film fences of semi-cylindrical shape for mid-December: 1 and 1'-if there is vegetation cover in the greenhouse; 2 and 2'-in the absence of vegetation cover.

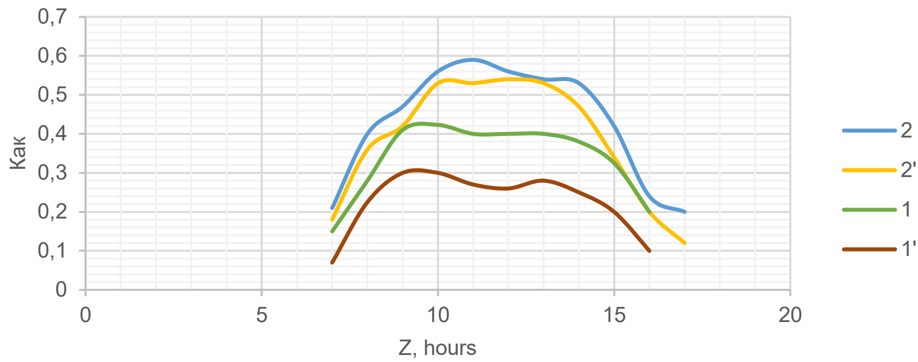
Source: [21].

From the analysis of Fig. 2, a and b, it follows that in March:

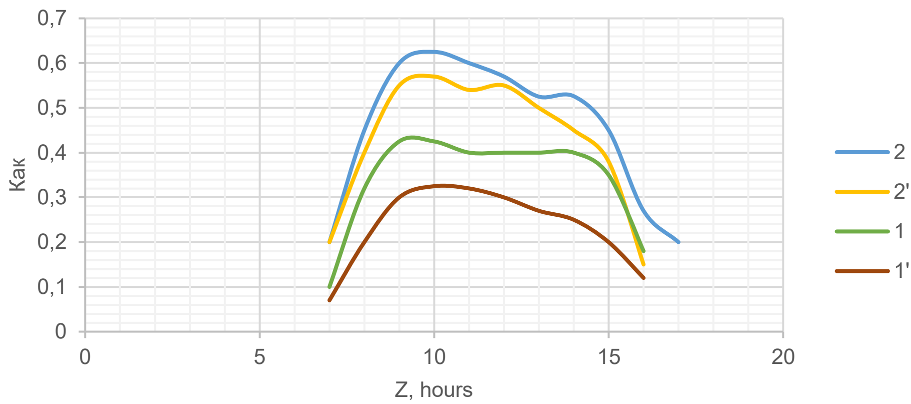
- in solar greenhouses having a two-layer translucent fence and a meridional orientation, the process of natural accumulation of heat of solar radiation in the soil begins half an hour earlier (at 7:00) and ends half an hour later (at 4:30 p.m.) than in similar solar greenhouses of equatorial orientation;

- the maximum values of k_{ak} in solar greenhouses having a meridional orientation, in the presence and absence of vegetation cover in them are 0.4363 (11:30 a.m.) and (11:00 a.m.), in solar greenhouses having an equatorial orientation -0.4643 and 0.6692, which is on average 6.5% more;

- as expected, the k_{ak} in the absence of vegetation cover inside the solar greenhouses is higher than in the presence of it, and at the maximum (11 a.m.) this difference is on average 44%.



(a)



(b)

Fig. 2. Daily courses of the coefficients of natural heat accumulation of solar radiation in the soil of the solar greenhouse for equatorial (a) and meridional (b) locations with one-(dotted) and two-layer (solid) translucent film fences of semi-cylindrical shape for mid-March:1 and 1'-in the presence of vegetation in the greenhouse; 2 and 2'-in the absence of vegetation.

Source: [21].

The difference in the graphs in Fig. 1, a and b (as well as Fig. 2, a and b) in the maximum and duration of k_{ak} during the day is explained by the influence of different values of the transmittance coefficients of translucent film fences in the compared solar greenhouses due to their different orientation to the cardinal directions [14].

From the comparison of the graphs in Fig.1 and Fig. 2, it also follows that for solar greenhouses with two-layer translucent film fences [15], k_{ak} value is 30-40% higher than for single-layer ones, if there is vegetation cover inside the considered solar greenhouses.

In the absence of vegetation cover inside solar greenhouses, this difference is 8-18%.

Value $t_{s_{2,z}}$ in (2) – (4), (8) and (9) are obtained from the temperature distribution over the depth of the soil inside the considered solar greenhouses, taking into account its initial distribution according to the formula (4).

The values $q_{abs\,p}$ and $q_{abs\,s}$ in the calculations are taken according to long-term actinometric data [15-18], taking into account the light transmission coefficients of one- and two-layer film fences [18] absorption beam of plant leaves and soil. The values t_0 are also borrowed from long-term static data [19, 20].

4 Conclusion

By adding to the existing methods for measuring the processes of unsteady thermal conductivity based on finite differences, calculation expressions are proposed that allow establishing the daily course of the temperature of the air environment and the soil surface inside the solar greenhouses under any changes in external meteorological factors, taking into account the residual thermal inertia of the soil of the solar heats.

Based on the analysis of graphical dependencies constructed according to the proposed calculations, the degrees of influence of the orientation of translucent film fencing of semi-cylindrical shape on the cardinal directions, the presence or absence of vegetation cover in solar greenhouses, layers of translucent fencing and external meteorological conditions on the formation of the daily course of air temperature and soil surface inside solar greenhouses are established.

A method for determining the coefficient of natural heat accumulation of solar radiation in the soil of a solar greenhouse is proposed and the degree of dependence of the latter on the number of layers of orientation of the translucent film fencing of solar greenhouses, the presence or absence of vegetation in solar greenhouses and the time of day and year is revealed.

The difference between the graphs in Fig. 1, a and b (as well as 2, a and b) in the maximum and duration of K during the day is explained by the fluctuation of different values of the transmittance coefficients of the translucent film fences in the compared solar greenhouses due to their different orientation to the cardinal points [12-17].

From a comparison of the graphs in Fig. 1 and Fig. 2 it also follows that for solar greenhouses with two-layer translucent film fences [12-17] the value of K is 30-40% greater than for single-layer ones, in the presence of vegetation inside the considered solar greenhouses.

Calculated expressions for the daytime running of the coefficient of natural heat accumulation of solar radiation in the soil of semi-cylindrical solar greenhouses and the optimal volume of additional heat accumulator for them, the actual thermal and operational performance of solar greenhouses with single- and double-layer film translucent semi-cylindrical fences in the conditions of the Syrdarya region.

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