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Balance of heat flows in autonomous bio-vegetation complex as basis for its design

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Abstract. Economic assessment, analysis and forecast of developing organic farming for the next ten years indicates the rapid growth of technologies for greenhouse vegetable growing in Russia. These positive trends are supported by factors such as worsening epidemiological situation in the world due to COVID-19 and transition to self-isolation of the majority of population, which requires providing healthy green products for a functional purpose. It is the need to strengthen the immune system that makes people consume vegetable products in accordance with the recommendations for rational consumption of vegetables that meet modern requirements for a healthy diet. To effectively solve the problem and in connection with the limitation of the imported products supply, the most rational solution is to modernize our domestic production of functional vegetable crops. The design of modern small-scale cultivation facilities makes it possible to ensure food security of various segments of the population living in any part of the Russian Federation. The structure autonomy and energy-saving technologies enable to operate the bio-vegetation complex all year round without being connected to an external power system. This is achieved due to the rational distribution of energy flows in the complex itself, and enables to efficiently operate it all the year round without serious additional financial costs for energy supply in the cold season. The paper presents energy-saving solutions and describes a thermophysical model of energy flows movement being an indispensable element in the design of such structures.

1. Introduction

The most energy-consuming process when growing vegetable and herbaceous crops in artificially created conditions is temperature control in cultivation structures. The rapid development of polypropylene materials manufacturing and creation of cellular polycarbonate predetermined the accelerated path of the development of energy-saving technologies in the greenhouse industry. The need to design autonomous cultivation facilities is due to the high cost of connecting to a centralized power system, significant operating costs especially in the winter, as well as inability to grow crops in the areas not covered by a centralized power supply network. This problem can be solved by using renewable energy resources, transforming them into the required type of energy. Moreover, it is possible to provide them with a cultivation facility to the extent required. The coordinated operation of several energy generators considered in this paper is possible due to the use of solar radiation and low-potential energy of the earth, which ultimately makes it possible to design a small and completely autonomous cultivation structure, whose operation does not require any additional investment [1,6,7, nine].

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The objective of the study is to develop general approaches to assessing the interaction of heat flows in the developed bio-vegetation complex functioning autonomously from centralized power systems.

2. Materials and methods

Today, the covering fence for cultivation facilities is made of light-transmitting materials, which include polyethylene film, glass, cellular polycarbonate. In order to increase the energy efficiency of processes in such a structure, it is possible to use various materials in combination. However, this approach can lead to deterioration in the light transmission and thermal insulation characteristics of the covering shell. Thus, it should be noted that using cellular polycarbonate is a modern solution for constructing cultivation facilities. The advantages of this polymeric material is its main characteristics being light transmittance similar to glass transmittance, increased mechanical strength, possibility to implement energy saving measures.

A sheet of cellular polycarbonate can have a different structure, which is determined by the number of layers in a sheet, absence or presence of stiffening fins and additional diagonal partitions, which add rigidity to the structure, but at the same time can reduce the light transmission capacity. An air gap between the layers performs the effect of an additional thermal gap, providing high thermal insulation. The luminous flux passing through the polycarbonate sheet has a pleasant scattering light inside the protected ground structures due to its reflection and refraction at the edges of the partitions [8, 12].

The energy efficiency of cultivation structures is influenced by the shape and volume of an inextricably linked supporting structure. Analysis of various design solutions showed that the supporting structure “Ivanov’s vegetarian” has the most effective implementation and, thanks to the insulated opaque northern wall, enables to mount or attach the structure to any freestanding capital structure [16].

Modern cultivation facilities with a polycarbonate cover are complex agricultural facilities that require a certain amount of labor and time to grow tasty, healthy, and beautiful harvest of greens and vegetables. To achieve the expected result, it is required to comply with certain standards for the construction, specifically, from climate control to control of the ecological component of the crop. It is also necessary to take into account the direction of the prevailing winds on the ground during the construction of a cultivation structure since the movement of air significantly increases energy losses through the fences of the cultivation structure [15, 17].

3. Thermophysical model of flows in bio-vegetation complex caused by renewable energy sources

As already noted, the stage of a theoretical model development is considered to be the fundamental point in pre-project activities. Application of this model greatly facilitates the design calculation of such cultivation facilities. It was decided to use the heat balance equation of the bio-vegetation complex as the main model [3, 5, 17].

Figure 1 shows a diagram of energy flows and their interaction in a bio-vegetation complex.

The flows of heat energy circulating in and around the bio-vegetation complex are divided into flows by heat sources, as well as flows that usefully consume heat for heating and flows of heat losses. To ensure optimal thermal equilibrium in the cultivation structure, the heat currents in the right and left parts of the thermophysical model must be equal to each other. The basic model of the heat balance of the bio-vegetation complex is described by the following equation:

$$\boldsymbol{Q_s = \sum_{i=1}^{n} Q_{ef} + \sum_{j=1}^{n} Q_l} \quad (1)$$

where:

- Q_s is amount of heat emitted by sources of thermal energy, W;
- Q_{ef} is amount of heat spent on useful heating of the soil, subsoil accumulator, airspace of the bio-vegetation complex, W;
- Q_l is amount of heat lost in the bio-vegetation complex W.

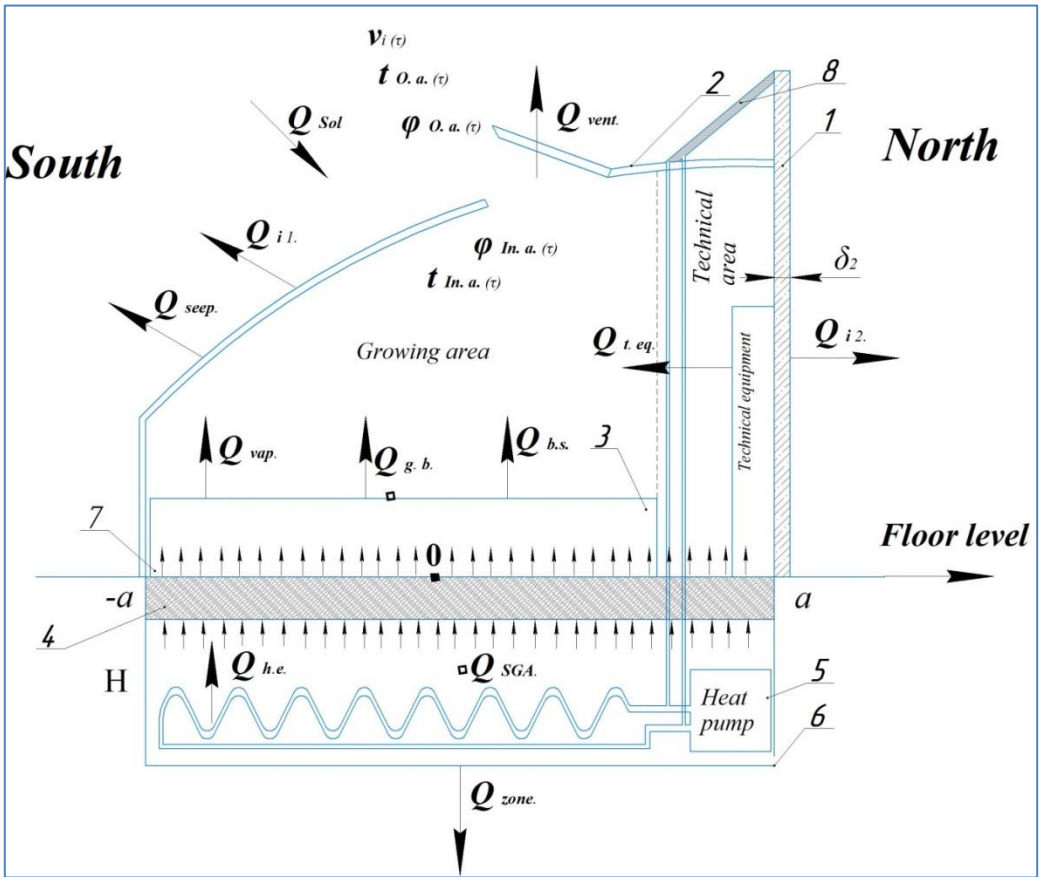

Figure 1. Scheme of energy (heat) flows in a bio-vegetation complex: 1 is insulated wall, 2 is light-transmitting covering material, 3 is soil bed array, 4 is concrete slab (element of a subsoil heat accumulator that receives heat energy by means of water heating circuits from a heat pump and solar collector), 5 is heating element (heat pump), 6 is thermal insulation from the outer soil layer, 7 is sand and gravel backfill (an element of a subsoil heat accumulator that receives heat energy through water heating circuits from a heat pump and a solar collector), 8 is solar collector

While considering each element of the thermophysical model (1) in great detail, there were identified thermal components being indicators that determine the amount of incoming and outgoing heat in the bio-vegetation complex, which can be considered the equation of heat fluxes.

$$Q^{i}_{SGA} + Q^{i}_{Sol} + Q^{i}_{t.eq} + Q^{i}_{vap} + Q^{i}_{b.s} = Q^{j}_{i} + Q^{j}_{vent} + Q^{j}_{seep} + Q^{j}_{acc} \quad (2)$$

where:

Q^{i}_{SGA} is the amount of heat from the subsoil accumulator, W;
Q^{i}_{Sol} is the amount of heat from solar radiation, W;
$Q^{i}_{t.eq}$ is the amount of heat from technological equipment, W
Q^{i}_{vap} is the amount of heat from moisture evaporation in soil, W
$Q^{i}_{b.s}$ is the amount of heat entering the air volume of the bio-vegetation complex from the soil surface in the beds and from the floor surface in the aisles, etc., W
Q^{j}_{i} is the amount of heat lost through the barriers, W
Q^{j}_{vent} is the amount of heat lost through ventilation, W
Q^{j}_{seep} is the amount of heat lost for infiltration through non-density structures, joints, cracks, etc., W;
Q^{j}_{acc} is the amount of heat used to heat the fittings of the beds, metal and walls, water for irrigation, etc., W.

Heat losses through fences are the main energy consumption in the heat balance. It is stipulated by the fact that due to the specificity of cultivation structures the covering material must have light transmitting properties, and this automatically affects the heat transfer coefficient of the material used and its thermal resistance [4]. The heat flux, which determines the losses through the barriers, is defined by the following expression:

$$\boldsymbol{Q_i^j = \sum_{i=1}^{m} k_i \cdot F_i \cdot (t_{in} - t_{out}) \cdot (1 + \beta_i)} \quad (3)$$

where:

k_i is heat transfer coefficient of the enclosure *i*, W/(m^2 °C);
F_i is area of the fence *i*, m^2;
t_{in} is indoor air temperature, °C;
t_{out} is outdoor air temperature, °C;
β_i is additional coefficient of heat loss by enclosing structures regarding land navigation and the nature of the prevailing winds.

In the bio-vegetation complex, a supply and exhaust automatic ventilation system is used. Heat loss is determined through it by the following expression:

$$\boldsymbol{Q_{vent}^j = 0,278 \cdot V \cdot \rho \cdot c \cdot (t_{in} - t_{out}) \cdot K} \quad (4)$$

where:

V is internal volume of the bio-vegetation complex, m^3;
p is outside air density at outside air temperature, kg/m^3;
c is specific isobaric heat capacity of air, kJ/(kg °C);
K is air exchange rate, 1/h.

In thermophysical calculations, several methods are used for accounting heat losses for infiltration, for example, a simplified method, in which 30% of losses occur through a fence, is used. In our opinion, these are significant heat losses in winter in such structures as a bio-vegetation complex. Therefore, this coefficient must be reduced with regard to all the factors affecting it. In our case, to estimate the losses for infiltration, an expression of the following form should be applied:

$$\boldsymbol{Q_{seep}^j = k \cdot F_{enc} \cdot (t_{in} - t_{out})} \quad (5)$$

where:

k is heat transfer coefficient, W/(m^2 °C);
F_{enc} is fencing area, m^2.

In the bio-vegetation complex, it is proposed to mount a soil heating and heat storage system in the form of a structure consisting of sand and gravel backfill and a concrete slab, with independent heating water circuits inside (Fig. 2). This design enables to implement a system of both heating the beds placed on the surface of a concrete slab (Fig. 3), and to use this structure as a thermal energy accumulator, which allows maintaining the technologically necessary temperature in the beds thickness in the cool time of the day and cold season, and surplus transfer to the air internal volume of the structure. The amount of heat entering the air volume of the bio-vegetation complex from the soil surface in the beds and the floor surface in the aisles is as follows:

$$\boldsymbol{Q_{b.s}^i = Q_{g.b} + Q_{accum.SGA} - Q_{area}} \quad (6)$$

where:

$Q_{g.b}$ is the amount of heat coming from the surface of the beds when they are heated by solar radiation, W;
$Q_{accum.SGA}$ is the amount of heat coming from the paths between the beds stored in the subsoil accumulator, W;
Q_{area} is the amount of heat lost through the soil zones that are in contact with the outer soil contour, W.

$$Q_{g.b} = \sum F_{g.b} \cdot \frac{\lambda_i}{\delta_i} \cdot (t_{2.g.b} - t_{1.g.b}) \quad (7)$$

where:

$F_{g.b}$	is	the area of the beds of a bio-vegetation complex, m^2;
λ_i	is	the thermal conductivity of soil massif of beds *i*, W/(m °C);
δ_i	is	the thickness of the soil backfill in the bed *i* of the complex, m;
$t_{1.g.b}$	is	bed surface temperature in the cultivation facility, °C;
$t_{2.g.b}$	is	surface temperature of the concrete slab, °C.

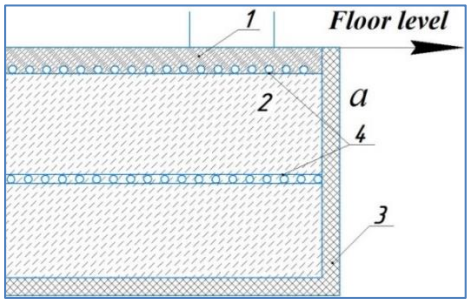

Figure 2. Scheme of subsoil heat accumulator:

1 is concrete slab, 2 is sand and gravel backfill, 3 is heat and hydro insulation from external soil, 4 is water heating circuits

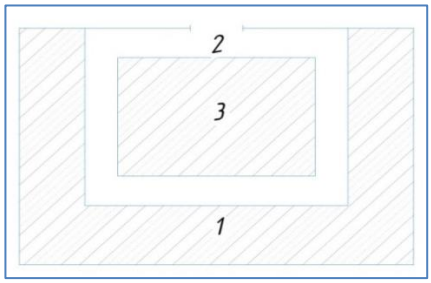

Figure 3. Layout of beds in bio-vegetation complex:

1 is a bed for low-growing crops, 2 is technological paths, aisles between the beds, 3 is a bed for tall crops

A subsoil accumulator is a set of elements being sand and gravel backfill and a concrete slab, in the thickness of which there are water heating circuits that receive heat energy from a heat pump and a solar collector (Fig. 2). This entire structure is supposed to be isolated from the layer of external soil by means of heat and waterproofing, which reduce the loss of heat energy outward and direct more heat into the cultivation structure. The heat from the heating water circuit is transferred to the sand and gravel backfill and the concrete slab (heat accumulator) and can be determined as follows:

$$Q_{SGA} = Q_{h.el} + (\sum F_i \cdot \frac{\lambda_i}{\delta_i}) \cdot (t_{SGA} - t_{out.gb}) \quad (8)$$

where:

$F_{h.el}$	is	surface area of sand and gravel backfill or concrete slab, m^2;
$Q_{h.el}$	is	heat flux from the heating water circuit, W;
λ_i	is	thermal conductivity of heat storage material of sand and gravel backfill or concrete slab, W/(m °C);
δ_i	is	thickness of sand and gravel backfill or concrete slab, m;
t_{SGA}	is	temperature of sand and gravel backfill and concrete slab, °C.

The amount of heat used to heat the fittings of the beds, wall metal, auxiliary devices, and water for irrigation. $\sum Q_{acc.}$ is found according to the formulas known from the theory of heat transfer for calculating convection heat transfer or heat transfer by thermal conductivity, and the surface temperature of the auxiliary devices is taken equal to the temperature of the heated material (soil, beds, irrigation water, etc.)

Having analyzed the right-hand side of the equation of the thermophysical model (1), it is necessary to estimate thermal energy inflow to ensure the maintenance of thermal equilibrium in the cultivation structure.

Let us consider the main sources that generate heat flows in an autonomous energy-efficient bio-vegetation complex.

The heat from the heat pump for the water heating circuits of the subsoil accumulator is consumed to maintain the optimal temperature regime in the soil and the air volume of the complex and it can be determined as follows:

$$\boldsymbol{Q_{h.p}^{i} = G_{h.w} \cdot c_{\text{p}}^{w} \cdot (t_d - t_b)} \quad (9)$$

where:

$G_{h.w.}$ is hot water consumption in the heating circuit, kg/s;
c_p^w is specific heat capacity of water, kJ/(kg °C);
t_d is direct water temperature in the water heating circuit system, °C;
t_b is return water temperature in the water heating circuit system, °C.

The amount of heat from the solar collector operating in parallel with the heat pump and also used for the water heating circuits of the subsoil accumulator is consumed to maintain the optimal temperature control in the soil and air volume of the complex and it can be determined as follows:

$$\boldsymbol{Q_{sol.col}^{i} = P_{max} \cdot F_{sol.col} \cdot sin\alpha} \quad (10)$$

where:

P_{max} is the average level of insolation at the geographical point at which the bio-vegetation complex is located in the cold season, W/m^2;
$F_{sol.col}$ is solar collector area, m^2;
$sin\ \alpha$ is angle of deviation of the solar collector plane from the south direction, °C

The main source of heat energy and light is the energy of solar radiation. The amount of heat in this case entering the bio-vegetation complex is as follows:

$$\boldsymbol{Q_{Sol}^{i} = 0,276 \cdot k_{c.m.} \cdot q_{c.m.} \cdot F_{c.m.}} \quad (11)$$

where:

$k_{c.m.}$ is coefficient depending on the type of the light-transmitting coating material
$q_{c.m.}$ is the amount of heat received from solar radiation through 1 m^2 of covering material, kJ/h
$F_{c.m.}$ is area of light-transmitting material, m^2

The amount of heat released inside the bio-vegetation complex from the operating technological equipment is as follows:

$$\boldsymbol{Q_{t.eq}^{i} = \sum P_e \cdot k_d \cdot (1 - k_{en} \cdot \eta + k_{\text{co}} \cdot k_{en} \cdot \eta) + (P_{l.} \cdot \eta)} \quad (12)$$

where:

$\sum P_e$ is total installed capacity of technical equipment in the bio-vegetation complex, W
$k_{d.}$ is coefficient of demand for electricity
k_{co} is coefficient of accounting for the completeness of the equipment load
k_{en} is coefficient of heat transfer to the growing area
η is equipment efficiency
$P_{l.}$ is lighting system power, W

The amount of heat entering the growing zone from moisture evaporating from the soil is determined by the following expression:

$$\boldsymbol{Q_{vap}^{i} = r_c \cdot \text{ŋ} \cdot B \cdot (C_{100}^{n} - \varphi_p \cdot C_{tp}^{n}) \cdot \frac{760}{P_b} \cdot F_{m.}} \quad (13)$$

where:

r_c is heat of evaporation, kW h/kg;

η	is	incompleteness coefficient of water content;
B	is	mass exchange coefficient, m/h;
C^{n}_{100}	is	vapor concentration at 100% saturation and soil surface temperature, kg/m^2;
φ_{p}	is	relative air humidity in the growing area,%;
C^{n}_{tp}	is	concentration of water vapor in the air in the growing zone at operating temperature, kg/m^3;
P_{b}	is	barometric pressure, mm Hg Art.
$F_{m.}$	is	surface of the moistened soil in the garden, m^2;

The bio-vegetation complex has a growing area in the form of separate beds (see Fig. 4) and a technical space. Polycarbonate is recommended for being used as a translucent covering material. The main bearing part of the complex should be installed with the use of bolted joints, which is necessary to increase the strength of the structure, and eliminate welding joints unsealing under snow and wind loads. The supporting structure is made of rolled metal with hot-dip galvanized structural elements increasing the service life of the supporting structure. The edges of load-bearing trusses are attached to the pile supports or to the surface of a concrete slab of a subsoil accumulator using anchor bolts. The foundation part is made of a concrete slab and sand and gravel backfill with water thermal circuits located inside these elements and equipped with devices for controlling and monitoring the state of the heat carrier. Thermal energy of solar radiation is generated by a solar collector located on the roof and transferred through water pipes to the water circuits of the subsoil accumulator. A heat pump is connected in parallel to the solar collectors [14]. Electrical energy is generated by flexible photovoltaic modules mounted on the enclosing structure of the bio-vegetation complex, directly on the surface of the covering material at an angle of inclination optimal for a specific geographic location to the incident sunlight. An electrical distribution cabinet with the appropriate electrical equipment is placed in the technological zone inside vegetation complex [2, 10, 11].

Having regarded the thermophysical model, chosen energy conservation equipment, evaluated heat flows and considered the rationale for the proposed design features of an autonomous bio-vegetation complex, its 3D model was developed.

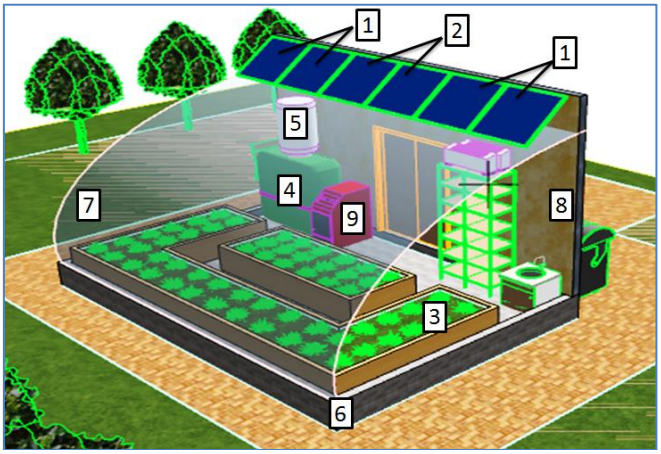

Figure 4. 3D model of technological equipment placement in bio-vegetation complex: 1 is solar photovoltaic modules, 2 is solar collector, 3 is beds, 4 is water tank, 5 is storage tank for storing thermal energy in water from a heat pump and solar collector, 6 is heat storage concrete slab with a subsoil heat accumulator, 7 is light-transmitting shell made of cellular polycarbonate, 8 is northern insulated wall, 9 is heat pump

Designing an autonomous bio-vegetation complex of small dimensions allows ensuring food security of various segments of the population in different climatic zones of the country. The autonomy of the structure and energy-saving technologies enable to operate the bio-vegetation complex all year round without being connected to an external power system. All this is achieved due to the rational distribution of energy flows in the complex, reasonable use of thermal and electrical

energy sources operating on renewable energy, and enables to effectively operate the facility all the year round without serious additional financial costs for energy supply in the cold season [13].

4. Conclusion

The presented thermophysical model is made in the form of a thermal balance of interacting heat fluxes both inside the bio-vegetation complex and outside it. Using the proposed model, it is possible to perform both a simplified and a more detailed heat engineering calculation for assessing the sources of thermal energy, choosing the materials used in the construction of a complex of materials and substantiating its optimal design. The autonomy of the complex does not require the use of energy sources associated with the central power supply, but is provided by the energy generated by renewable local energy carriers.

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References

[1**]**→ Yudaev I V, Popov M Yu and Popova R V 2020 Autonomous greenhouse operating on renewable energy resources *Bulletin of agrarian science don.* **1 (49)** 30-37
[2]→ Hassanien R, Hassanien E, Li M et al. 2016 Advanced applications of solar energy in agricultural greenhouses *Renewable and Sustainable Energy Reviews* **54** 989–1001
[3]→ Taki M, Rohani A and Rahmati-Joneidabad M 2018 Solar thermal simulation and applications in Greenhouse *Information processing in agriculture* **5** 83–113
[4]→ Sengar S H 2008 Thermal modeling and performance evaluation of arch shape greenhouse for nursery raising. *African Journal of Mathematics and Computer Science Research* **1(1)** 001-009
[5]→ Khalid A J and Farhan A A 2015 A dynamic model and an experimental study for the internal air and soil temperatures in an innovative greenhouse *Energy Conversion and Management* **91** 76–82
[6]→ Wang T, Wu G, Chen J et al. 2017 Integration of solar technology to modern greenhouse in China: Current status, challenges and prospect *Renewable and Sustainable Energy Reviews* **70** 1178-1188
[7]→ Patil R and Gawande R 2016 A review on solar tunnel greenhouse drying system *Renewable and Sustainable Energy Reviews* **56** 196-214
[8]→Yudaev I V 2016 Study of the light transmission properties of cellular polycarbonate - a covering material for year-round greenhouses *Scientific journal KubSAU* **120 (06)** 239-252
[9]→ Yanfei C, Haiwei J, Shumei Z et al. 2017 Optimization of roof projection width and wall height of solar greenhouse *Transactions of the Chinese Society of Agricultural Engineering* **7** 183-189
[10]→ Cossu M, Murgia L, Ledda L et al. 2014 Solar radiation distribution inside a greenhouse with south-oriented photovoltaic roofs and effects on crop productivity *Applied Energy* **133** 89-100
[11]→ Gao Y, Dong J, Isabella O et al. 2019 Modeling and analyses of energy performances of photovoltaic greenhouses with sun-tracking functionality *Applied Energy* **233-234** 424-422
[12]→ Kurpaska S 2014 Energy effects during using the glass with different properties in a heated greenhouse *Technical Sciences* **17(4)** 351–360
[13]→ Daus Y V, Pavlov K A, Yudaev I V et al. 2019 Increasing Solar Radiation Flux on the Surface of Flat-Plate Solar Power Plants in Kamchatka Krai Conditions *Applied Solar Energy (English translation of Geliotekhnika)* **55 (2)** 101-105.
[14]→ Kharchenko V, Sychov A, De Angelis P L et al. 2020 Monitoring System of a Heat Pump Installation for Heating a Rural House Using Low-grade Heat from a Surface Watercourse *Sensor and Actuator Networks* **9 (1)** 11-27
[15]→ Vardiashvili A B 1990 *Heat exchange and hydrodynamics in combined solar of greenhouse with substrate and heat accumulation* (Tashkent: Fan)
[16]→ Zhang X, Wang H, Zou Z et al. 2016 CFD and weighted entropy based simulation and optimization of Chinese Solar Greenhouse temperature distribution *Biosystems engineering* **142** 12-26

[17]→ Klimov V V 1992 *Equipment of greenhouse for subsidiary and personal farms* (Energoatomizdat)
[18]→ Uzakov G N and Davlonov K A 2018 Modeling of the heat and moisture balance of the hello-greenhouse with pyrolysis heating installation and the heat energy utilization *European science review* **12** 262-267