Environmental aspects of subsurface irrigation and development of a mathematical model of a double-circuit solar heating system

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Abstract. This article discusses the method of subsurface irrigation of agricultural crops. A technological system for subsoil irrigation has been developed using an industrial base for the production of perforated polyethylene pipes of small diameter. In the first moments of water supply for irrigation, when the soil has low initial moisture, the flow through the perforations is maximum. This leads to an intensive increase in the humidification circuit. As the water flow stabilizes, the increase in the size of the circuit in the horizontal and vertical directions practically stops, and further deformation of the humidification circuit occurs mainly due to gravitational forces. When the hydrostatic head at the entrance to the subsurface irrigation system increases above 70 cm, the spread of moisture in the soil in the horizontal and vertical directions increases slightly, but this can lead to the danger of soil destruction and water wedging out on the soil surface. A mathematical model of thermohydraulic processes in a thermosiphon system designed for watering the cultivation layer in solar greenhouses during the cold season according to the subsoil irrigation scheme has been developed. The dynamics equations of all functional blocks were taken into account in accordance with the accepted assumptions.

1 Introduction

One of the promising areas of water reclamation is subsoil irrigation of agricultural crops, which has a number of advantages compared to traditional methods of watering plants:

- the possibility of creating effective systems that allow the implementation of optimal air, heat, humidity and nutritional regimes, ensuring the achievement of high yields;
- a significant reduction in the amount of irrigation water due to reduced evaporation into the atmosphere;
- complete mechanization of the water supply process, weakening of the requirements for the planning of the surface layer of soil;

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- the possibility of water circulation in the irrigation system without the use of external energy sources;
- -uniform distribution of moisture in the root layer;
- combining irrigation and soil heating at low ambient temperatures;
- reduction in the growing season of plant development, reduction in the number of weeds.

The main disadvantages of subsurface irrigation systems are the relatively high cost of their construction and the poor development of the industrial base for the production of perforated polyethylene pipes of small diameter.

The mechanism of moisture distribution in the soil can be represented as follows.

The movement of water in a capillary-porous medium is carried out due to hydrostatic pressure, gravitational forces and capillary pressure. When liquid enters through a hole in a perforated pipeline, a humidification circuit is created around it, limited by a capillary border. Directly adjacent to the perforation zone is an area of complete soil saturation. Under the influence of moisture gradients, water in the soil spreads in vertical and horizontal directions.

In the first moments of water supply for irrigation, when the soil has low initial moisture, the flow through the perforations is maximum. This leads to an intensive increase in the humidification circuit. As the water flow stabilizes, the increase in the size of the circuit in the horizontal and vertical directions practically stops, and further deformation of the humidification circuit occurs mainly due to gravitational forces. The bulk of the liquid moves downwards.

When the hydrostatic head at the entrance to the subsurface irrigation system increases above 70 cm, the spread of moisture in the soil in the horizontal and vertical directions increases slightly (about 5÷7 cm), but this can lead to the danger of soil destruction and water wedging out on the soil surface.

2 Materials and methods

When developing a technological scheme for subsurface irrigation in greenhouses intended for growing vegetable crops, irrigation systems based on existing and standard methods of subsurface irrigation were used. The technological scheme of double-circuit solar heat supply was designed in order to provide subsoil moisture, humidifiers, the depth of their immersion in the soil and the levels of hydrostatic water pressure at the entrance to perforated pipelines. A mathematical model of a combined thermosyphon system has been developed taking into account the dynamics equations of all functional blocks in accordance with accepted assumptions. When developing the technological scheme, information software was used.

3 Results and discussion

From the research of the authors from Uzbekistan it is known that the range of active moisture in the soil is in the range from 0.6 HB to 0.8 HB depending on the mechanical composition of the soil [1,4,7-9].

In contrast to furrow irrigation, with subsurface irrigation it is possible to almost continuously maintain the soil moisture regime, which provides optimal conditions for the biological development of plants. It should also be noted that if the required irrigation norm is exceeded, the moisture contour may close with groundwater.

An important circumstance for low-pressure subsurface irrigation is that with proper reclamation, the top layer of soil 5-7 cm thick is usually not wetted. This leads to the fact that a crust does not form on the surface, conditions for the development of weeds worsen, there is no need for loosening after irrigation and air exchange inside the cultural layer improves, which has a beneficial effect on the growth of agricultural crops.

Currently, a number of industrial subsoil irrigation systems have been created that are successfully operated in various regions of the country for the cultivation of grain and vegetable crops, and cotton. As a rule, in these systems, irrigation water is distributed through perforated polyethylene pipes laid at a certain depth in the soil. For this purpose, ceramic pipes are sometimes used, the use of which allows solving two problems at once - watering and, if necessary, heating the soil in the cold season. The diameters of the polyethylene pipes used are in the range of 20 ÷ 40 mm. The diameters of the perforation holes are 0.5÷2÷2.5 mm, the perforation pitch in almost all systems is 250 mm.

There are many studies and proposals for improving the elements of furrow irrigation technology with the introduction of water-saving irrigation technologies and the development of rational elements. [1,4,7-9]

When creating subsurface irrigation systems, the choice of the pitch between the humidifiers, the depth of their immersion in the soil and the levels of hydrostatic water pressure at the entrance to the perforated pipelines is very critical. The distance between the pipes primarily depends on the formation of humidification contours near the perforation holes. The determining factors in determining the step for laying humidifiers are also the specific cost of funds for the construction of an irrigation system, the cost of water for irrigation and the yield of cultivated plants.

In the practice of constructing subsurface irrigation systems, the distance between humidifier pipes is I ÷ 1.5 m. The introduction of special anti-filtration screens makes it possible to increase the laying step to 5 meters. The location of the pipes also depends on the soil structure. For example, for clayey floodplain soils the maximum distance is 0.5 m, since when it increases, part of the space between the perforated pipes will not be moistened.

The depth of humidifiers is usually 0.2÷0.5 m. If the pipes are located less deeply, mechanical tillage becomes more difficult due to the possibility of damage to the irrigation system.

The hydrostatic water pressure at the entrance to the irrigation system for various subsurface irrigation schemes usually does not exceed 0.2÷0.7 m. As already indicated, exceeding this level is undesirable due to liquid seepage onto the soil surface. These recommendations were obtained experimentally and are valid only for the studied structures of the cultivation layer.

The economic efficiency of using subsoil irrigation is quite high.

With subsurface irrigation, an important task is to establish a rational irrigation regime that eliminates water loss due to filtration. Watering must be stopped as soon as the moisture contour under the influence of gravity is significantly extended downwards and water losses are observed in the deep layers of soil [2,3,5,6,10].

Grigorov M.S. found that the use of subsoil irrigation gives an increase in yield in the following volumes compared to conventional furrow irrigation: corn - 297%, tomatoes - 44%, carrots 132%. With this irrigation method, the soybean yield increases by 1.7 times, and the potato yield by 41.1 c/ha [6].

Great prospects open up when using subsoil irrigation in greenhouses intended for growing vegetable crops. For example, in Dagestan, with different irrigation methods, but with the same specific water consumption, the yield of tomatoes with subsoil irrigation was 1.5–2 times higher than with surface irrigation. At the same time, the period of ripening of vegetables decreased by 7 days.

In the conditions of Central Asia, in particular in Uzbekistan, where the greenhouse industry is intensively developing, operating mainly in the cold and winter seasons, one of the pressing problems is ensuring the irrigation of vegetable crops with warm water (293÷298 K).

Not all places have stationary heating plants, and the creation of individual thermal power units in each household is economically unprofitable. At the same time, this region of the country has accumulated extensive experience in using solar energy for heat supply purposes. Therefore, heating of irrigation water can be organized not only using traditional energy sources, but also through the use of solar power plants.

For medium-sized greenhouses with an area of up to 500 m^2, solar heating systems operating on the thermosyphon principle are economically effective. Trouble-free operation of such installations at sub-zero ambient temperatures can be ensured by the use of antifreeze in the primary circuit of the solar system and the location of the irrigation water tank (secondary circuit) directly in the greenhouse.

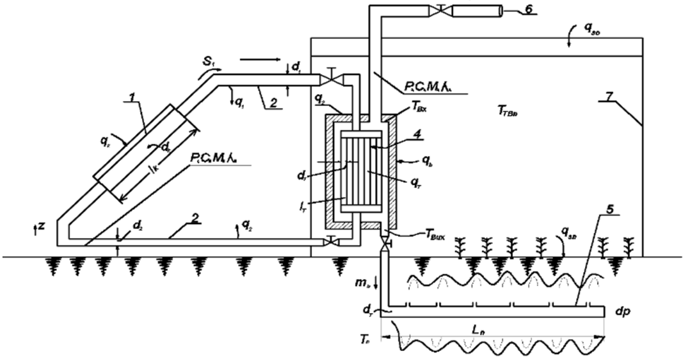
One of the most important advantages of such a heat supply system is that it is completely passive and does not require electrical energy to ensure circulation in the solar system circuits: in the primary circuit the liquid moves due to the difference in coolant densities, and in the secondary circuit due to capillary suction of the soil This significantly increases the efficiency of the installation and facilitates the operation of the system as a whole [11-14].

With subsurface irrigation, an important task is to establish a rational irrigation regime that eliminates water loss due to filtration. Watering must be stopped as soon as the moisture contour under the influence of gravity is significantly extended downwards and water losses are observed in the deep layers of soil [2, 3].

Let's consider a mathematical model of thermohydraulic processes in a thermosiphon system designed for watering the cultivation layer in solar greenhouses during the cold season according to the subsoil irrigation scheme.

The schematic diagram of the developed system is shown in Figure 1. The irrigation heat supply system consists of two circuits - an external one, filled with antifreeze, and an internal one, in which water for irrigation is circulated. The presence of an external circuit with antifreeze makes it possible to operate the installation at significant sub-zero ambient temperatures.

The thermosyphon accumulator tank in the upper part is constantly fed with tap water having a temperature of 283-287 K.



1-Solar collector, 2-connecting pipes, 3-accumulator tank, 4-heat exchanger, 5-perforated pipe, 6-feed pipe, 7-greenhouse fence. 2.2, a – raising and lowering pipelines of the external circuit of the thermosiphon. 4 – storage tank with water located inside the solar greenhouse, 5 – heat exchanger inside the battery tank, 6 – perforated pipeline for subsoil irrigation, 6 – feeding pipeline.

Fig. 1. Scheme of a double-circuit thermosiphon solar installation for heating water for subsurface irrigation.

Due to heat transfer from the internal heat exchanger, the water in the tank is heated to the temperature required for irrigation and enters the polyethylene pipelines for subsurface irrigation. The liquid, moving in the soil due to seepage, moisturizes it and provides the necessary conditions for the development of plants cultivated in the solar greenhouse.

The developed thermosyphon system for subsoil irrigation consists of the following functional blocks.

The environmental parameters inside the solar greenhouse, where the battery tank and heat exchanger are located, are considered known.

When developing a mathematical model of a combined thermosyphon system, the dynamics equations of all functional blocks were taken into account in accordance with the accepted assumptions, the main ones of which can be formulated as follows.

1. The movement of the coolant in the collector and pipelines of the external circuit is laminar.
2. The equation of motion of antifreeze is considered in the Boussinesq approximation.
3. The unevenness of the temperature field in the collector plate is not taken into account
4. The movement of water in the tank - battery - one-dimensional
5. The temperature field in the wall of the tank - battery is not considered
6. Air parameters in the solar greenhouse are considered known

In accordance with the accepted assumptions, we write down the dynamics equations for the solar system under consideration.

Energy equations for thermosyphon elements.

1. The equation for the energy of fluid moving in the reservoir has the following form:

$$\frac{\partial T_{\text{к}}}{\partial \tau} + W_{\text{к}} \frac{\partial T_{\text{к}}}{\partial s} = \frac{4 q_{\text{к}}}{q_1 c_1 d_{\text{к}}} \tag{1}$$

2. The equation of fluid energy in the rising and falling pipelines can be written in the following form:

$$\frac{\partial T_1}{\partial \tau} + W_1 \frac{\partial T_1}{\partial s} = -\frac{4q_1}{q_1 c_1 d_1}$$

$$\frac{\partial T_2}{\partial \tau} + W_2 \frac{\partial T_2}{\partial s} = -\frac{4q_2}{q_1 c_1 d_2}$$

3. The fluid energy equation in the heat exchanger has the form:

$$\frac{\partial T_m}{\partial \tau} + W_1 \frac{\partial T_m}{\partial z} = -\frac{4q_m}{q_1 c_1 d_m} \tag{2}$$

4. Energy equation for water in a storage tank:

$$\frac{\partial T_{\text{б}}}{\partial \tau} + W_1 \frac{\partial T_{\text{б}}}{\partial z} = a_2 \frac{\partial^2 T_{\text{б}}}{\partial z^2} + \frac{1}{q_2 c_2 F_{\text{б}}} (\pi m_m d_m q_m + \pi_{\text{б}} q_{\text{б}}) \tag{3}$$

We consider the process of water movement in a perforated pipeline to be isothermal.

Let us write down the equation of motion of coolants in the elements of the solar system:

1. Equation of movement of antifreeze in the external circuit of the heating system.

In accordance with [11], we write the equation of motion of a closed external contour as follows:

$$\rho_1 \frac{\partial W_\kappa}{\partial \tau}\left[l_k + l_1 \frac{m_k f_k}{f_1} + l_2 \frac{m_k f_k}{f_2} + l_m \frac{m_k f_k}{f_t m_t} \right] =$$
$$= \varnothing\, q_1 q \beta_1 \left(T - T_0\right) d\cancel{z} * - \frac{q_1 W_k^2}{2}\left[\left(\xi_k \frac{l_k}{d_k} + K_k\right) + \frac{m_k^2 f_k^2}{f_1^2}.\right.$$
$$\left.\left(\zeta \frac{l_1}{d_1} + K_1\right) + \frac{m_k^2 f_k^2}{f_k^2}\left(\xi_2 \frac{l_2}{d_2} + K_2\right) + \frac{m_k^2 f_k^2}{f_t^2 m_t^2}\left(\xi_t \frac{l_t}{d_t} + K_t\right)\right] \quad (4)$$

2. Equation for make-up pipeline.

With isothermal movement of water in the make-up pipeline, we can write:

$$m_g = m_n \quad (5)$$

3. Equation of fluid motion in a perforated pipeline.

Water consumption for subsoil irrigation can be determined by the dependence:

$$m_n = \varphi(H_0 T_n \tau, \text{soil properties}) \quad (6)$$

Finding a specific type of relationship (8) presents the greatest difficulties in the problem under consideration, since the flow rate depends on a number of interrelated parameters: initial soil moisture, its mechanical characteristics, diffusion and thermal diffusion coefficients, etc.

4. Equation of water movement in a tank-battery.

Using the balance equations for the battery tank, we can write:

$$m_b = m_n \quad (7)$$

According to the statement of the problem, we set boundary and boundary conditions.

Boundary conditions:

1. Forming the initial conditions of the problem

Temperature initial conditions are formed as follows:

$$T_1 = T_2 = T_k = T_{10} \quad (8)$$
$$T_b = T = T_0{}^* = T_{20} \quad (9)$$

Condition (11) assumes that at the initial moment of time the temperature of the antifreeze in the heat exchanger is equal to the temperature of the water in the tank - accumulator, and in the entire volume of the tank a temperature is established that coincides with the ambient temperature, i.e. with the average temperature of the cultivation facility $T_0 *$.

2. Let us assign boundary conditions

Boundary conditions in the elements of the thermosyphon and storage tank are assigned based on the conditions of constant mass flow rates of coolants:

$$W_1(\tau) = W_\kappa(\tau)\frac{m_\kappa f_\kappa}{f_1} \qquad W_2(\tau) = W_\kappa(\tau)\frac{m_\kappa f_\kappa}{f_2}$$
$$W_m(\tau) = W_\kappa(\tau)\frac{m_\kappa f_\kappa}{m_m f_m} \qquad W_b(\tau) = U_n(\tau)\frac{f_{nm}}{F_B} \quad (10)$$

Where FБ - normal cross-sectional area of the tank minus the area occupied by the heat exchanger tubes, fпт - cross-sectional area of perforated pipelines.

The boundary conditions for temperature can be written as follows

$$T_{\kappa 1} = T_{22} T_{\kappa 2} = T_{11} T_{12} = T_{m1} T_{m2} = T_{21}$$
$$T_g = T_{31} = T_{B1} T_{B2} = T_n \quad (11)$$

To implement numerical solutions, it is necessary to specify the initial data and closing relations:

Physical properties $(\mathrm{C}, \rho, \mu, \beta)$ water and antifreeze depending on temperature

1. Physical properties of water and antifreeze depending on temperature.

2. Geometric characteristics of system elements.
3. Coefficients of hydraulic resistance of thermosiphon circuit elements.
4. Heat transfer coefficients for determining heat flows q_1, q_2, q_m and q_B.
5. Dependencies for calculation q_κ
6. Irrigation water consumption depending on the physical properties of the soil, its initial moisture content, hydrostatic pressure H_0 and geometric characteristics of the humidifier.

4 Conclusions

The developed subsurface irrigation system uses and combines technological elements of drip and subsurface irrigation. For medium-sized greenhouses with an area of up to 500 m^2, solar heating systems operating on the thermosyphon principle are economically effective. One of the most important advantages of such a heat supply system is that it is completely passive and does not require electrical energy to ensure circulation in the solar system circuits: in the primary circuit the liquid moves due to the difference in coolant densities, and in the secondary circuit due to capillary suction of the soil. This significantly increases the efficiency of the installation and facilitates the operation of the system as a whole.

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