EXPERIMENTAL STUDY OF A PILOT UNIT OF A GROUND REGENERATOR FOR GREENHOUSES

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ABSTRACT

The object of research: the process of heat exchange in a packing in the form of a dense layer of crushed stone as part of a thermal regenerator designed to utilize the low-grade heat of the air in a greenhouse.

Investigated problem: increasing the efficiency of air heat accumulation in the greenhouse during the daytime by a regenerative heat exchanger with a granular packing. Conducting experimental tests of regenerator models with a packing in the form of a dense layer of granular material under natural conditions is necessary to improve the design and optimize technological parameters.

The main scientific results: the analysis of temperature curves of air changes at the inlet and outlet of the regenerator installed in the mock-up greenhouse with a volume of 0.25 m^3, and the packing material was carried out. During the heating period of the nozzle, the accumulated heat was Q=8·104 J, which can be used when the temperature in the greenhouse decreases. During the pause, the loss from the heat exchange channel to the environment is 48,000 J. The duration of the period was 358 min, while the average heat flux corresponded to 2.2 W. Heat losses during the pause period are significant due to its duration, however, the average heat transfer coefficient has a low value of k=2.3 W/m^2K, so strengthening the insulation of the heat exchange channel is irrational.

The area of practical use of the results of the study: greenhouses, allowing the possibility of installing additional heat exchange equipment.

Innovative technological product: the innovativeness of the technical solution is determined by the possibility of using the heat of the air in the greenhouse and the implementation of contact heat exchange between the air flow and the packing particles. The design of the regenerator, the simplicity of its manufacture and operation, as well as the efficiency of air heat accumulation in the greenhouse during the daytime, allow to recommend it for use in greenhouse farms.

The scope of the innovative technological product: regenerative heat exchangers with a dense layer of granular material for the utilization of low-grade air flows generated in food production enterprises, ventilation systems and greenhouses.

1. Introduction

1. 1. The object of research

The process of heat exchange in a packing in the form of a dense layer of crushed stone as part of a thermal regenerator designed to utilize the low-grade heat of the air in the greenhouse.

1. 2. Problem description

The use of solar energy batteries for heating greenhouses proves to be promising [1, 2]. Of interest are regenerators, where a dense layer of granular (loose) materials is used as an accumulating body [3]. The intensity of heat transfer increases significantly due to the developed heat transfer surface, which is the total surface of all particles in the apparatus [4]. Similar regenerators can be used to maintain the required temperature level in greenhouses [5]. The average temperature in a greenhouse should be between +16 and +25 degrees, and at night it should fall by no more than 5–8 degrees. It is known that the air in greenhouses in the spring in regions with a temperate climate in the daytime is intensely heated by solar radiation, and at night it is significantly cooled due to temperature differences. This determines the rationality of developing a regenerator capable of accumulating heat during the day and using it to heat the internal volume of the greenhouse at night. The relevance of the work is determined by the need to save energy resources for heating greenhouses and maintaining the required temperature conditions.

The study of three methods of heating greenhouses: using heating pipes on the ground, using air heaters and combined based on them are given in [6]. It was found that the use of these methods require large amounts of energy to heat the air in the greenhouse at night. To reduce energy costs, it is proposed to use a system of solar collectors [7]. Studies have shown that the corresponding modernization of traditional greenhouses can save up to 70 % of energy. The paper [8] presents the results of an experimental study of the heat balance of a greenhouse without heating in a hot and arid climate. It has been shown that greenhouse soil is an important source of heat at night and can provide up to about 44.03 W/m^2. Compared to an artificial heating system that requires approximately 78 W/m^2, this heat source will be sufficient to keep the greenhouse air temperature between 15 °C and 18 °C. It has been established that the use of dense layers of granular material has the main advantage in low-potential energy storage systems [9]. As an energy accumulator, it is advisable to use granulated natural and ceramic materials, the effectiveness of which was experimentally studied by the authors of [10] in relation to concentrating solar power plants. It has been established that ceramic materials have some technological advantages, but natural materials are much cheaper. Thermal energy storage systems are the central elements of various types of devices in the thermal power industry [11]. The authors of [11] consider a device for accumulating solar energy, which is a tank filled with a granular layer through which a liquid coolant circulates. However, in such devices, the tank may be subject to an accumulation of thermal stresses during the heating and cooling cycles due to different thermal expansion of the storage material and the tank itself. In [12], the general characteristics of bulk materials and their behavior under static and dynamic conditions are discussed, and the influence of porosity and bulk density of solid particles on the main thermal characteristics is studied. However, in general, the work is devoted to the study of the characteristics of particles in their motion. Due to the multifactor nature of the heat transfer process in regenerators, especially taking into account the significant non-stationarity of the transfer phenomena, special attention should be paid to experimental studies [13]. Additional knowledge is needed about the design features of a soil regenerator, taking into account the heat exchange between the gas flow and solid particles [14]. Particular attention should be paid to the choice of granular material. When conducting research, it is required to establish the influence of the determining parameters on the efficiency of devices, in particular, regenerative-type heat exchangers. A similar work was carried out by the authors of [15], where the influence of various parameters of stationary impulse regenerative heat exchangers used for ventilation on their thermal efficiency was studied. Geometric (length, diameter and wall thickness of one equivalent nozzle channel), thermophysical (density and heat capacity of the material) and operational (air flow through the regenerator and the time of one stage of accumulation/regeneration of thermal energy) energy) parameters are taken into account.

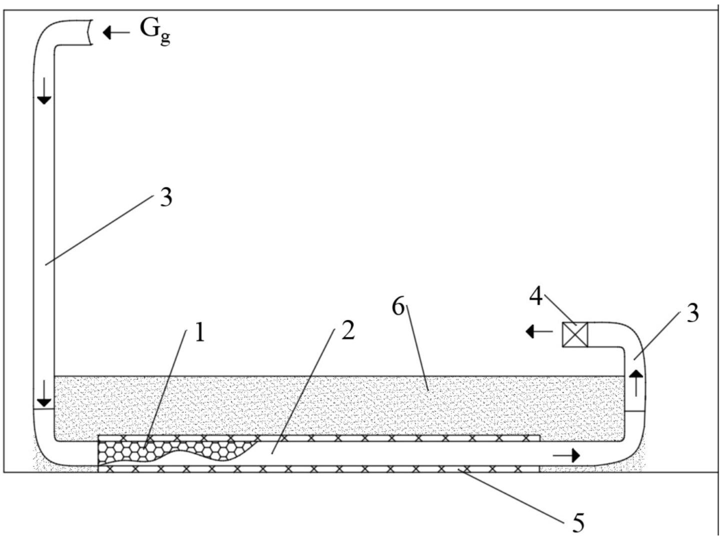
1. 3. Suggested solution to the problem

Studies of heat transfer processes in regenerative heat exchangers with a dense layer of granular material are designed to create cost-effective and technically rational heat exchange devices to maintain the required temperature level in greenhouses.

The aim of research is to determine the efficiency of the pilot unit of a soil regenerator during the day based on the analysis of changes in air temperatures at the inlet, outlet and particle temperatures in various sections along the length of the channel.

2. Materials and Methods

The idea of creating a soil regenerator is based on information about the intensity of air heating in a greenhouse from solar radiation during the daytime and the efficiency of contact heat exchange between air and a layer of particles. The circuit design assumes air intake from the top of the greenhouse, which ensures the supply of air flow to the channel at maximum temperature. At the same time, during the heating period of the nozzle, both the heating of the crushed stone in the channel and the decrease in the air temperature in the greenhouse are carried out, which protects the plants from overheating. The layout of the soil regenerator in the greenhouse is shown in **Fig. 1** [5].



a

b

Fig. 1. Soil regenerator for greenhouses. a – layout of the soil regenerator in the greenhouse: 1 – granular material, 2 – heat exchange channel, 3 – air duct, 4 – exhaust fan, 5 – insulation, 6 – soil in the greenhouse, b – photo of the installation of the pilot unit

During the heating period, the air through the air duct 3 is blown by the fan 4 into the heat exchange channel 2 with granular material 1, heating it. To reduce heat losses, the heat exchange channel is covered with insulation 5. The heat exchange channel is located under the soil of the greenhouse 6. During the cooling period, heat from the heated granular material is transferred to the air passing through the channel. The heated air enters the internal volume of the greenhouse, heating it.

The heat exchange channel and the air channels of the ground regenerator are made of circular channels Vents d100/0.5. Gravel, fraction 40–60 mm, was used as a granular packing.

For thermal insulation of the heat exchange section during the pause period, an automatic damper d-100 mm was used. The air circulation in the channels was provided by a Domovent VKO 100 fan. The air and particle temperatures were measured with TemPer 2.0

thermocouples. The thermocouple data were received on a computer and converted in the TemPer V-27 software product. The intensity of solar radiation was determined with a TAB8131 Lux Meter. The heat exchange channel was covered with an insulating material: milled rubber 12 mm thick. As a cover for the greenhouse, a film for greenhouses was used, which was fixed on metal rods.

The scheme of the heat exchange channel with areas for the placement of thermocouples is shown in **Fig. 2.** The total length of the heat exchange channel with a crushed stone packing was 1 m. To measure the temperature of the particles, 5 thermocouples (numbers 3, 4, 5, 6, 7) were installed, the distance between them was 20 cm. The thermocouples were laid in such a way that the sensitive element of the thermocouple was in direct contact with the particle. The first thermocouple was located at a distance of 10 cm from the entrance to the channel, the last one, at a distance of 10 cm from the exit. The air temperature at the inlet was measured by thermocouple 1 installed at the inlet to the air duct of the regenerator, and the air temperature at the outlet was measured by thermocouple 2 installed at the outlet of the air duct. Thermocouple 8 was used to determine the ambient temperature. Data from thermocouples were recorded at 3 s intervals.

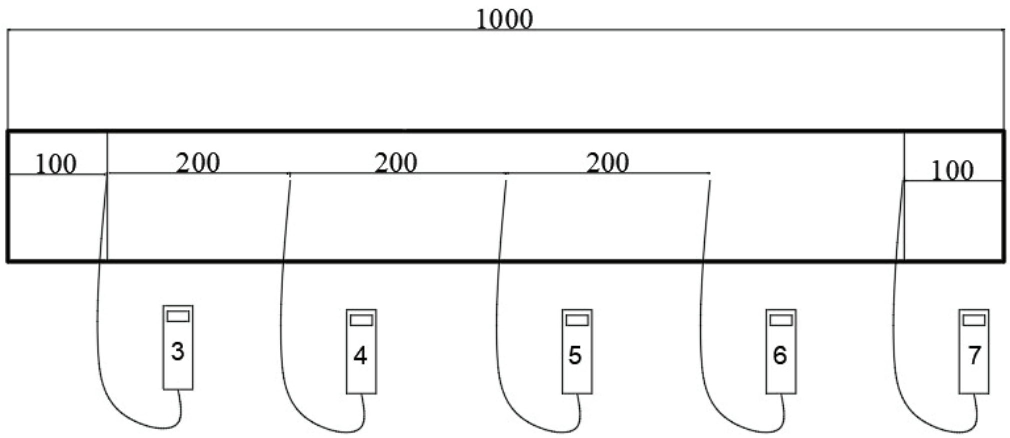


Fig. 2. Layout of thermocouples along the length of the heat exchange channel

After reaching the set temperature in the greenhouse, the fan was turned on and the heating of the crushed stone in the nozzle began. The regenerator heating stage continued until the packing temperature stabilization mode was reached. Then the shutters were automatically closed and a pause period began, which lasted until the set temperature in the greenhouse was reached. After that, the dampers opened and the fan turned on.

3. Results

The results of temperature measurements are shown in **Fig. 3.** Measurements started at 9 am (zero mark on the graph) and continued until 5 am the next day. The operation of the regenerator was divided into the following periods. During period I, the fan was switched off and the granular packing did not heat up. The air temperature in the greenhouse increased to the set value (38 °C). At the beginning of period II, the fan was turned on, the air from the upper part of the greenhouse was driven through the nozzle, heating it. In period III, the fan was turned off, the dampers were closed. In period IV, the fan worked, driving air through the nozzle. The range of variation of the intensity I of solar radiation in accordance with the indicated periods was as follows: I: I=314.78–915.08 W/m^2, II: I=915.08–805.271 W/m^2, III: I=805.271–789, 17 W/m^2, IV: I=789.17–0 W/m^2.

Fig. 3 shows the curves of changes in the temperature of particles of granular material over time along the length of the heat exchange channel, the air temperatures at the inlet to the channel and at the outlet from it, and the air temperature outside the greenhouse.

An analysis of the temperature curves shows the following. Curve 3 (the temperature of the particles closest to the inlet) is located below curve 4, which characterizes the change in temperature at a distance of 20 cm relative to thermocouple 3 (**Fig. 2**) in the direction of the air flow. Curve 5 is located below thermocouple 4, which correctly characterizes the process of heat accumulation by particles in the direction of the warm air flow. Temperature curve 6 is also below curve 5. Thus, curves 5, 6, 6 logically correctly reflect the process of successive accumulation of heat by layers of granular material. However, curve 7 at the outlet of the heat exchange channel is located above curves 5 and 6. An analysis of the temperature curves allows to conclude that the thermocouples mounted on the particles reflect the change in temperatures in different heat exchange zones according to the heat exchange conditions. Probably, thermocouples 3, 5, and 6 fell into stagnant airflow zones, while thermocouples 4 and 7 were located in the zone of intense convective heat exchange between particles and air. Thus, the contribution of various components of heat transfer – thermal conductivity and convection – was observed. Therefore, for a better analysis of the operation of the regenerator, it is advisable to average the data on the readings of thermocouples installed on the particles. **Fig. 4** shows a plot of air inlet, outlet and average particle temperatures.

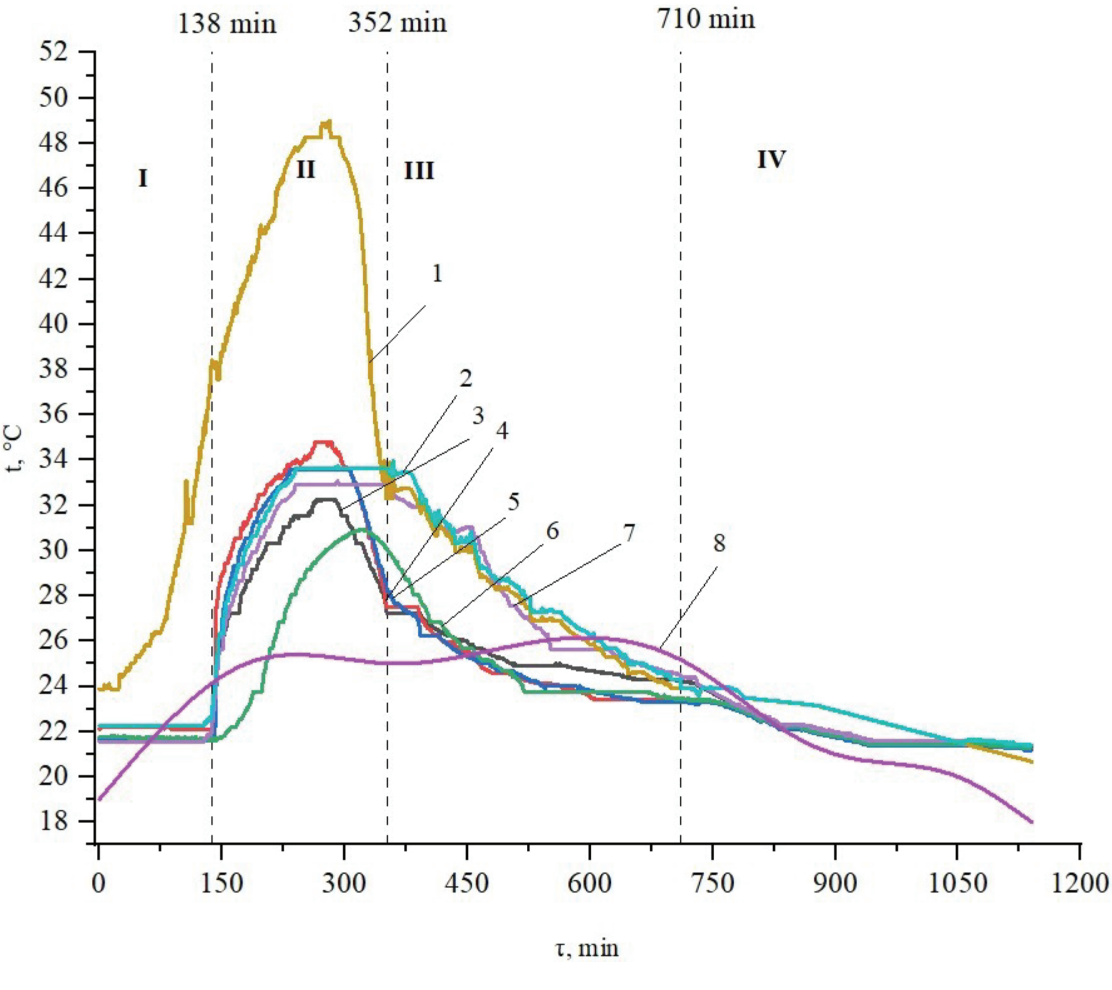


Fig. 3. Curves of temperature changes in time. 1 – air temperature at the inlet to the heat exchange channel, 2 – air temperature at the outlet of the heat exchange channel, 3–7 – temperature of granular material (according to the diagram in **Fig. 2**), 8 – air temperature outside the greenhouse

The temperature of the material in period II (curve 3) decreases after a corresponding decrease in the inlet air temperature (curve 1), while the outlet air temperature also decreases. Obviously, this is due to the loss of heat into the ground. In period III (the granular packing is closed with shutters), there are heat losses from the granular packing, as a result of which its temperature drops. An analysis of the curves of temperature changes in period III shows that the existing insulation does not exclude heat losses to the ground. These losses are not caused by insufficient thermal tightness of the shutters, since the air temperature remains above the temperature of the granular bed. When the dampers were opened and the fan turned on in period IV, the nozzle began to transfer heat to the air after 1080 min, which corresponded to 3 am. With good insulation, it was possible to dispose of the heat Q=8×10^4 J accumulated during the heating period. During the pause, the loss from the heat exchange channel to the environment is 48,000 J. The duration of the period was 358 min, while the average heat flux corresponded to 2.2 W.

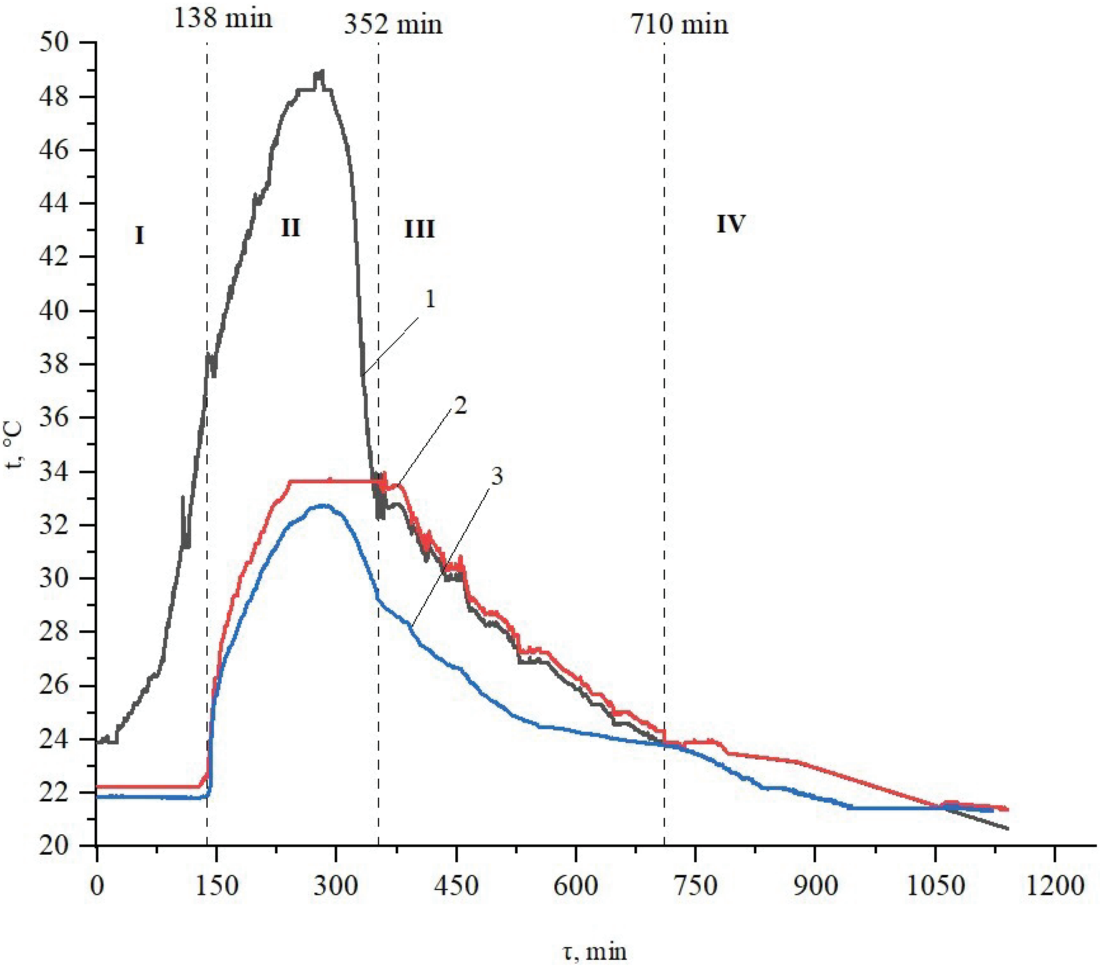


Fig. 4. Temperature change of the soil regenerator in time. 1 – air temperature at the inlet to the heat exchange channel, 2 – air temperature at the outlet of the heat exchange channel, 3 – average temperature of the granular material along the channel length

For the III period, the average value of the heat transfer coefficient from the granular packing to the soil was obtained: k=8.3 W/(m^{2}K).

4. Discussion

Analysis of the results shows that at the maximum temperature of the granular material (τ=240 min), the heat absorbed by the material is significantly lower than the heat transferred from the air to the heat exchange channel. This can be explained by the fact that during the heating of the nozzle and, accordingly, the increase in the temperature difference between the particles of the material and the soil, there is a significant increase in heat losses, despite the enhanced thermal insulation. It can be concluded that it is rational to place the heat exchange channel with granular material not in the ground, but directly on its surface in the greenhouse.

In this case, the temperature difference between the nozzle of the heat exchange channel and the air in the greenhouse will be less, which will lead to a decrease in heat losses from the heat exchange channel.

An analysis of the temperature curves allows to conclude that in order to increase the efficiency of the soil regenerator, it is necessary to complete the heating period, turn off the fan and close the dampers when going to the period of a steady decrease in the temperature of the material. Then, under the conditions of the experiment, the heating period should have ended by 290 min.

Research is limited to single channel testing. In the future, it is planned to test ground heat exchangers with other geometric characteristics and a different load mass. In addition, tests are planned in a wide range of ambient temperature and solar radiation intensity.

5. Conclusions

The air temperature in the greenhouse in the daytime is significantly higher than the ambient temperature, which allows the accumulation of heat with a granular nozzle with the possibility of its use at night.

To ensure the rational operation of the regenerator, the heating period must end at the moment when the average temperature of the packing decreases. After that, the dampers limiting the heat exchange channel are closed. A pause period begins, which lasts until the temperature of the air in the greenhouse drops below the temperature of the nozzle.

The average value of heat losses in the III period (pause) from the granular packing into the soil was 2.2 W, which corresponded to the heat transfer coefficient k=2.34 W/(m^{2}K). The low value of the heat transfer coefficient allows to conclude that strengthening the insulation of the heat exchange channel is irrational.

In order to increase the efficiency of the soil regenerator during the transition to the period of a steady decrease in the temperature of the material, complete the heating period, for which it is necessary to equip the regenerator with an automation system.

Improving the efficiency of the regenerator is possible by changing the conditions of its placement in the greenhouse. Due to the long pause period, the ground regenerator cools down significantly. Due to the impossibility of eliminating heat losses, it is advisable to install the regenerator directly in the air space of the greenhouse, while the temperature difference between the nozzle and the air in the greenhouse will be significantly less than the temperature difference between the nozzle and the soil.

Conflict of interest

There is no conflict of interest between the authors of the article.

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