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Modeling and Research of Heat Transfer Process in Soil Accumulators of Natural Cold

Uzakov Gulom Norboevich , Yakhshiboev Shukhrat Komilovich, Ruzikulov Gulom Yusupovich, Khusunov Shakhboz Khayrullougli

Dean of the Faculty of Energy, Doctor of Technical Sciences, prof. Karshi engineering-economics institute, Karshi, Uzbekistan
Doctoral student, Department of "Thermal Power Engineering", Karshi engineering-economics institute, Karshi, Uzbekistan
Assistant, Department of "Thermal Power Engineering", Karshi engineering-economics institute, Karshi, Uzbekistan
Student, Department of "Thermal Power Engineering", Karshi engineering-economics institute, Karshi, Uzbekistan

ABSTRACT: The article presents the results of experimental studies of the heat transfer process in soil accumulators of natural cold. The simulation results based on the application of the similarity and dimension method are presented, the values of the heat transfer coefficient are obtained depending on the speed of cold natural air during movement of the battery duct, and the hydrodynamic similarity condition for the full-scale sample and installation model is substantiated.

KEYWORDS. Ground cold accumulator, physical model, conductive heat transfer, heat transfer coefficient, natural cold, soil mass, underground fruit and vegetable storage, experimental setup.

I. INTRODUCTION

In modern refrigeration supply systems for fruit and vegetable storages, vapor compression refrigeration machines with a relatively low refrigeration coefficient are used. Traditional vapor compression refrigeration equipment is expensive, energy-intensive and requires large operating costs. An analysis of the operation of vapor compression refrigeration units to generate artificial cold in air conditioning and refrigeration systems shows that 1 kW of electric energy is consumed to obtain 2.5-3.5 kW of cooling power [1]. Therefore, the development and implementation of energy-efficient methods of heat and cooling using NIE is an urgent scientific and technical problem.

One of the energy-saving technologies for refrigeration supply systems for fruit and vegetable storages is the accumulation of natural cold in the underground soil massif. Accumulation of natural cold has a number of potential advantages over traditional refrigeration systems and, as the cost of traditional energy resources grows, it is increasingly used in various countries.

The authors of this work propose a system of accumulation of natural cold for cold supply of underground fruit and vegetable storages. Developed soil accumulator of natural cold (SANC).

II. METHODS AND MATERIALS

To determine the heat transfer coefficient in the soil cold accumulator, experimental studies were conducted on a physical model. The design of the channels of the cold accumulator consists of reinforced concrete pipes with a diameter and length. The channel is surrounded by an infinite soil massif characterized by a coefficient of thermal conductivity, coefficient of thermal conductivity, specific gravity, heat capacity.

The accumulation of cold in the soil is carried out by blowing atmospheric cold air through the channel in the cold periods of the year. In warm periods of the year, the dispersion of cold is carried out conductively in the soil mass due to thermal conductivity.

These heat transfer conditions were modeled on a physical model of a soil heat exchanger. For this, an experimental stand of Fig. 1 was developed, the circuit diagram of which is shown in Fig. 2. The stand consists of a soil (sand) battery 1 located in a foam thermostatic tank 2.

Fig. 1. General view of the experimental setup.

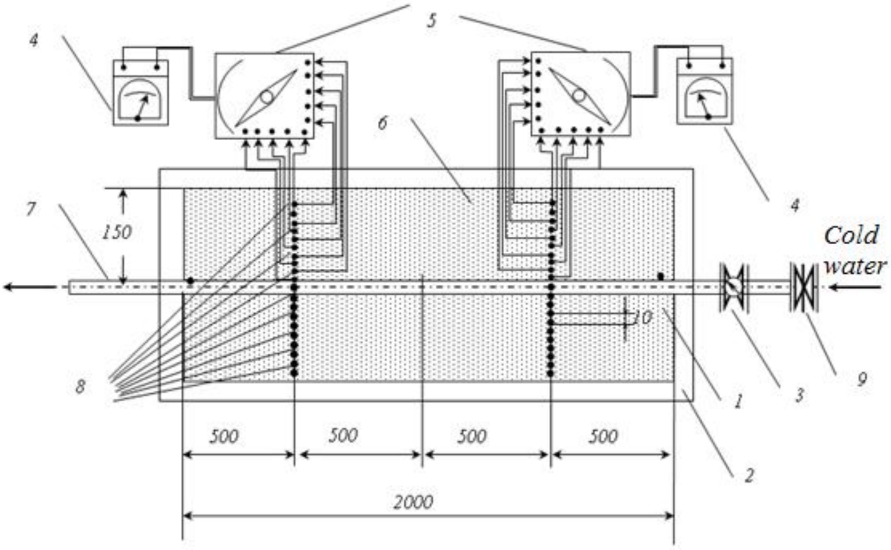

Fig. 2. The scheme of the experimental setup for studying changes in the temperature field of the soil near the surface of the underground channel of the cold accumulator.

1– soil accumulator; 2- thermostatically controlled tank 3 - water meter; 4- nonequilibrium electric bridge; 5– switch of 10 circuits; 6– layer of material modeling the soil massif; 7– aluminum pipe d = 20mm; 8 - thermocouples (the diagram shows thermocouples placed in the first and last sections of the temperature field), 9 - control valve d = 25mm.

As a coolant in the installation model, water with a thermal conductivity coefficient, heat capacity, specific gravity that moves along channel 3, with a diameter.

III. EXPERIMENTAL RESEARCH

To simulate and study heat transfer processes in the SANC installation, the method of similarity and dimension theory was used [2]. The differential heat transfer equations of the natural sample and physical model are determined by the expression:

$$\alpha_1 = -\frac{\lambda_a}{\Delta t} \cdot \frac{\partial t_1}{\partial n_1} \qquad \alpha_2 = -\frac{\lambda_l}{\Delta t} \cdot \frac{\partial t_2}{\partial n_2} \tag{1}$$

Denote the similarity constants

$$C_\alpha = \frac{\alpha_2}{\alpha_1}; \quad C_\lambda = \frac{\lambda_l}{\lambda_a};\ C_n = \frac{n_2}{n_1} = \frac{d_2}{d_1} \qquad C_t = \frac{\Delta t_2}{\Delta t_1} = \frac{t_2}{t_1} \tag{2}$$

It follows from the definition of Const of similarity that

$$\alpha_2 = \alpha_1 \cdot C_\alpha; \qquad \lambda_l = \lambda_a C_\lambda; \qquad d_2 = d_1 C_d;\ \ t_2 = t_1 C_t \tag{3}$$

Substitute (3) in equation (1)

$$\alpha_1 = -\frac{C_\lambda \lambda_a C_t}{C_\alpha d_1 C_d \Delta t_1 C_t} \cdot \frac{\partial t_1}{\partial n_1} \ \text{or}\ \ \alpha_1 = -\frac{C_\lambda}{C_\alpha C_d} \cdot \frac{\lambda_a}{\Delta t_1} \cdot \frac{\partial t_1}{\partial n_1} \tag{4}$$

$$\text{Hence,} \quad \frac{C_\lambda}{C_\alpha C_d} = 1 \ \text{or}\ \frac{\lambda_l \alpha_1 d_1}{\lambda_a \alpha_2 d_2} = 1 \tag{5}$$

It follows from (5) that

$$\frac{\alpha_1 d_1}{\lambda_a} = \frac{\alpha_2 d_2}{\lambda_l} = Nu$$

For similar phenomena at similar points, the criteria should have the same value [2, 3, 4, 5].
We write the heat equation for the full-scale sample and physical model.

$$\frac{\partial t_1}{\partial \tau_1} + W_{X_1}\frac{\partial t_1}{\partial x_1} + W_{Y_1}\frac{\partial t_1}{\partial y_1} + W_{Z_1}\frac{\partial t_1}{\partial z_1} = a_1 \nabla^2 t_1 \tag{6}$$

$$\frac{\partial t_2}{\partial \tau_2} + W_{X_2}\frac{\partial t_2}{\partial x_2} + W_{Y_2}\frac{\partial t_2}{\partial y_2} + W_{Z_2}\frac{\partial t_2}{\partial z_2} = a_2 \nabla^2 t_2 \tag{7}$$

Denote the similarity constants

$$C_t = \frac{t_2}{t_1};\ C_\tau = \frac{\tau_2}{\tau_1};\ C_w = \frac{W_{x_2}}{W_{x_1}} = \frac{W_{y_2}}{W_{y_1}} = \frac{W_{z_2}}{W_{z_1}}; \tag{8}$$

$$C_l = \frac{l_2}{l_1} = \frac{x_2}{x_1} = \frac{y_2}{y_1} = \frac{z_2}{z_1} = \frac{r_2}{r_1} \text{ and } C_a = \frac{a_2}{a_1}. \tag{9}$$

Passing to the physical model through similarity constants (8), we obtain the identity of the following quantities

$$\frac{C_l^2}{C_a \cdot C_\tau} = 1 \text{ and } \frac{C_W \cdot C_l}{C_a} = 1 \tag{10}$$

Identical equalities can be rewritten in the form

$$\frac{a_1 \cdot \tau_1}{r_1^2} = \frac{a_2 \tau_2}{r_2^2} \text{ и } \frac{W_1 \cdot r_1}{a_1} = \frac{W_2 \cdot r_2}{a_2} \tag{11}$$

where r_1, r_2 -Identical equalities can be rewritten in the form; a_1 -thermal diffusivity of air; a_2 - thermal diffusivity of water; $W_{1,}$ W_2 - velocities of moving media in kind and in the model, respectively.

The first of the criteria in (11) is called the Fourier criterion, and the second is called the Peclet criterion

$$Fo = \frac{a\tau}{r^2}; \quad Pe = \frac{W \cdot r}{a} \tag{12}$$

For similar heat transfer phenomena at similar points, these criteria should be the same. In our case, we are dealing both in a full-scale object and in a model with a steady-state flow regime of media. From the mass conservation equation (continuity equation), similarity criteria are not derived. In the study of heat transfer, the Prandtl test is often used instead of the Peclet criterion.

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$$\mathrm{Pr} = \frac{Pe}{\mathrm{Re}} = \frac{W \cdot l \cdot \nu}{aWl} = \frac{\nu}{a} \tag{13}$$

Thus, as a result of the analysis of the differential equations of heat transfer phenomena, a functional dependence is obtained

$$Nu = f(\mathrm{Re}, \mathrm{Pr}). \tag{14.}$$

The equality of the Nusselt criteria for nature and in the physical model, according to the third similarity theorem, indicates that the physical processes of heat transfer in the simulated object and in the model are similar [3, 6, 7, 8].

The experimental setup for modeling the process of heat transfer in a soil massif containing a channel of a soil accumulator is calculated in compliance with the above similarity criteria. It consists of a thermally insulated box with sand simulating an endless soil mass, inside of which there is an aluminum pipe d = 20 mm of an earth cold accumulator, with thermocouples placed around it, packet switches of 20 circuits, a measuring bridge and a water meter. The installation works in two modes.
1-mode - accumulation of cold.

In this mode, cold (relative to the surrounding sand) water at the speeds indicated in Table 2 passes through a pipe simulating an underground channel of an underground cold accumulator. In this case, the process of heat exchange occurs between the water moving in the pipe and the surrounding sand backfill. As shown above, this process is similar to the process of heat exchange between cold air and the soil mass during the through ventilation of the underground channels of the soil cold accumulator. The change in the temperature field near the pipe was measured by thermocouples radially located relative to its axis.
2-mode - storage of cold accumulated in the first mode.

In this mode, the water supply to the pipe stops. The change in the temperature field of sand occurs due to conductive heat transfer. The change in the radius of the thermal influence of the pipe is fixed using thermocouples.

Based on experiments on the study of heat transfer [3,4], the following generalized dependence was obtained with the movement of liquids inside pipes.

$$Nu = \frac{\alpha d}{\lambda} = 0{,}023\ \mathrm{Re}^{0{,}8}\ \mathrm{Pr}^{0{,}43}\ , \tag{15}$$

where the diameter of the pipe (d) is taken as a characteristic linear dimension.

IV. RESULTS

The results of the experiment.
The initial data for the calculation of heat transfer are given in table 1.
Thermophysical properties of air and water [5].

Table 1.

№	Name of substance $t,\ ^0C$	γ, $\frac{kg}{m^3}$	C_P, $\frac{kDJ}{kg\cdot℃}$	λ, $\frac{W}{m\cdot℃}$	a, $\frac{\mathrm{m}^2}{c}\cdot 10^{-6}$	ν, $\frac{\mathrm{m}^2}{c}\cdot 10^{-6}$	Pr
1	Airt=0	1,252	1,00979	0,02	18,75	13,61	0,723
2	Airt=-20	1,365	1,00979	0,0194	16,5	11,66	0,724
3	Water t=0	998,8	4,24028	0,474	0,1305	1,7777	13,7
4	Watert=10	999,6	4,21514	0,494	0,1361	1,2777	9,56

The values of the Nu criterion calculated by the formula (15) for a ground cold accumulator with a pipe diameter d = 300 mm and a physical model (t= 0, ^{0}C) Are presented in Table 2.
SANC simulation results.

Table 2.

Ground battery, d = 300 mm.			Physical model d = 50mm			Physical model d = 20 mm		
W_1, m/s	Nu_1	α_1, $\frac{W}{m^2 \cdot ℃}$	W_2, m/s	Nu_2	α_2, $\frac{W}{m^2 \cdot ℃}$	W_3, m/s	Nu_3	α_3, $\frac{W}{m^2 \cdot ℃}$
2	103,88	8,05	0,32	103,25	1139,28	0,64	103,25	2278,56
4	180,87	14,02	0,64	180,90	1995,95	1,29	180,90	3991,98
6	250,18	19,40	0,97	250,73	2766,44	1,94	250,73	5532,97
8	314,92	24,43	1,29	314,96	3475,25	2,58	314,96	6950,45
10	376,47	29,20	1,61	376,99	4159,62	3,22	376,05	8298,55

V. CONCLUSIONS

Analysis of table 2. Shows that the similarity of heat transfer processes for a full-scale sample (air movement through an underground duct d = 300 mm.) And a physical model (water movement through a pipe d = 20 mm located in the sand) of a natural cold accumulator is performed in the following speed range:
a) for air from 2 to 10 m/s;
b) for water 0.64 to 3.22 m/s.

Thus, to simulate the heat transfer process that occurs when air moves with temperature t = 0, ^{0}C through the underground SANC duct with a diameter of d =300 mm and with speeds of 2,4,6,8,10 m/s, it is necessary to provide water movement with t in the physical model in a pipe d=20 mm, with speeds of 0.64; 1.29; 1.94; 2.58; 3.22 m/s, respectively.

The obtained experimental data on heat transfer in the SANC model allow us to design energy-efficient cold accumulators for modern underground fruit and vegetable storages.

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