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Investigation of heat transfer processes at a full-scale object in a fruit and vegetable storage with a natural cold ground accumulator

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Abstract: This article studies the heat exchange processes between the natural cold of outdoor air and the soil battery in an experimental setup. In addition, the temperature field temperature between the surface of a reinforced concrete pipe with a diameter of d = 300 mm and the soil mass, the heat transfer coefficient, and the Fourier number were calculated and graphs were obtained. The accepted theoretical dependences for describing the processes of conductive heat transfer of a ground cold accumulator differ by 10-15% from the experimental data obtained on a physical model for various Fourier numbers.

1 Introduction

Currently, food safety is considered one of the most important issues, and a number of works are being carried out based on the principle of cultivation, storage, processing, and from field to table of agricultural products grown in different regions of Russia and our country. In particular, fruit and vegetable warehouses of various sizes consume a large amount of electricity not only in our Republic but also in the practice of the whole world. Conducted scientific studies show that during the operation of modern vapor compression refrigeration machines, 1 kW of electricity is consumed to obtain 2.5÷3.5 kW of cooling capacity per ton of fruit and vegetable products [1]. In accordance with the size of the storage warehouse and the stored product, the capacity of the refrigeration machine increases, which in turn leads to a sharp increase in electricity consumption. Abroad (China, Japan, Sweden, and Russia) this problem is partially solved by using natural sources of cooling. For example, ice water and snow water are used to store various products in underground fruit storage warehouses in Japan and Sweden. Therefore, the study of heat transfer processes in warehouse storage is an important task [2-17].

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2 Material and methods

To conduct a full-scale experiment, the ventilation system of the experimental storage of vegetables with a capacity of 500 tons was reconstructed.

In the ventilation system of this storage facility, as a source of cold in the warm season, the project provided ground heat exchangers - reinforced concrete pipes laid in the ground filling of the storage along the outer walls. After minor alterations and the replacement of the ventilation unit of the system with a more powerful one, it was possible to mount an installation that allows the accumulation of the natural cold of the outside air in the ground.

A schematic diagram of the experimental setup for cold accumulation in the ground bedding of the storage facility is shown in figure 1.

The installation consists of two wells 2.5m deep, connected by a channel for the passage of air L=48000mm, d=300mm, σ = 35mm, laid in the soil filling of the storage at a depth of 3m. To pump air through the channel, the unit is provided with an air duct system, a fan, and shut-off and control valves, which allows you to switch air flows into three modes: 1-mode for charging a cold accumulator, 2-mode for storing stored cold and 3-mode for discharging the battery or removing excess heat in storage. Experimental studies in a full-scale object were carried out according to well-known methods of thermomechanical measurements and experimental studies [3].

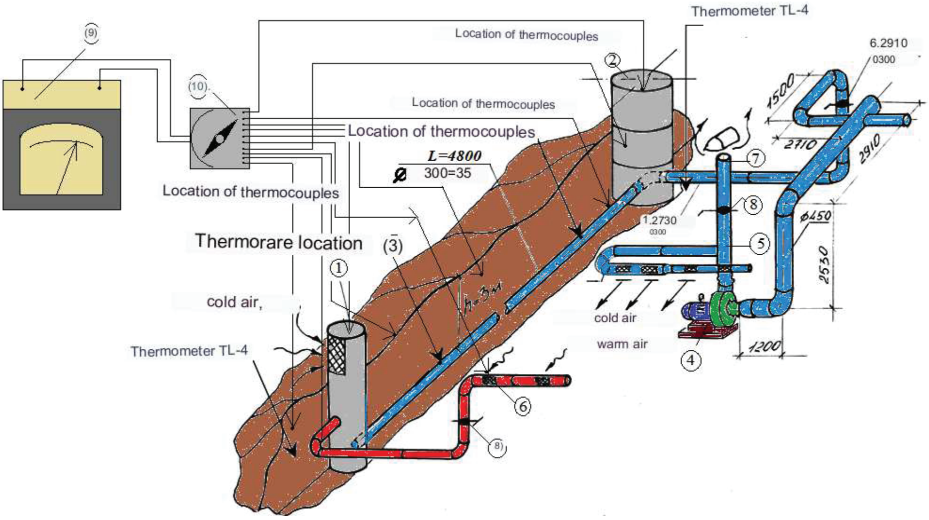

Figure 1. Technological scheme of the energy-saving refrigeration system of the underground storage facility using natural cold ground accumulator (NCGA): 1-air intake well; 2-manhole; 3-underground channel of a ground accumulator of natural cold; 4-fan unit 90TSS240; 5-air duct for through ventilation mode, 6-air duct for heat removal mode; 7-exhaust pipe; 8- valves; 9-self-beeping device KSP-4; 10-switch.

During the test experiment, on a full-scale object, the experimental setup worked in the first and second modes. When the unit was operating in the first mode, the outside air, with a temperature lower than the temperature of soil $t_A < t_S$, was taken in by fan 4 through air intake well 1, passed through the underground channel 3, and was removed into the atmosphere.

In the second mode, fan 4 was turned off, and the gates on wells 1 and 2 were closed. To measure the temperatures of the outside air, soil filling and the surface of the wall of the underground channel, mercury thermometers TL-4 and KhK thermocouples and an optical pyrometer brand M6-0/300 0C were used. Outside air temperatures during the experiment were measured with thermometers. The air velocity was determined using an MMN-2400 (5)-1.0 multirange micromanometer with an inclined tube and a Megeon 11006 anemometer.

In the first operating mode of the installation, the air velocity was set constant in the range of values indicated in table 1.

For a pipe d=300 mm, thus ensuring the equality of the Nusselt criteria for the full-scale object and the experimental setup. Aerodynamic characteristics of fan 90CF24 [4].

Table 1. Results of heat transfer calculations in NCGA.

Ground accumulator, d=300 mm (air)			Physical model d=50 mm (air)			Physical model d=20 mm (water)		
W_1, m/s	Nu_1	$\alpha_1, W/m^2 \cdot K$	W_2, m/s	Nu_2	$\alpha_2, W/m^2 \cdot K$	W_3, m/s	Nu_3	$\alpha_3, W/m^2 \cdot K$
2	103.88	8.04	0.32	103.25	47.908	0.64	103.25	2845.57
4	180.87	14.01	0.64	180.90	83.93	1.29	180.90	4985.60
6	250.18	19.38	0.97	250.73	116.338	1.94	250.73	6910.11
8	314.92	24.41	1.29	314.96	146.14	2.58	314.96	8680.29
10	376.47	29.17	1.61	376.99	174.92	3.22	376.05	10363.93

3 Results and discussions

Let us evaluate the convergence of the surface temperatures of the underground channel NCGA, obtained in the course of a full-scale experiment with experimental values. To do this, we will use the algorithm developed in earlier reports and the data of temperature measurements from one of a series of experiments conducted on a full-scale object from October to March 2019-2020. The duration of the cold accumulation period in this experiment was 10 days (from December 1, 2019 to January 10, 2020). The average value of the outdoor air temperature for this period is -12, see the appendix. Measurements of the surface temperature of the wall of the underground channel in the second mode continued until it reached equality with the temperature of the surrounding soil massif.

The average temperature of the soil filling of the storage at a depth of 3 m for the specified period is -$t_{gr.} = +6^0 C$. The duration of the stored cold storage period was 45 days (from 12.15.19 to 01.28.20) [5-6].

Graphs of the dependence of the relative temperature on R, for various values of the heating time, built according to the solution.

$$t(U) = n_1 + n_2 \cdot U + n_3 \cdot U^3 - n_4 \cdot e^U + n_5 \cdot e^{-U} \tag{1}$$

For $r_0 = 0{,}15\,\text{m}$ are presented in Fig.2. To calculate the distribution of the absolute temperature of the soil for the case of cooling an area with an initial temperature $t_{gr.} = +6^0 C$, limited from the inside by a pipe d = 300 mm, the surface temperature of which is maintained constant $t_{c.s.} = -12^0 C$ for 10 days, you can use the method described. To do this, the graphs shown in Fig. 2 were rebuilt in absolute temperature coordinates, moreover, the initial temperature of the soil was taken equal to $t(R,0) = 0^0 C$ and the temperature of the pipe surface $t(r_0, \tau) = +18^0 C$.

The soil temperature change curves obtained in this way, during its heating from the initial temperature $t(R,0) = 0^0 C$ to the pipe surface temperature $t(r_0, \tau) = +18^0 C$, for different values of the numbers Fo are shown in Fig.3.

As shown in paragraph 1. this process is equivalent to the process of cooling the soil, which has an initial temperature $t(R,0)$=+6 ^0C, to the temperature of the pipe surface d=300mm $t(r_0, \tau)$=-12 ^0C.

The value of the approximation coefficient n, for the duration of the cold accumulation period τ= 10 days (F_o=20), was calculated by approximating the curve of temperature change of the soil surrounding the pipe (Fig. 3), for Fo=20 according to a function of the form $t(0,x)=t_{c.s.}\cdot e^{-n_i x}$. For the soil temperature distribution curve after cooling it with outside air for a time = 10 days, the coefficient n = 2.4. After determining the approximation coefficient, the analytical values of $\theta(0,\tau)$ were calculated from dependence (2).

$$F(x,\tau)=\frac{2}{\pi}\int_0^\infty e^{-q^2 a\tau}\cos(qx)\frac{n}{n^2+q^2}dq=\exp(n^2 a\tau)erfc(n\sqrt{a\tau}) \tag{2}$$

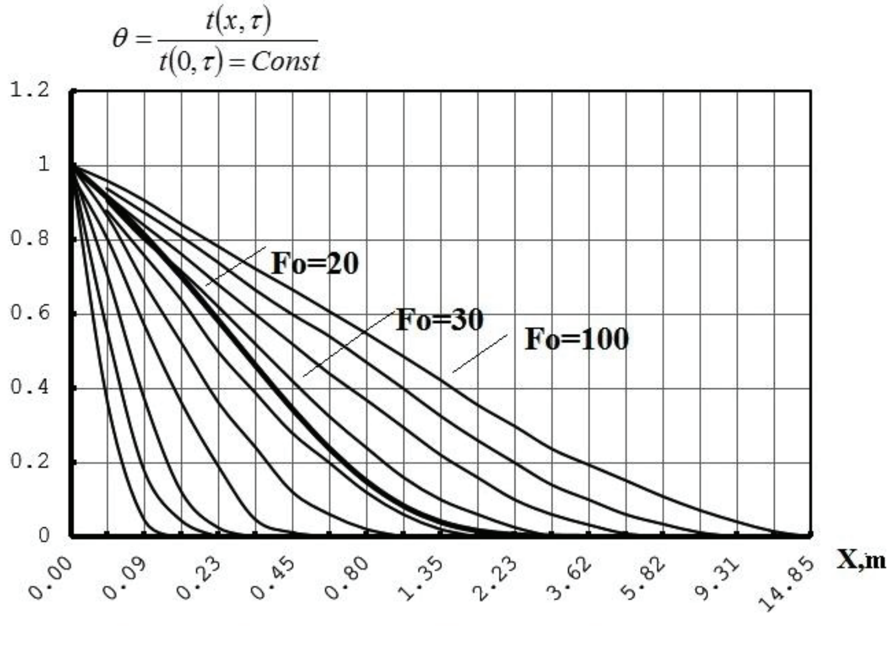

Figure 2. Temperature distribution in a region bounded from the inside by a cylinder r_0 = 0.15 m, the initial temperature is zero, and the surface temperature is constant.

$$t_{c.s..}=Const\,, x=R-r_0\,. \tag{3}$$

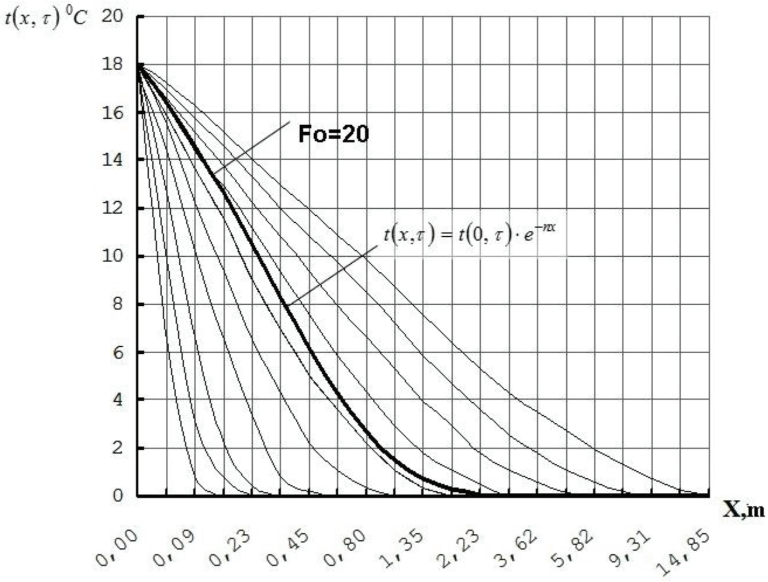

Figure 3. Temperature distribution in a region bounded from the inside by a cylinder r_0 = 0.15 m, the initial temperature is zero, and the surface temperature is constant.

$$t_{c.s.} = Const = 18\,^0C, \;\; x = R - r_0. \tag{1}$$

1 - according to the experiment.

2 - calculated analytically.

Graphs of changes in the temperature of the inner surface of the pipe d = 300 mm depending on the duration of time τ, the mode of storage of stored cold, built analytically, and according to measurements on a full-scale object, are shown in Fig. 4.

An analysis of the graphs in figure 4, as well as a comparison of experimental and analytical data during a series of experiments, shows that the use of dependence (2) to determine the surface temperature of the underground NCGA channel after the cold accumulation mode has stopped in the region of negative temperatures can be recommended for engineering calculations, as as the average discrepancy between the experimental and calculated data is 10-15%.

In addition to the temperature factor, the reliability of the results of calculations according to formula (2) significantly depends on the accuracy of determining the calculated values of the thermophysical characteristics of the soils of the construction site - thermal conductivity coefficients, λ, $W/m\cdot K$, and heat capacity $C_{gr}\ kDj/kg\cdot grad$, the volumetric weight of sand $\gamma\ kg/m^3$ [5-7].

The need to use experimentally obtained data in assessing the convergence required an analysis of errors and inaccuracies of both measuring instruments and the entire experiment as a whole.

4 Conclusions

An experimental installation of a ground accumulator of natural cold (NCGA) was developed and, based on the simulation of the heat transfer process, experimental studies were carried out in the modes of accumulation and storage of natural cold. The heat transfer coefficient for a full-scale object and in a physical model is determined.

It has been established by experiment that in order to simulate the process of heat transfer that occurs when air moves with temperature t=0^0C through an underground air duct d=300mm in kind and at speeds of 2,4,6,8,10 m/s, it is necessary to ensure in the physical model the movement of water from $t = 0^0C \div +4^0C$ in a pipe d=20mm, with speeds of 0.64; 1.29; 1.94; 2.58; 3.22 m/s, respectively. For air in the physical model at , it is necessary to provide in the pipe d=50mm velocities of 0.32 to 1.61 m/s.

The curves of the temperature change of the cooled soil due to conductive heat exchange are obtained, and tuned for a full-scale object, according to the data of an experiment carried out on a physical model for different durations of the period of storage of accumulated cold.

The duration of the natural cold accumulation mode in the natural cold ground accumulator d = 300 mm located in sandy soil on a full-scale object was determined, which amounted to $\tau = 6750 \text{ min} = 5\,days$.

The accepted theoretical dependences for describing the processes of conductive heat transfer of a ground cold accumulator differ by 10-15% from the experimental data obtained on a physical model for various Fourier numbers.

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