Heat and Mass Transfer of a Coolant in Horizontal Seasonal Cooling Devices

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Abstract. The heat-mass transfer in the seasonal cooling device with air coolant is considered in this article. This device works during the cold period of year at the expense of the difference between temperatures of soil and air. Their thermal calculation which comes down to drawing up thermal balance for determination of temperature of coolant, being its main characteristic is considered. The engineering method of calculation of heat fluxes of the soil and the pipeline laid in the thickness is developed. Also, there were made a natural measurements of the cooling system. Experimental research was made for the purpose of establishment of qualitative and quantitative regularities of communication of the key parameters characterizing operation of the seasonal cooling devices: air temperatures and speeds of its circulation with the defining factors – the air temperature, wind speed, temperature of soil and its heat-physical properties. Results of researches were used also as the actual material during the checking and justification of theoretically determined formulas.

1. Introduction
The construction and operation of various engineering structures, buildings and communications in the conditions of the Far North is complicated by the sharply continental climate and the presence of permafrost. Cooling pipes are provided to preserve permafrost soils, buildings are arranged on piles and foundations on the bedding soil. In the bases of industrial, warehouse buildings and auxiliary facilities for a smaller impact on the soil and warnings from the defrost of the soil. Compared to Central Russia, the concept of a seasonally thawed layer is introduced on the territory of the distribution of permafrost soils, depending on the parameters of the ambient air during the year.

The most rational and frequently used method for increasing the strength of soils in permafrost regions is to lower their temperature to values that correspond to the solid-permeable state. The effectiveness of this method is due to the inexhaustible "cold resources" in our areas.
2. Relevance of the study
The temperature difference of the seasonal cooling devices can be used for preliminary fuel-less heating of the air required for combustion of the boiler. The temperature of the outside air passing through the seasonal cooling devices on the one hand is heated, and on the other – cools the ground base. Cooling, seasonal cooling devices provide reliability, efficiency and controllability of the base in areas of permafrost. The heated air increases the efficiency and stability of combustion of the boiler.

3. Scientific significance
Modern ideas about the temperature regime of frozen foundations of structures, its quantitative patterns are based on the works of Soviet permafrost scientists - G.V. Porkhaeva, N.S. Ivanova, L.N. Khrustaleva, V.A. Kudryavtsev, H. Karslow, A.A. Konovalov et al. Also, at present, the topic is widely studied by both Russian and foreign scientists [1-18].

4. Problem statement
Thermal calculation of seasonally cooling devices is reduced to the compilation of heat balance to determine the temperature of the coolant, which is its main characteristic.

The equation of energy conservation and momentum for the mass flow is:

\[ c_a \rho_a \frac{dt}{dt} = \frac{d}{dx} \left( \lambda \frac{dt}{dx} \right) - c_a \rho_a v_{av} \frac{dt}{dx} + f \]  

(1)

where \( c_a, \rho_a \) - specific heat capacity and density of air, respectively kJ/(kg °C) and kg/m³; \( \lambda \) — thermal conductivity coefficient, W/(m °C); \( v_{av} \) — average coolant velocity, m/s; \( f \) is the function of the receipt of heat sources from the soil, kJ/m³.s.

5. Solution method
The diffusivity of dispersed phase characterizes the rate of change in the potential of moisture due to saturation or dehydration. It is estimated by the diffusion coefficient of moisture, which depends on temperature, humidity, ice content, salinity, particle size distribution, etc. [19]. Since diffusion heat transfer can be neglected in this case, the equation will take a simpler form:

\[ \frac{dt}{dt} + v_{av} \frac{dt}{dx} = f \]  

(2)

The construction of a general solution of this equation after integration reduces to the following by [20]:

\[ \Phi (v_{av} \tau + x; v_{av} T + fx) = 0 \]  

(3)

where \( \Phi \) is an arbitrary function.

From here we get the system of equations:

\[
\begin{align*}
v_{av} \tau - x &= c_1 \\
v_{av} T - fx &= c_2
\end{align*}
\]

(4)

The formula describing the temperature at the outlet of the seasonally cooling devices channel is:

\[ t'' = t' + \tau f \]  

(5)

where \( t'', t' \) - the temperatures at the exit and at the entrance to the channel, respectively, °C, \( \tau \) is the time, sec.
The function f contains the specific heat flux, which characterizes the heat exchange of air moving in the pipe with the environment (soil surrounding the pipe). It is usually considered that this convective heat transfer occurs according to Newton’s law.

The general form of the function f is as follows:

\[ f = \frac{a_{ef}(T_b - T_s)}{c_a \rho_a \pi d} \]  

where \( a_{ef} \) is the effective coefficient of convective heat exchange between the soil and air, W/(m\(^2\) °C), calculated according to equation [21]; \( T_b - T_s \) - respectively, the temperature in the building and the soil, °C; d - diameter of the soil channel, m.

Questions of the movement of liquids and gas in pipeline systems were considered with one or another completeness by many authors both in our country and abroad [22-26]. Currently, there are fairly accurate hydraulic models that take into account all the physical important phenomena occurring in moving liquids and gases.

Also, according to the equation of motion of a real gas in horizontal pipelines [21], an equation is derived that allows to calculate the final air temperature at the exit of the cooling pipes:

\[ \frac{dT}{dx} = \frac{\pi D a}{c M} (T_s - T) \]  

\[ T = T_s + (T_0 - T_s) \cdot e^{-\frac{\pi D a}{c M} x} \]  

Concentrated linear positive and negative heat sources are active in the soil mass. Positive heat sources are designated + Q, negative heat sinks are –Q.

The thermal resistance of the soil is determined according to the simplified Forchgramer formula:

\[ R_s = \frac{1}{2 \pi \lambda_s} \cdot \ln \frac{4h}{d} \]  

where \( \lambda_s \) is the soil thermal conductivity, W/(m°C); h - the depth of the pipeline from the surface of the earth to its axis, m; d - diameter of the pipeline, m.

There is an analytical model in figure 1 to calculate the thermal regime of the soil.

**Figure 1.** Analytical model.

Based on the known dependencies, the heat balance with permissible simplifications is as follows:

\[ \begin{cases} 
-dQ_a = L_\alpha \rho_a c_a dt \\
-dQ_s = k_\alpha \pi D (t_s - t_a) dy 
\end{cases} \]  

(10)
where $dQ_a$ is the change in the negative heat sink, W; $dQ_s$ - change in heat flux from a source of heat, W; $L$ - air flow, m$^3$/h; $c_a$, $\rho_a$ - heat capacity and air density, respectively, kJ/(kg ∙K); $k_s$ - linear heat transfer coefficient from ground to air, W/(m∙K); $t_s$, $t_a$ - temperature of the soil and air, respectively, °C.

6. Results of experimental studies

Field measurements of seasonally cooling devices in Yakutsk were carried out from November 15, 2017 to April 19, 2018 at the Greenhouse facility of the Yakut Botanical Garden of the Institute for Biological Problems of the Cryolithzone of the Siberian Branch of the Russian Academy of Sciences, which was built in 1976 (figure 2) The building is 39x7 m in plan. The purpose of the building is a greenhouse. At the base of the building, a cooling pipe system is installed with the natural circulation of the air coolant.

![Figure 2. Botanical greenhouse in Yakutsk.](image)

A distinctive feature of the operation of greenhouses in areas of permafrost occurrence is that the high constant temperature inside the structure, the penetration of moisture (water with different mineral salts) under the foundation lead to a change in thermal and mechanical properties of soils. The construction of greenhouses should be carried out according to principle I. Different technological conditions (for example, the greenhouse needs free access to solar energy) requires the construction of one-story buildings and structures. In this case, well-justified year-round greenhouses on the dressing with cooling tubes. The system with cooling pipes has two entrances (both located in the Northern part of the building) and two exits (from the South-East and South-West sides, respectively).

Cooling pipes are stacked at a certain depth in the bedding of coarse-grained or sandy ones parallel to the short side of the structure and are connected by common collectors, through which cold air enters the pipes in winter.

Measurements were made of the speed of movement and the temperature of the air coolant at the exits from the cooling pipe system using a Testo 435-4 thermal anemometer. Also, the outside air temperature was measured (table 1).

| №  | Date         | Output 1 (South-East) | Output 2 (South-West) | Inlet temperature $t'$, °C |
|----|--------------|-----------------------|-----------------------|---------------------------|
| 1  | 15.11.2017   | -1                    | 0.5                   | -3.9                      | 0.61                      | -28                      |
| 2  | 22.11.2017   | -3.6                  | 0.58                  | -5.2                      | 0.64                      | -32                      |
| 3  | 30.11.2017   | -5.1                  | 0.5                   | -9.2                      | 0.5                       | -39                      |
| 4  | 14.12.2017   | -8.6                  | 0.55                  | -10.1                     | 1.08                      | -37                      |
| 5  | 28.12.2017   | -8.8                  | 0.54                  | -9.7                      | 0.65                      | -39                      |
| 6  | 11.01.2018   | -8.5                  | 0.51                  | -8.9                      | 0.68                      | -37                      |
| 7  | 25.01.2018   | -7.9                  | 0.5                   | -8.6                      | 0.64                      | -35                      |
| 8  | 08.02.2018   | -7.8                  | 0.53                  | -8.5                      | 0.63                      | -32                      |
| 9  | 22.02.2018   | -5.5                  | 0.55                  | -7.2                      | 0.51                      | -28                      |
The table shows the good performance of the cooling system - air velocity at an average of 0.5 m/s or more at a wind speed of only 1 m/s.

Comparing the calculated values of the temperatures at the outlet of the seasonally cooling device with the actual data, one can speak of a good convergence of the actual and calculated by formula (5) results (figure 3).

![Temperature graph at the exit of the seasonally cooled device in a botanical greenhouse](image)

**Figure 3.** Temperature graph at the exit of the seasonally cooled device in a botanical greenhouse.
1 – The temperature at the exit of the seasonal cooling device by calculation.
2 – The temperature at the outlet of the seasonally cooling device by field measurements.

### 7. Conclusion
The proposed method of calculation has good convergence and is used to calculate the temperature at the outlet of the seasonal cooling device. This temperature is mainly influenced by the heat transfer coefficient, which in turn depends on the air velocity, in accordance with the solutions presented.

This technique is used for a complex system for the preservation of frozen soil and preliminary fuel-free heating of air [27]. Here, on the basis of the proposed methodology, it is necessary to find the optimal air mass flow rate through the seasonal cooling device, as for cooling the soil, and to increase the efficiency of the boiler room.

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