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HEAT ABSORPTION OF COOLING COLUMNS (O TEPLOPOGLOSHCHENII ZAMORA--ETC(U)
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NOTICE

THE HEAT ABSORPTION OF COOLING COLUMNS

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[O Teplopogloshchenii Zamorazhivayushchikh Kolonok]

The heat absorption of cooling columns is the quantity of heat per unit of time which passes from the ground to cooling columns and is drawn off by the brine circulating in the columns.

Several specialists working in the area of ground freezing [1, 2] have pointed out the considerable divergences between the calculated and actual values of heat absorption and the approximate nature of existing methods of determining it. The amount of heat absorbed by columns serves as the basis for thermotechnology calculations of ground freezing, and therefore in a number of cases, for instance in calculating the freezing of water-permeable ground, it is necessary to determine it more precisely.

The goal of this article is to develop a refined method for determining the heat absorption of columns.

1. Calculation Methods Used

Up till now two methods have been used to determine the heat absorption of columns.

According to the first and most common method, the heat absorption of a unit of freezing column surface is considered to be a constant value which is equal to 250 kcal/m^2·hr [1, 4]. Thus, if we designate the column radius as r_0 and its length as L, then the heat absorption of the column Q_c will be determined by the following expression:

$$Q_c = 250 \cdot 2\pi r_0 L. \quad (1)$$

Heat absorption constancy requires that the temperature of the brine in the column be constantly reduced during active freezing.

The second method is based on the assumption that the temperature of the brine during freezing remains constant and the heat absorption of the column decreases as the thermal resistance between the columns and the surfaces of the freezing ground increases [5, 6].

Thus, we can write:

$$Q_c = \frac{\vartheta_0 - \vartheta_{co}}{R}. \quad (2)$$

where

ϑ_0 is the freezing temperature of the ground;

ϑ_{co} is the constant temperature of the brine;

R is the thermal resistance of the frozen ground.

As we see, these two methods of calculation are based on diametrically opposite precepts, which naturally leads to contradictory results.

Example. By using the above-mentioned two methods of calculation, we will determine the heat absorption of columns before the frozen ground cylinders join, if we know that

radius of freezing columns...........	r_o = 0.05 m
total length of freezing columns.....	L = 100 m
radius of frozen ground cylinders....	r = 0.2 m
freezing temperature of soil.........	ϑ_o = 0°C
brine temperature in columns.........	ϑ_{co} = -20°
thermal conductivity of frozen ground..	λ = 2 kcal/m·deg·hr.

According to the first method

$$Q_c = 250 \cdot 2\pi \cdot 0.05 \cdot 100 = 7860 \text{ kcal/hr}$$

In order to determine the thermal conductivity of the columns by the second method, we first find the thermal resistance of the frozen ground cylinders:

$$R = \frac{1}{2\pi\lambda L} \ln \frac{r}{r_0} = \frac{1}{2\pi \cdot 2 \cdot 100} \ln \frac{0.2}{0.05} =$$
$$= 1.11 \cdot 10^{-3} \text{ deg·hr/kcal.}$$

Then according to expression (2), we obtain:

$$Q_c = \frac{20}{1.11 \cdot 10^{-3}} = 18\,000 \text{ kcal/hr}$$

Thus, we see that the results of the calculations performed by the two methods differ considerably. The calculations of other examples may provide larger or smaller differences than shown here. It is difficult to say which of the results is more correct; it is completely possible that both results are wrong since the two methods are based on precepts which have little theoretical basis and are not confirmed by practice. On the other hand, numerous practical data have shown that ground freezing as a rule, first occurs in the presence of a variable (decreasing) brine temperature, and then with the brine at a constant temperature. The same materials indicate that the heat absorption of the columns during freezing decreases steadily.

Figure 1 shows a characteristic graph of the changes in brine temperature plotted from the work of N. G. Trupak [7]; Figure 2 shows a graph of the cold flow rate constructed by Kh. R. Khakimov [2].

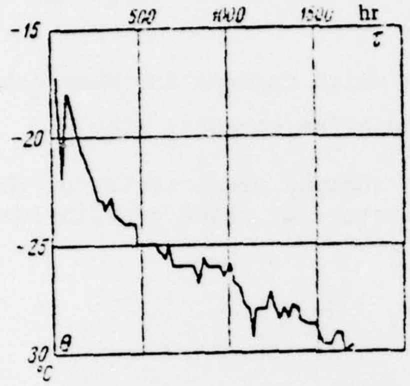

Figure 1. Graph of Brine Temperature Changes During Ground Freezing.

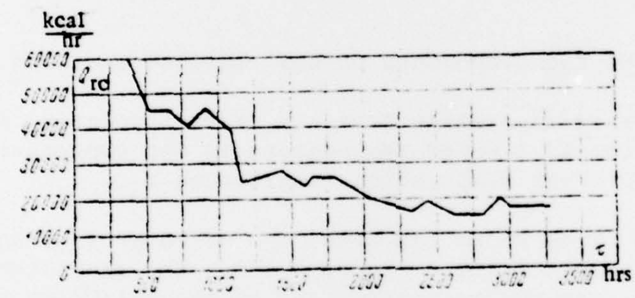

Figure 2. Graph of Cold Flow Rate [Heat Discharge] During Ground Freezing.

While analyzing the method proposed in this paper for calculating the heat absorption of columns, the following paragraph will show that the changes in heat absorption and brine temperature observed in practice are not random, but rather obey completely determined laws.

2. Proposed Calculation Methods

The heat balance equation of the refrigeration mechanism has the following form:

$$Q_{rc} = Q_c + Q_l + Q_b . \tag{3}$$

where

Q_{rc} is the operating refrigeration capacity of the compressor;

Q_c is the heat absorption of the freezing column;

Q_l is the thermal flux which comes from the outside to the brine from the refrigeration device to the freezing columns (cold losses);

Q_b is the thermal flux which changes the heat content of the brine system (the brine, the brine conduit, etc.).

We will show that each thermal conductivity of the frozen ground correspond to a brine temperature at which equilibrium occurs, as expressed by the equations:

$$Q_{rc} = Q_c + Q_l, \quad (4)$$

$$Q_b = 0, \quad (5)$$

and therefore the brine temperature ϑ changes to follow the course of the ground freezing, while approaching values at which this equilibrium occurs.

Let us examine the components of heat balance equation (4).

The operative refrigeration capacity of reciprocating compressors at given rpm and constant water temperature in the condenser depends primarily on the coolant evaporation temperature t_e.

This dependency is known for each type of compressor and is called the compressor characteristic. Figure 3 shows the characteristic of the AG compressor from the test materials of the All-Union Scientific Research Institute of the Refrigeration Institute [2].

The difference between the evaporation temperature and the temperature of the brine can be assumed to be constant (usually -5 - -7°C), and it is then possible to present the compressor characteristic in the following form:

$$Q_{rc} = f_1(\vartheta), \quad (6)$$

where θ is the brine temperature.

Dependency (6) determines the first component of equation (4). Component Q_l, which characterizes the cold loss, can be determined by a generally accepted method [2] and is expressed as a function of the brine temperature:

$$Q_l = f_2(\theta). \quad (7)$$

There remains the task of writing the dependency for the heat absorption of the column.

Considering, as does I. A. Charnyy [5], that the temperature distribution at any moment of time corresponds to the established thermal state, we can write:

$$Q_c = \frac{\vartheta_0 - \vartheta}{R}. \tag{8}$$

Here, in contrast to formula (2) the brine temperature is a *variable*.

Thus, we find that all three components of heat balance equation (4) are a function of brine temperature.

By substituting (6), (7) and (8) into equation (4), we obtain:

$$f_1(\vartheta) = \frac{\vartheta_0 - \vartheta}{R} + f_2(\vartheta),$$

from which we find

$$R = \frac{\vartheta_0 - \vartheta}{f_1(\vartheta) - f_2(\vartheta)}. \tag{9}$$

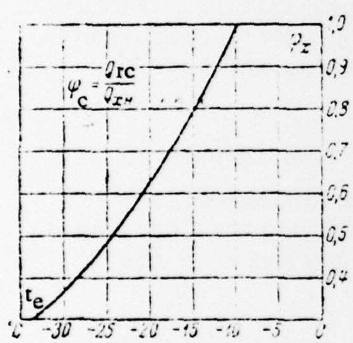

Figure 3. Compressor Characteristics of Compressor AG (According to the Data of the All-Union Scientific Research Institute of the Refrigeration Industry).

This equation determines the dependency between the brine temperature and thermal resistance of the frozen ground. Expressing this dependency in the form

$$\vartheta = f_3(R) \tag{10}$$

and substituting it into equation (8), we find the desired calculation equation for the heat absorption of the columns:

$$Q_c = \frac{\vartheta_0 - f_3(R)}{R}. \tag{11}$$

Strictly speaking, equation (11) is correct only in the presence of thermal equilibrium when the thermal flux which changes the brine temperature is equal to zero. However, for practical purposes maintenance of this condition is not essential since the other components of heat balance equation (3) are large relative to Q_l. Therefore we may consider that the refrigeration device passes in turn through a series of thermal equilibrium positions, each of which corresponds to a given frozen ground thermal resistance.

This makes it possible to represent how the refrigeration mechanism operates to freeze the ground in the following fashion.

The decisive parameter is the thermal resistance of the frozen ground. An increase in the thermal resistance causes a change in all of the device's heat balance components and a reduction in brine temperature. In this case the sequence is the following: an increase in the thermal resistance causes a reduction in the columns' heat absorption; the thermal equilibrium of the refrigeration device in this case is disrupted because of the excess of compressor refrigeration capacity which is expended on reducing the brine temperature; a reduction in the brine temperature in turn causes a reduction in the compressor's refrigeration capacity and an increase in the cold losses; the heat absorption of the columns increases somewhat, but does not reach its initial value. The reduction in brine temperature continues until the thermal equilibrium expressed by equations (4) and (5) is restored.

In actuality the process is continuous: the increase in the thermal resistance of the frozen ground is simultaneously accompanied by a reduction in brine temperature, an increase in cold losses and a reduction in the compressor's refrigeration capacity.

The reduction in brine temperature has a limit, and when this limit is reached freezing continues at a constant temperature. In this case the above-described course of the refrigeration unit's operation is disrupted, and the use of the calculated formula for the heat absorption of the columns (11) becomes uneven.

The minimum temperature of the brine θ_{min} is known in each particular case. When the water temperature in the condenser is known, this value depends basically on the number of compression stages in the compressor since the ratio of the discharge pressure to the suction pressure should not exceed a certain value.

For single-stage ammonia devices $\theta_{min} \approx -20°C$, and for dual-stage units $\theta \approx -40°C$. At $\theta = \theta_{min}$ the heat absorption of the columns is equal to:

$$Q_c = \frac{\vartheta_0 - \theta_{min}}{R}. \qquad (12)$$

Thus we see that we should distinguish between two freezing periods: the first period during which the brine temperature drops and the second period during which the brine temperature is constant.

The heat absorption value at which the first period ends and consequently the second period begins is determined by dependency (9) by substituting the minimum brine temperature into it:

$$R_{min} = \frac{\vartheta_0 - \theta_{min}}{f_1(\theta_{min}) - f_2(\theta_{min})}; \qquad (13)$$

in this case R_{min} is the thermal resistance at which the brine temperature reaches its minimum value.

As long as $R \leqslant R_{min}$ (the first freezing period), the heat absorption of the columns must be determined from equation (11); when $R \geqslant R_{min}$ (second freezing period), it is necessary to use equation (12).

The use of the calculation method proposed here will be illustrated by way of an example.

3. Sample Calculation

Assume that it is necessary to determine the heat absorption of freezing columns and the brine temperature when a frozen ground wall 4 m thick is formed.

The following data are known:

the columns are arranged in a single row, column radius............................	$r_0 = 0.05$ m
distance between column axes...............	$S = 2$ m
height of frozen ground wall...............	$h = 10$ m
length of frozen ground wall...............	$l = 10$ m
number of columns	$N = 50$
thermal conductivity of frozen ground......	$\lambda = 2$ kcal/m·deg·hr
freezing temperature of ground............	$\vartheta_0 = 0°C$
temperature of water in condenser..........	$t_w = 17°C$
temperature of air (ground) surrounding brine pipe..............................	$\vartheta = 5°C$
specific losses of cold (per degree of difference between temperature of brine and surrounding medium)..................	$q_l = 400$ kcal/hr·deg.

The columns are frozen by a refrigeration unit of the 4 AU15 type.

The difference between the condensation temperature of the ammonia and the temperature of the water in the condenser is 18°C; consequently, the condensation temperature $t_c = 17 + 8 = 25°C$.

This is sufficient data to solve the stated problem.

The dependency of the compressor's refrigeration capacity operation on the brine temperature is found from the compressor characteristic (Figure 4). In this case the difference between the brine temperature and the ammonia evaporation temperature is assumed to be equal to 5°C. Figure 4 shows the curve $Q_{rc} = f_1(\theta)$.

The cold losses as a function of brine temperature are determined by the formula

$$Q_l = q_l(\vartheta - \theta) = 400(5 - \theta) = 2000 - 400\theta.$$

Figure 5 shows a graph of the function $Q_l = f_2(\theta)$.

The minimum brine temperature is found from the condition that for vertical compressors such as the 4 AU15, the ratio of the freezing pressure to the suction pressure should not exceed eight.

Assuming that the condensation pressure is $t_c = 25°C$, from the table of saturated ammonia vapors we will find the vapor pressure corresponding to the temperature $p_c = 10.2$ kg/cm^2 [7]. Consequently, the suction pressure should be at least

$$p = \frac{10.2}{8} = 1.27 \text{ kg/cm}^2;$$

at this pressure the temperature of saturated vapors is -29°C.

Allowing for the temperature drop between the brine and the ammonium in the evaporator, we obtain the desired minimum brine temperature:

$$\theta_{min} = -29 + 5 = -24° \text{ C}.$$

The thermal resistance of the frozen ground at which the brine temperature drops to its minimum value is determined from the formula (13).

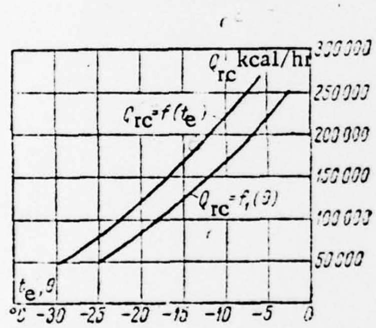

Figure 4. Characteristic of Compressors of Type 4 AU15.

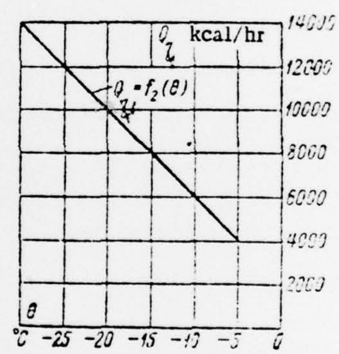

Figure 5. Cold Losses as a Function of Brine Temperature.

Utilizing Figures 4 and 5, we find that at brine temperature $\theta = -24°$ the operative cold capacity of the compressor is 55,000 kcal/hr and the cold losses are 11,000 kcal/hr. Then from formula (13) we find:

$$R_l = \frac{\theta_0 - \theta_{min}}{f_1(\theta_{min}) - f_2(\theta_{min})} = \frac{24}{55\,000 - 11\,000} = 5.55 \cdot 10^{-4} \text{ deg} \cdot \text{hr/kcal}$$

The thermal resistance which corresponds to the calculated frozen ground wall thickness is determined from the formula

$$R = \frac{n + X_1}{2\lambda L S}.$$

where X_1 is the half-thickness of the wall, equal in this case to 2 m.

From the works of Charnyy [8] we know that

$$n = \frac{S}{\pi}\ln\frac{S}{2\pi r_0}.$$

In this case

$$n = \frac{2}{\pi}\ln\frac{2}{2\pi\cdot 0.05} = 1.18\ \text{m}$$

and consequently when the calculated thickness is reached

$$R = \frac{1.18 - 2}{2\cdot 2\cdot 10\cdot 50\cdot 2} = 7.97\cdot 10^{-4}\ \text{deg}\cdot\text{hr/kcal}$$

We determine how brine temperature depends on the thermal resistance of the frozen ground by using these equations:

$$Q_{rc} = f_1(\theta)\ \&\ Q_{\tau} = f_2(\theta).$$

For instance, for the value of the brine temperature -15° we find from Figures 4 and 5 that the compressor's refrigeration capacity is equal to 125,000 kcal/hr, and the cold losses are 8000 kcal/hr.

By substituting these values into equation (9), we find:

$$R = \frac{\theta_0 - \theta}{f_1(\theta) - f_2(\theta)} = \frac{15}{125\,000 - 8000} = 1.28\cdot 10^{-4}\ \text{deg}\cdot\text{hr/kcal}$$

In the same way we will calculate the thermal resistance values of other temperatures.

The dependency $\theta = f_3(R)$ is presented in Figure 6.

After the thermal resistance reaches $5.53\cdot 10^{-4}$ deg·hr/kcal, the second freezing period begins during which the brine temperature is constant and equal to -24°C.

We will determine the heat resistance function of the columns from thermal resistance for the first period by using the previously calculated relationship between thermal resistance and brine temperature. For instance, from Figure 6 we find: when thermal resistance is $0.6\cdot 10^{-4}$ deg·hr/kcal, brine temperature is equal to -10°C.

By substituting these data into formula (11) we find:

$$Q_c = \frac{\theta_0 - f_3(R)}{R} = \frac{10}{0.6\cdot 10^{-4}} = 167\,000\ \text{kcal/hr}$$

During the second freezing period the heat absorption of the columns is calculated according to formula (12). For instance, when R = $6\cdot 10^{-4}$ deg·hr/kcal, we will find

$$Q_c = \frac{\vartheta_0 - \vartheta_{min}}{R} = \frac{24}{6\cdot 10^{-4}} = 40\,000 \text{ kcal/hr}$$

The way in which the heat absorption of the columns depends on thermal resistance is presented in Figure 7 and, along with the above-noted dependency of brine temperature in the columns on thermal resistance, makes it possible to solve the stated problem. We see that in this example freezing begins at a column heat absorption value exceeding 200,000 kcal/hr and ends at a value of 30,000 kcal/hr.

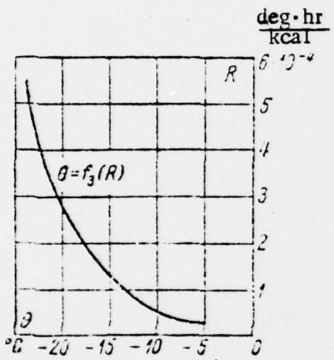

Figure 6. Calculated Dependency of the Brine Temperature Course.

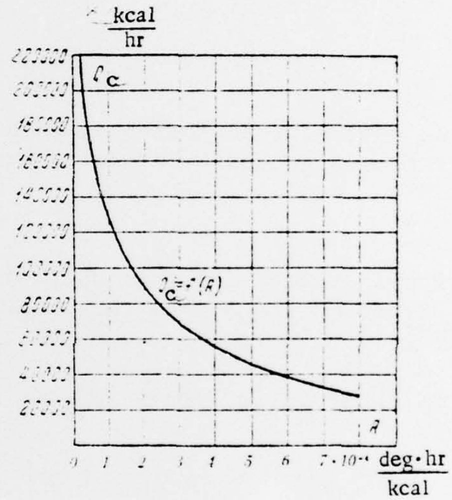

Figure 7. Calculated Dependency of the Change in Heat Absorption of the Freezing Columns.

In conclusion we should note that in a number of cases, for instance in calculating the freezing rate, it is necessary to express the heat absorption of the columns not only as the function of thermal resistance as we have done here, but also as a function of the geometric dimensions of the frozen ground: the radius of the cylinder or the thickness of the wall.

It is not difficult to make this transition by using the following relationships:

$$r = r_0 e^{2\pi LR} \tag{14}$$

and

$$X_1 = 2\pi LSR - n, \tag{15}$$

where, as before

$$n = \frac{S}{\pi} \ln \frac{S}{2\pi r_0}.$$

Obviously, relationship (14) is valid only until the frozen ground cylinders join, i.e., as long as $r \leqslant S/2$, and therefore

$R = \frac{1}{2\pi\lambda L} \ln \frac{S}{2r_0}$. After the cylinders join, it is necessary to use relationship (15).

The dependency of the columns' heat absorption on the geometric dimensions of the frozen ground can also be determined by directly substituting expressions $R = f(r)$ or $R = f(X_1)$ into computation equations (11) and (12).

4. Conclusions

The material analyzed in this article allows us to draw the following conclusions.

1. The heat absorption of freezing columns changes very significantly as the ground freezes. The law governing the change in the columns' heat absorption is determined by the characteristic of the refrigeration device and by the thermal resistance of the frozen ground.

2. It is necessary to distinguish between two freezing periods. During the first period the brine temperature drops, and during the second period the brine temperature is constant.

3. The course of the change in the columns' heat absorption during the first period is expressed by function (11), and during the second period it is expressed by function (12).

4. The moment of transition from the first to the second period of freezing is determined by formula (13).

5. We have to reject the generally accepted precept that the intensity of the heat absorption of freezing columns is constant and equal to 250 $kcal/m^2 \cdot hr$.

6. In some special cases it is permitted to carry out thermal calculations of freezing by assuming that the heat absorption of the columns or the temperature of the brine is constant (the average value of heat absorption in this case may differ significantly from the value of 250 $kcal/m^2 \cdot hr$). However, in these cases as well it is also necessary to first determine the actual course of the changes in the columns' heat absorption since it is only on this basis that these simplifications can be introduced.

The use of the proposed method of calculation may prove to be of value primarily where it is necessary to determine the value of the columns' heat absorption, if necessary as precisely as possible, for instance calculating the freezing rate of filtering ground, and in thermal calculations of large freezing objects and to check simplified design methods.

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