ENERGY CRITERION FOR ASSESSMENT OF EFFICIENCY OF UNDERGROUND STRUCTURES PLACEMENT

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ABSTRACT

For preliminary assessment of expediency of underground placement of structures with different purposes a criterion was developed that allows a comparison of energy expenses for creation and maintenance of normative microclimate parameters in the underground structure and its surface equivalent. Provided are examples of usage of the criterion in assessment of efficiency of construction of underground storages and refrigerators in different climate zones. An assessment of reliability of use of the criterion with random (stochastic) initial data was conducted. It was demonstrated that the use of the criterion in engineering practice is possible with both deterministic and stochastic character of initial data. It was determined that in many practically relevant cases, the underground placement of coolers allows to achieve decrease in operating costs of maintaining normative parameters of microclimate beginning already with the first year of the structure's exploitation. Over time, the efficiency increases, and the lower the normative temperature of storing the goods, the higher the energy efficiency of underground location as opposed to surface placement of the storage.

Keywords: *underground refrigerator, thermal regime, energy saving, reliability, efficiency*

INTRODUCTION

The use of underground space for storage of edible and industrial goods is one of the prospective directions of complex resource use that has been known for a long time [1], [2], [3], [4], [5]. At the same time, in the regions of the North where the average yearly temperature reaches minus ten to minus fifteen degrees Celsius, it is impossible to state with certainty that underground placement of storage chambers will be more efficient from the point of view of energy use (the energy expenses required to support a normative storage temperature). Especially taking into account the decrease in capital expenses, the construction of surface storage chambers with the use of contemporary thermal protection materials is considered more efficient [6]. The purpose of the present work is the general assessment of energy efficiency of placing the storage chambers and coolers underground in the conditions of continental climate characteristic for the far North.

In order to achieve this aim, a simple indicator of the energy efficiency (assessment criterion) will be introduced in the form of the following relation:

$$Э_N = \frac{N_п}{N_н}, \qquad (1)$$

Where $N_п$ - the amount of energy expended to support the given temperature conditions in the underground structure (J); $N_н$- correspondingly, in the surface equivalent of the structure (J);

It is clear that if $Э_N > 1$, it is not energetically efficient to locate the structure underground. For the surface structure, the value of $N_п$ can be roughly assessed according to this formula:

$$N_н = \sum_{i=1}^{3} N_{нi} , \qquad (2)$$

where $N_{н1}$ — the amount of energy lost through the surface of the structure (J); $N_{н2}$, $N_{н3}$ — the amount of energy incoming through ventilation of the structure and due to absolute sources of thermal radiation (J).

Considering that for single type of structure the values $N_{н2}$ and $N_{н3}$ have to be equal for both the surface and underground version, the equation for $Э_н$ can be presented in the form:

$$Э_N = \frac{N_{п1}}{N_{н1}} \qquad (3)$$

The value $N_{н1}$ will be determined using the formula:

$$N_{н1} = \int_0^{\tau} \sum_{i=1}^{к} \alpha_i F_i \left(t_п - t_в(\tau)\right) d\tau \text{ , J} \qquad (4)$$

where α_i— coefficient of thermal conductivity of i-th surface, W/м^2· K;

F_i— the surface with constant thermal resistance, м^2; $t_н$— air temperature in the structure, ºC; $t_в(\tau)$ — outside air temperature, ºC; τ — the duration of the considered period of time, h.

The value N_{nl} will be determined using the following formula:

$$N_{n1} = \int_0^{\tau} \sum_{i=1}^{k} k_{\tau i} F_i \left(T_e - t_в(\tau)\right) d\tau \text{ , J} \qquad (5)$$

where T_e - temperature of the rocks in the location of the foundation of the structure, °C;

$t_в(\tau)$ - temperature inside of the structure, °C; $K_{\tau i}$ - coefficient of non-stationary heat exchange whose value is determined based on the type of structure, W/м²·K; F_i - the surface of the thermal exchange, м².

For structures with cylindrical symmetry, the coefficient of non-stationary thermal exchange is determined using the formula [7]:

$$K\tau = \frac{\lambda}{R_0}\left\{\frac{Bi}{1+Bi\ell n\delta}\right\} = \alpha \cdot f(\tau), \quad (6)$$

where λ — coefficient of thermal conductivity of the rocks, W/м·K ; R_0 — equivalent radius of the structure, м.

The parameter δ is determined using the formulas presented in works [8], [9].

For a structure of spherical symmetry (chamber type) based on the following dependency [10]:

$$K\tau = \frac{\lambda}{R_0}\left\{\frac{Bi}{1+Bi/\delta}\right\} = \alpha \cdot f(\tau), \quad (7)$$

where δ is determined based on the dependencies from the work [11]. Here, *Bi* — Biot number; *Fo* — Fourier number.

An ideal case will be considered: the structures have equivalent surface of thermal exchange (the equivalent surface of the storage chambers); are exploited at a constant normative temperature; have an equal coefficient of thermal transfer. In the ideal case, the energy criterion is equal to:

$$\overline{Э}_N = \frac{\alpha \cdot f(\tau)(T_e - t_н)F}{\alpha_в(\bar{t}_в - t_н)F} = \frac{f(\tau)(T_e - t_н)}{\bar{t}_в - t_н} \quad (8)$$

Where $t_н$ — average yearly air temperature, °C. At the moment $\tau=\tau_{кк}$ the value $f(\tau) = f_0$, and $0 < f_0 < 1$. The analysis of expression (8) shows that with equal conditions of exploitation the equality of energy expenses will be achieved only in case when:

$$(\bar{t}_в - t_н) / (T_e - t_н) \le 1$$

Since according to the absolute values, the average yearly air temperature is always higher than the temperature of rocks at the depth of yearly temperature changes, the above condition can almost never be satisfied. From this follows that from the energy efficiency point of view, it is always more efficient to place the structures underground. The depth needs to be chosen such that it has minimum difference between the natural temperature of rocks and normative temperature in the structure.

A specific example of calculation of energy criterion for an underground cooling storage, located in a suburban area near Yakutsk, will now be considered. The natural temperature of rocks in the location region is -3°C. The average yearly air temperature in the Yakutsk region is -11,6°C. Exploitation temperatures in the cooling storage are -18°C and -25°C. The function f(τ), calculated according to the (6) and (7) formulas, equals 0,34 for the first year, 0,31 for the second and 0,29 for the third.

The values of energy criterion will correspondingly be equal, in case of the exploitation temperature being -18°C: 0,80; 0,73 and 0,68. In case of -25°C exploitation temperature, the values will be: 0,66; 0,60 and 0,56. That is, starting from the first year of exploitation, the energy expenses will be decreasing for the underground structure as opposed to the surface structure. The lower the normative temperature of exploitation for the structure, the more efficient it is to locate it underground.

Now, the energy efficiency of placing a structure with a positive exploitation temperature - for example, a vegetables storage - underground will be considered. The normative storage temperature is +4°C. Other parameters are the same as for the cooling storage. The values of the energy criterion for the first, second and third year will correspondingly be as follows: 0,15; 0,14; 0,13. That is, the total yearly energy expenses in case of underground placement of the vegetable storage will be 6,7; 7,1 and 7,7 times lower than in case of its surface equivalent.

Since the idea of introducing assessment criteria requires compactness and demonstrativeness, the time functions can be linearized with sufficient precision in case that t≥ ≥ 2 years. In this case, f(t) = a + bt and for the case considered f(t) = 0,34 – 0,015 t where t≥ ≥ 2 years. Considering this, the criterion will take a form convenient for the assessments:

$$Э_N = \overline{f}(\tau)\frac{T_e - t_н}{\bar{t}_в - t_н}, \quad (9)$$

where $\overline{f}(\tau) = 0{,}34 - 0{,}0075\tau$.

Any criterion has validity only when it is a stable indicator of the observed process or a phenomenon. The stability (reliability) of a criterion is determined by the extent of its dependence from random variation of the data. In case that within the given boundaries of the data indeterminacy the size of the mathematical expectation of the criterion changes within the boundaries of previously selected qualitative and quantitative characteristics, it is possible to speak about reliability (stability) of the given criterion. In the considered case, such a value for the criterion is the number equal to one. Therefore, if in the given degree of reliability of the result the value of the mathematical expectation of the criterion does not exceed one, it is possible to claim energy efficiency of the underground structure placement with the same degree of reliability. In the considered case the probability characteristic primarily applies to temperatures: temperatures of rocks, the outside air and the exploitation. The assessment of the criterion's stability will be conducted relying on the methodology described in the works [12], [13], [14]. We will consider that the criterion is representative with the given degree of reliability in case that:

$$Э'_N = Э_N \pm \kappa\sigma_N \;, \quad (10)$$

where κ = 1, 2, 3, ..., n and depends both on the way the random values are distributed and on the given degree of reliability; $Э_N$ - the value of the criterion calculated at the average value of the data; σ_N - the average quadratic error of the determination of the energy criterion.

The reliability of the assessment (the probability that the error does not exceed the maximum permitted value) depending on the value *K* and the way of dispersion is presented in the table [12].

The parameter σ_N can be found according to the formula:

$$\sigma_N = \sum_{j=1}^{n}\left(\frac{\partial Э_N}{\partial t}\sigma_j\right)^2 \quad (11)$$

where $\sigma_j = \Delta_j / 6$, Δ — maximum interval of possible variation in values of the observed parameter.

Having differentiated the expression (9), the following condition for finding the average quadratic deviation of the energy criterion is received:

$$Э_N = \overline{f}(\tau)\left\{\frac{\delta_T}{\delta_в} \pm \frac{\kappa\cdot\Delta}{6|\delta_в|}\sqrt{1+\left(\frac{\delta_T}{\delta_в}\right)^2}\right\}, \quad (12)$$

where $\delta_T = (T_e - t_н)$ and $\delta_в = (t_в - t_н)$.

Calculating the value of σ_N for previously considered examples where $\Delta_в$ = 4°C and $\Delta_т$ = 2°C. For the vegetable storage: $\delta_в$ = -17,6°C; $\delta_т$ = -7°C. For the cooler, correspondingly, at temperatures of -18°C and -25°C: $\delta_в$ = 6,6°C; $\delta_т$ = 15°C; and $\delta_в$ = 13,4°C; $\delta_т$ = 22°C. Calculation of the average quadratic error of the energy criterion when the vegetable storage is located underground:

$$Э'_N = \overline{f}(\tau)[0{,}4 \pm \kappa\cdot 0{,}021] \qquad \text{when } \kappa = 3$$

$$Э'_N = \overline{f}(\tau)[0{,}4 \pm 0{,}064]$$

As can be seen, with 99,7% reliability, the criterion is showing that in this case it is more efficient to locate the structure underground.

Having completed analogous calculations for the cooler (second year of exploitation) we will receive: at the exploitation temperature of -18°C and -25°C, we have, correspondingly: $Э'_N = 0{,}76 \pm \kappa \cdot 0{,}049$ $Э'_N = 0{,}53 \mp \kappa \cdot 0{,}021$

With $\kappa = 3$, it is possible to speak of energy efficiency of underground placement of the coolers with reliability of 99,7%. The lower the exploitation temperature in the cooler, the more efficient it is to locate it underground.

CONCLUSION

1. A simple, sufficiently reliable criterion for engineering calculations has been developed that allows to quickly conduct assessment calculations of energy efficiency of underground placement of storage chambers of coolers in comparison with their surface equivalents in different climatic zones.

2. It was established that in many cases significant for practice, the underground placement of storage chambers of coolers permits to decrease operating costs for maintaining the normative parameters of microclimate, starting from the first year of exploitation of the structure. In addition, the lower the given normative temperature of the goods storage, the higher the energy expediency of underground placement.

3. The further research needs to be directed to sectioning the territory of the country into regions using the developed criterion (depending on the geocryological and climatic conditions of regions) based on the level of energy efficiency of construction of underground coolers.

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