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Absolute heat sources as a method to check the accuracy of temperature prediction in underground structures within cryolithozone

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Abstract
Forecasting the thermal regime of mine workings and the surrounding rock mass is a necessary element of the design of underground structures in cryolithic zone. This is particularly necessary when substantiating and selecting reliable methods and means of rock supporting, in order to ensure safe operation of underground structures during the entire standard service life. Changes in the temperature of discontinuous permafrost rocks in the range of negative values (below the ice point in the rock) can lead to a decrease in their strength characteristics, and consequently to a decrease in the stability of workings. The aim of the research was to compare two ways of considering absolute heat sources (point sources and sources uniformly distributed along the length of a mine working) when forecasting the thermal regime in mine workings of underground structures. The dependencies used to determine temperature differences in various methods of considering absolute heat sources were established. For the sake of generality, the dependencies were produced in dimensionless (criterial) form. The variants were calculated, and the results are presented in the form of graphs. The aim is to visually present the influence of the method of heat sources when considering the accuracy of air temperature prediction in an underground facility. Key qualitative and quantitative features of the formation of thermal regime in workings at different methods of considering absolute heat sources were established. It was shown in particular that during the transition from a negative temperature in a working to a positive one, incorrect consideration of the action of absolute heat sources can lead to an almost 30 % (1.26 times) difference (i.e., error) in the calculated depth of thawing of discontinuous rocks.
It was also established that at a positive temperature, when the initial air temperature in a structure is more than 7.5 °C, there is no fundamental difference in engineering calculations results depending on the method of considering of absolute heat sources.

Keywords
underground structure, cryolithozone, safety, thermal regime, forecast, heat source, method of considering, temperature

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СВОЙСТВА ГОРНЫХ ПОРОД. ГЕОМЕХАНИКА И ГЕОФИЗИКА

Научная статья

Влияние способа учета абсолютных источников тепла на точность прогноза температуры в подземных сооружениях криолитозоны

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Аннотация
Прогноз теплового режима выработок и окружающего их массива горных пород является необходимым элементом проектирования подземных сооружений криолитозоны, в частности, при обосновании и выборе надежных способов и средств крепления породных обнажений, обеспечиваю-

щих безопасную эксплуатацию подземных сооружений в течение всего нормативного срока. Даже изменение температуры дисперсных мерзлых пород в диапазоне отрицательных значений (ниже температуры плавления льда в породе) приводит к уменьшению их прочностных характеристик, а следовательно, и к снижению устойчивости выработок. Целью исследований было сравнение двух способов учета абсолютных источников тепла (как точечных источников и как равномерно распределенных по длине выработки источников) при прогнозе теплового режима в горных выработках подземных сооружений. Получены расчетные зависимости для определения температурных отклонений при различных способах учета абсолютных источников. Для общности анализа расчётные зависимости получены в безразмерном (критериальном) виде. Проведены вариантные расчеты, результаты которых представлены в виде графиков, позволяющих наглядно оценить влияние способа учета источников тепла на точность прогноза температуры воздуха в подземном сооружении. Установлены основные качественные и количественные особенности формирования теплового режима в выработках при различных способах учета абсолютных источников тепла. В частности, показано, что при переходе от отрицательного теплового режима в выработке к положительному неправильный учет действия абсолютных источников тепла может привести к изменению глубины оттаивания дисперсных пород почти на 30 % (в 1,26 раза). В то же время установлено, что при положительном тепловом режиме для начальной температуры воздуха в сооружении больше 7,5 °С принципиальной разности для инженерных расчетов в способе учета абсолютных источников тепла нет.

Ключевые слова
подземное сооружение, криолитозона, безопасность, тепловой режим, прогноз, источник тепла, способ учета, температура

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Introduction

The reliability and safety of engineering structures in cryolithozone (permafrost zone) are largely determined by climatic conditions, and the variability of the properties of soils and rocks under the influence of external factors, natural [1–3] and anthropogenic [4–6] ones. This applies to both aboveground [7–9] and underground engineering structures [10–12]. The scientific community, engaged in research of the processes of interaction between engineering structures and frozen soils, have already established that the main technical and technological parameters determining the safe operation of underground structures in the cryolithozone (both mining and non-mining related) directly depend on the thermal regime of workings during their construction [13–15] and operation [16–18]. First of all, this can be explained by the temperature dependence of the strength characteristics of most frozen sedimentary host rocks [19–21]. Even changes in the temperature of frozen rocks in the negative value range (below the ice point in the rock, $T \leq T_{\text{melt}}$) can lead to a decrease in their strength characteristics. This can consequently lead to a decrease in the stability of workings [22–24]. Many types of discontinuous rocks, such as ice-saturated sandstones, have zero strength at positive temperatures [13, 16, 17]. Therefore, predicting the thermal regime of mine workings and the surrounding rock mass is necessary for the design of underground structures in cryolithic zone. This is the case, in particular, when substantiating and selecting reliable methods and means of rock supporting, thus ensuring safe operation of underground structures during the entire standard service life [14, 25, 26]. The thermal regime of mines and underground structures is determined by the action of two groups of heat sources: absolute and relative [13, 17, 27]. In this case, it would be appropriate to present a qualitative characterization of the groups of these sources, as given by A.F. Voropaev [17]. “The first group includes absolute heat sources that release heat, and heat and air by the same value at the same amount of released heat regardless of the actual air temperature. The second group includes relative heat sources, heat transfer and heating of air due to temperature difference – temperature head”. Relative heat sources include such sources as: the surface of mine workings; pipelines of various purposes; and transported minerals, inter alia. The group of absolute heat sources includes: energy losses in power grids; lighting devices; working machines and mechanisms, among others. A sufficient number of scientific studies consider various aspects of the influence of absolute heat sources [28–30], including diesel vehicles [29, 31, 32], on the formation of the thermal regime in underground structures of various purposes. In the construction of mathematical models for predicting the thermal regime in underground structures/workings, absolute heat sources as a rule are considered either as point sources, or as evenly distributed along the length of a working.

The aim of the research was to compare two ways of considering absolute heat release sources when predicting the thermal regime of mine workings in underground structures: a) as point sources; b) as sources uniformly distributed along the length of a working.

Research techniques

Taking into account the dependencies [17, 27, 33] previously obtained for the prediction of air temperature in mine workings of various purposes using the concept of unsteady heat transfer coefficient [34–36], the initial formulas for calculations can be written in the following form:

Temperature difference at the end point with different methods of considering absolute heat sources

$$\Delta t = t_{k1} - t_{k2} = Q_2[Z(Kr+1)-1], \quad Z = \exp(-Kr). \tag{1}$$

Temperature at the end of a working when a heat source is distributed along the whole length

$$t_{k1} = T_e + (t_0 - T_e + Q_1)Z. \tag{2}$$

Temperature at the end of a working under the action of a point heat source

$$t_{k2} = T_e + Q_2 + (t_0 - T_e + Q_2)Z. \tag{3}$$

The parameters included in formulas (1)–(3) are determined using the following dependencies:

$$Q_1 = \frac{q}{GC_p}; \quad Q_2 = \frac{q}{FK_\tau}; \quad \mathrm{Kr} = \frac{FK_\tau}{GC_p}, \tag{4}$$

where t_{k1}, t_{k2} – air temperature in the end of a mine working at the distributed (1) and point (2) heat source, °C; T_e – natural temperature of rocks, °C; t_0 – initial (at the entrance to a working) air temperature, °C; q – heat source power, W; G – mass flow rate of air in a working, kg/s; C_p – specific heat capacity of moist air, J/kgK; F – a working surface area, m^2; K_τ – unsteady heat transfer coefficient, W/m^{2}K; Kr – Kremnev criterion.

An unsteady heat transfer coefficient for mine workings of different symmetry can be determined using expressions familiar to mining thermal physics and given in [17, 27].

The formula for calculating the relative error that can arise in temperature prediction is as follows:

$$e = \left(1 - \frac{t_{k1}}{t_{k2}}\right) 100\ \%. \tag{5}$$

Following the known postulates for engineering calculations, we assume that if the condition $e \le 10\ \%$ is met, then the method of considering absolute heat sources in mine workings when predicting thermal regime is not crucial.

Findings Discussion

Analysis of the dependencies shows that, when using the first method (a point source), we formally change the initial temperature of the air supplied into a working. Considering absolute sources as uniformly distributed along the length of a structure (the second method) in the mathematical model is equivalent to a change in the natural temperature of rocks. The objective is to assess the degree of influence of the natural rock temperature and the initial air temperature in the structure on the accuracy of the temperature prediction at the end of a working. A simple comparison of formulas (2) and (3) allows an obvious conclusion to be drawn: the equality of temperature values at the end of a working, using different methods of considering the action of absolute sources, is possible only if the source power is zero. Therefore, the lower the source power, the lower the unknown difference in air temperature at the end of a working. Quantitative analysis should answer the following question: "At what power of absolute sources does the method of considering them in temperature predictions result in an error greater than the acceptable error in engineering practice?" In order to answer this question using the above formulas, variant calculations were carried out. The results are presented as 2D and 3D graphs in Figs. 1–4. Fig. 1 shows the temperature difference at the end of the calculation section of a working. This is taken as a function of Kremnev criterion Kr at different methods of considering absolute heat sources and at different reduced power of a source Q2.

The graphs show that the temperature difference in the considered range of initial data does not exceed 1.5 °C. Note that the following pattern is observed: the lower the source power and the value of Kremnev criterion, the lower the difference in air temperatures at the end of a working. Thus, the dependence of the final result on the method of considering absolute heat sources becomes weaker with lowering the source power.

Fig. 2 presents 3D graphs of the temperature difference at the end of the calculation section of a working. This is a function of Kremnev criterion Kr and reduced power of a source Q2 at different methods of considering absolute heat sources.

The graphs in the Figure show that when we consider a heat source as distributed along the length, we always underestimate the air temperature at the end of a mine working. Note that this does not depend on the value of power of the sources Q2 operating in a working, or the conditions of heat exchange of air with rocks. Thus, the error cannot be attributed to the calculation features (design margin). The absolute value of the temperature difference (Fig. 3) is relatively low on the whole when considered (typical for underground structures in cryolithozone) range of variation of the initial parameters of the thermal regime simulation.

The graphs show that for the characteristic operating conditions of underground structures in cryolithic zone, the temperature difference does not exceed 1.6 °C. This value could be considered quite acceptable, since it is within the accuracy of the engineering forecast. However, it should be notes that this difference may not always be attributed to the calculation features. For example, when selecting the method and means for working supports, one of the key design parameters is the depth of rock thawing. Thawing depth and air temperature are related to

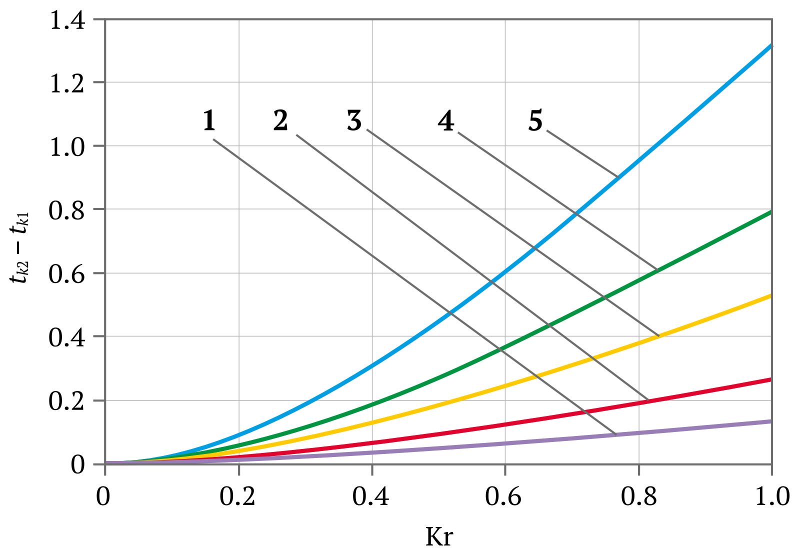

Fig. 1. The temperature difference (°C) at the end of the calculation section of a working as a function of Kremnev criterion Kr at different methods of considering absolute heat sources and at different reduced power of a source Q2: *1* – 0.5; *2* – 1.0; *3* – 2.0; *4* – 3.0; *5* – 5.0

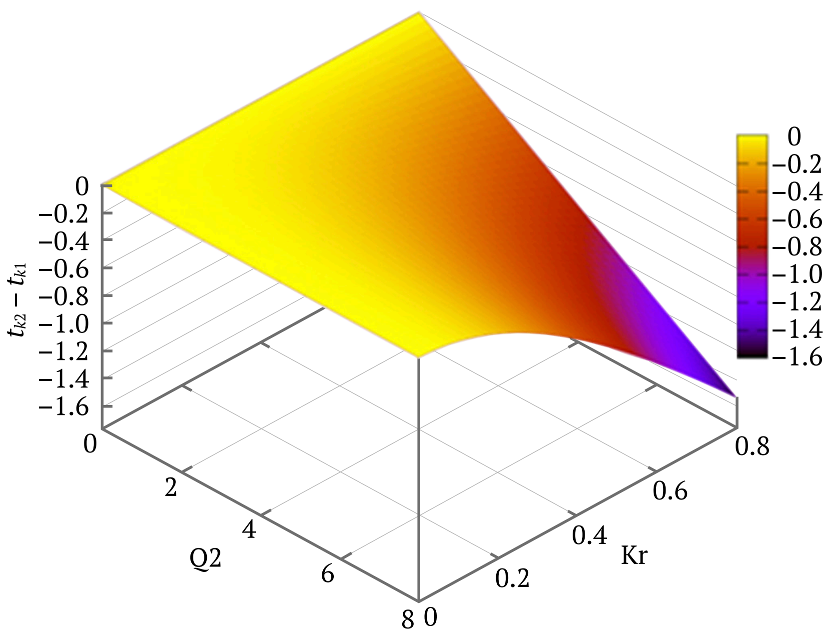

Fig. 2. The difference in air temperature (°C) at the end of the calculation section of a working as a function of Kremnev criterion Kr and reduced power of a source Q2 at different methods of considering absolute heat sources

each other by a relationship close to a quadratic. For example, when temperature positive-going zero crossing in an underground structure due to the action of absolute heat sources happens, the change in air temperature in the structure by 1.6 °C (all other conditions being equal) will lead to an increase in the thawing depth by 1.26 times. This exceeds the allowable value of 10 % in engineering practice. Therefore, in such cases, it is necessary to rely on the calculated value obtained by modeling absolute sources as point sources. In this case, the choice of the method of considering sources is decisive for obtaining a correct and reliable final result of the calculation of the design parameter. Naturally, everything referred to above depends on the initial air temperature in an underground structure. Fig. 4 shows the area of initial temperatures, at which the error in calculating the thawing depth will not exceed the permissible value (highlighted in blue in the figure).

If the initial air temperature in a structure is less than or equal to about 7.5 °C, then the method of considering absolute sources is important for the accuracy of the temperature prediction. Otherwise, the method is not important.

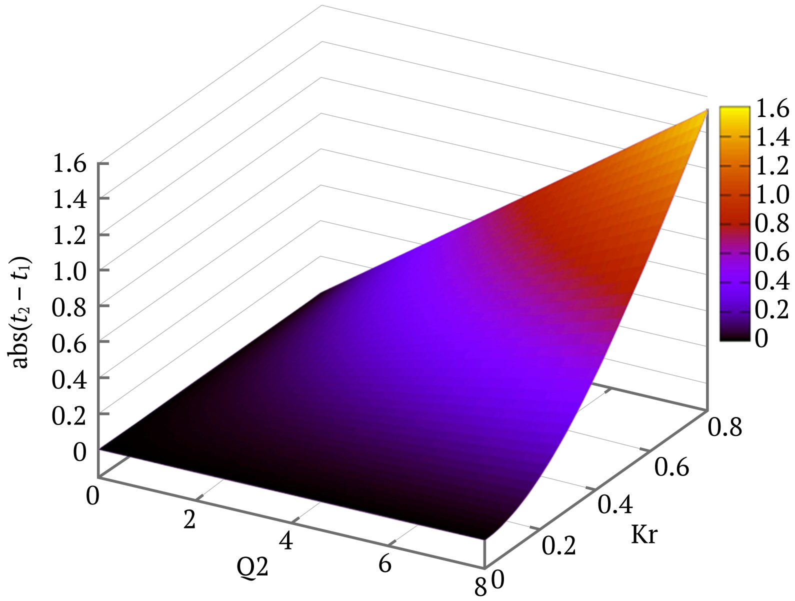

Fig. 3. Absolute value of the air temperature difference (°C) at the end of the calculated section of a working as a function of Kremnev criterion Kr and reduced power of a heat source Q2

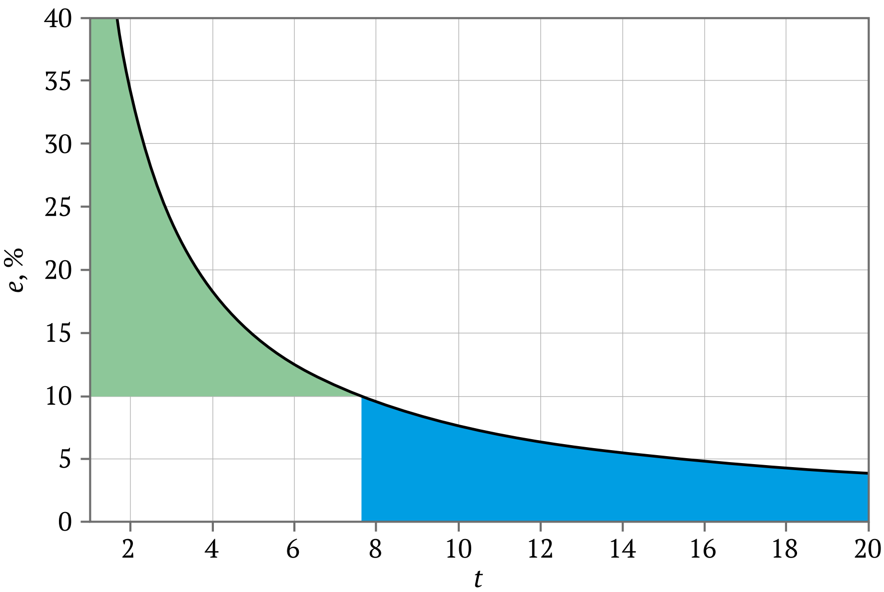

Fig. 4. Error in determining the depth of thawing of frozen rocks around an underground structure as a function of initial air temperature t, °C

Conclusion

Key conclusions, practical significance of the study, and the area of future research. Qualitative and quantitative assessment was undertaken of the effect of the method of considering absolute heat sources on predicted air temperature in mine workings when forecasting the thermal regime of underground structures in cryolithozone. Two possible ways were considered of taking into account absolute heat sources in the mathematical modeling of heat processes in mine workings: point sources, and sources uniformly distributed along the length of a working. The study presents formulae for determining the air temperature at the end of a mine working depending on the method of considering absolute heat sources. For the sake of generality of the analysis, the calculation formulas are presented in the form of functional dependences on Kremnev criterion and the reduced total power of absolute heat sources. Qualitative analysis of the dependencies obtained showed that using the first method of considering (as a point source) is equivalent to the change in the initial temperature of the air supplied into a working. Considering absolute sources as uniformly distributed along the length of a structure (the second method of considering) in the mathematical model is equivalent to a change in the natural temperature of rocks. Quantitative analysis showed, in particular, that the lower the source power and the value of Kremnev criterion, the smaller the dependence of the final result (air temperature at the end of a mine working) on the method of taking into account absolute heat sources when predicting thermal regime. As an example, we considered the influence of the method of absolute sources on the accuracy of predicting the depth of thawing of discontinuous frozen rocks around a working. It was shown that during the transition from a negative temperature in a working to a positive one, incorrect consideration of the action of absolute heat sources can lead to an almost 30% (1.26 times) difference (i.e., error) in the calculated depth of thawing of discontinuous rocks. This can produce a significant impact on the selection of support parameters of mine workings driven in discontinuous frozen rocks, which (the selection) directly depends on the temperature regime of the rocks. It was also found that at a positive temperature, when the initial air temperature in a structure is more than 7.5 °C, there is no fundamental difference in engineering calculations results depending on the method of considering absolute heat sources. On the whole, it was found that for the characteristic conditions of construction and operation of underground structures in cryolithozone, such as underground gold mines, there is no fundamental difference in the methods of considering absolute heat sources when predicting the thermal regime. The differences in the values of air temperature at the end of a mine working obtained using different methods of consideration, as a rule, do not exceed the values allowed in engineering practice.

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