Calculation of thermal conductivity coefficient of thermal insulation mixtures

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Abstract. The majority of prospective deposits of oil and natural gas in the Russian Federation are located in the zones of permanently frozen rocks - the permafrost. This region is characterized not only by harsh climatic conditions, causing difficulty in development of the deposits, but also by negative cryogenic processes impacting the reliability of construction and use of various engineering structures. It is necessary to know the regularities of and to be able to forecast the thermal regime of the soils and rocks in order to forecast the degree of influence of cryogenic processes on the engineering structures. In particular, the depth of thawing and freezing of soils in the locations of underground and surface structures, such as pipelines, is of importance. The depth of thawing of soil is an important indicator for the choice of the method of construction on the frozen surfaces. Control of the thawing/freezing depth can be ensured with the use of thermal insulation as well as replacement of the soil itself with an artificial soil with preselected properties. Transportation of oil and natural gas is realized using pipelines laid through frozen rocks. In order to decrease cryogenic impact on the pipes, special thermal insulation beddings replacing a section of soil are used. To determine the thermal insulation properties of beddings made out of polystyrene, variant calculations of thermal conductivity coefficient have been done according to the Odelevski and Schwertfeger formulas. Calculations were done for beddings in thawed and frozen state with different polystyrene content concentration. The conclusion is that both formulas can be used for theoretical determination of thermal conductivity coefficient. Absolute and relative errors do not exceed those permissible in engineering calculations for a wide range of conditions.

1. Introduction

The majority of prospective deposits of oil and natural gas in the Russian Federation are located in the zones of permanently frozen rocks - the permafrost. This region is characterized not only by harsh climatic conditions, causing difficulty in development of the deposits, but also by negative cryogenic processes impacting the reliability of construction and use of various engineering structures. [1,2,3,4]. Frost cracking and bursting of soils and periodic freezing and thawing of rocks are examples of such negative processes. It is necessary to know the regularities of and to be able to forecast the thermal regime of the soils in order to forecast the degree of influence of cryogenic processes on the engineering structures. In particular, the depth of thawing and freezing of soils in the locations of underground and surface structures, such as pipelines, is of importance.[5,6,7,8]. The depth of thawing of soil is an important indicator for the choice of the method of construction on the frozen surfaces [9,10]. Control of the thawing/freezing depth can be ensured with the use of thermal insulation as well as replacement of the soil itself with an artificial soil with preselected properties.
The first method is typically applied in construction of residential and industrial buildings, underground structures and mining ranges when mineral deposits are developed using the open-pit method. The second method is usually applied in construction of linear engineering structures in frozen soils. For example, structures such as railroads and roads, underground laying of water supply pipes, gas supply pipes and cable communications lines. This method allows for control of such important thermal physical parameters of soils as humidity and thermal conductivity. It is important to note that for a majority of rock types (soils), these two parameters are closely connected. The higher is the humidity of frozen rocks (soils), the higher is their thermal conductivity coefficient. During the thawing of rocks (soils), their thermal conductivity coefficient decreases because the thermal conductivity coefficient of water is almost four times lower than the thermal conductivity coefficient of ice. In addition, because of the change in the volume of pores and cracks filled with moisture during the thawing of rocks (soils), the amount of air in the pores increases, which also leads to a decrease in the thermal conductivity coefficient of rocks (soils). For this reason, it is important to be able to precisely forecast the change of thermal physical characteristics of the artificial soils when choosing the type and granulometric composition of the soil for the construction and use of engineering structure (facility).

For protection from cryogenic impacts (mounding, cracking caused by frost), various thermal insulation beddings [11] are applied to linear utility constructions (cable systems, water pipes) located in the active soil layer (the layer where the water state changes), replacing a section of the soil around the utility construction.

Use of polystyrene granules as a bedding is one of the efficient methods of such protection. However, over time, watering of the bedding takes place and both its thermal resistance and thermal protection properties deteriorate rapidly. As constant water state changes are occurring in the process of freezing and thawing of the active soil layer, the change in the thermal conductivity coefficient of the bedding is season-dependent.

For accurate prognosis of the depth of the active soil layer, which in many ways determines the extent of cryogenic impact on the utility construction, it is necessary to know the change in thermal conductivity coefficient of the bedding depending on the degree of watering and aggregate state of the water. The purpose of this work is the analytical determination of the thermal conductivity coefficient of watered polystyrene bedding in the thawed and frozen state.

2. Methodology

For analytical determination of the thermal conductivity coefficient watered polystyrene bedding will be considered as a structure with closed inclusions where the connecting component is ice (water) and the polystyrene granules themselves represent the inclusions. For similar structures, classical formulas of Odelevski [12,13,14] and Schwerdtfeger [13,15], received for calculation of binary mixtures, are used to determine the thermal conductivity coefficient. It is also of interest to determine the extent of possible discrepancies in results of calculations based on the two formulas. That is, to determine the reliability of the prognosis. The calculation algorithm was formulated in the following way.

1) Determine the thermal conductivity coefficient of ice with polystyrene inclusions according to the Odelevski and Schwerdtfeger formulas. 2) Determine thermal conductivity coefficient of water with polystyrene inclusions according to the Odelevski and Schwerdtfeger formulas. 3) Calculate the absolute and relative margin of error of the thermal conductivity coefficient calculation for every aggregate state. 4) Compare the thermal conductivity coefficients of mixtures depending on the polystyrene content.

The original formulas have the following form:

- Odelevski formula [14].
where:

- $\lambda_{sv}$ - coefficient of thermal conductivity of the binding material (water or ice), W/(m K);
- $\lambda_{vk}$ - coefficient of thermal conductivity of polystyrene granules, W/(m K);
- $m$ - relative volume content of polystyrene granules.

The initial values for variation calculations were as follows. The coefficient of thermal conductivity of polystyrene granules is equal to 0.037 W/(m K). The thermal conductivity coefficient of water is 0.6 W/(m K). The thermal conductivity coefficient of ice is 2.0 W/(m K). The relative volume content of granules in the mixture in the solid (ice) and liquid (water) was changing from 0 to 1.

3. Examples

Results of variant calculations of the thermal conductivity coefficient of the bedding in the thawed and frozen strata have been conducted while changing the percentual share of granules in total volume from 0 to 1 (0 to 100%). It needs to be taken into account, that the border values of 0 and 1 were selected for checking the compliance of formulas to limit characteristics and do not have a practical meaning of their own. For better illustration, the results of calculations based on the Odelevski formula ($\lambda_1$) and Schwerdtfeger ($\lambda_2$) are presented as graphs on figure 1. and figure 2. for every researched material. In addition, graphs on figure 3. and figure 4. are presented which are describing the change in absolute and relative margin of error of determination of thermal conductivity coefficient depending on the composition (percentual content of polystyrene) in the ice-polystyrene mixture.
Figure 1. Values of the thermal conductivity coefficient of a mixture of ice and polystyrene.

Figure 2. Values of thermal conductivity coefficients of a mixture of water and polystyrene.

Figure 3. Absolute margin of error (W/m K) of determination of thermal conductivity coefficient of a mixture of ice and polystyrene.

Figure 4. Relative margin of error (%) of determination of thermal conductivity coefficient of a mixture of air and polystyrene.
4. Conclusion
Analysing the calculation results it is possible to arrive at the following conclusions. For both watered thawed mixture and mixture in the frozen state both calculation formulas are yielding similar results. The absolute margin of error in the calculations does not exceed 0.14 and 0.036 W/(m K) correspondingly for mixture in frozen and thawed state. The relative margin of error does not exceed 10% in either case, which is acceptable in engineering calculations. Independently of aggregate state of the water in the mixture, the maximum discrepancy in calculation results of the two formulas is observed when the concentration of polystyrene is around 15%. This option is rather hypothetical in practice. In the area of real concentrations, the formulas are giving very similar results and in practical calculations it is possible to use either of them.

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