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Screening Optimal Thickness of an Underground Pipeline's Thermal Insulation with the Aim of Minimizing Thawing Halo in the Ground in Conditions of Central Yakutia

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Abstract. The paper describes a study of thermal interaction between underground gas pipeline and surrounding permafrost and seasonally thawing soil. A forecast of the soil's thermal mode depending on thermal insulation on the pipeline is made by means of numerical simulation with finite elements method. The analysis accounts for air temperature, thermal radiation balance of the ground surface, wind speed and snow thickness.

1. Introduction

Development of gas fields in remote arctic areas raises up a need to build in-field and cross-counrty main gas pipelines in permafrost. Thermal interaction of the gas pipeline with permafrost can lead to negative phenomena both inside the pipeline itself and in surrounding soils. For instance, cooling the gas can lead to the formation of its hydrates [1-7]. Further, the effect of heated gas on frozen ground can lead to its thawing, and on the other hand, the effect of throttling during transport will cause cooling of natural gas and, consequently, cooling of surrounding soils. Both thawing and freezing can cause a variety of destabilizing effects, such as subsidence of the upper layer of the soil massif, frost punching, erosion [8, 9].

In [2-7], the conjugate problem of heat exchange between an imperfect gas in a pipeline and the environment (rocks) is considered. The problem is reduced to solving differential equations describing the non-isothermal flow of gas in the pipeline and the heat-transfer equations in rocks with the corresponding conjugation conditions. In this case, the quasi-stationary mathematical model of formation (dissociation) and hydrate deposition in gas wells [2-6] and gas pipeline [7] takes into account the dependence of the heat transfer coefficient between the gas and the hydrate layer on the time-varying cross section of the flow over time. In this model, the flow of real gas in the pipes is described in the framework of pipe hydraulics. And the dynamics of hydrate formation is described in the framework of the generalized Stefan problem, where the temperature of the gas-hydrate phase transition depends critically on the pressure in the gas flow. It is shown that hydrate plugs formation time increases significantly with the conjugate formulation, in contrast to the case when the temperature of the surrounding rocks is considered constant. It was shown in [7] that if the gas is not dried sufficiently, the gas pressure at the outlet can fall below the permissible limit in about 6 to 7 hours, and for completely dry gas it is possible to reduce the cost of thermal insulation of the pipeline at least twice.

The purpose of this study is to analyze the thermal interaction of a main gas pipeline with the surrounding permafrost by means of numerical simulation, at various thicknesses of thermal insulation on the pipeline, taking into account weather conditions on the surface, but not considering formation of gas hydrates.

2. Numerical simulation

The gas and soil temperatures are calculated sequentially at each time step. First, the gas temperature and pressure are calculated, then, knowing the temperature of the gas and taking into account the convective heat transfer condition on the pipeline wall, the temperature of the surrounding soil is determined. To describe the change in the temperature of a gas flowing in a pipe, equations from the monograph [1] are used.

Calculation of the temperature field in the ground is carried out in two-dimensional domains, in a plane perpendicular to the axis of the gas pipeline. Here the Stefan problem is solved using the finite element method without explicit identification of the phase transition front [11] [12]. On the upper side of the two-dimensional domains, a third type boundary condition is set with the mean monthly values of the air temperature and the thermal radiation balance. In this case, we take into account the dependence of the convection coefficient of the ground surface on the wind speed and snow cover. On the other boundaries of the two-dimensional domains, i.e. on the conditional distance of the thermal effect, the heat flux is assumed to be zero.

The sizes of the two-dimensional domain are 15 m in depth and 20 m in width, diameter of the gas pipeline – 1.4 m, depth of the gas pipeline – 2 m from the surface, calculation time – 2 years, time step – 1 month, mesh size – 0.5 m. The length of the gas pipeline is 100 km and the mesh size for the calculations of gas dynamics is 2 km.

Physicochemical properties of the soil are selected as the most typical for Central Yakutia: volumetric heat capacity of a frozen soil is $2.31\cdot10^6$ J/(m$^3\cdot$°C) and of a thawed soil is $2.57\cdot10^6$ J/(m$^3\cdot$°C), thermal conductivity of a frozen soil is 1.93 W/(m·°C) and of a thawed soil is 1.69 W/(m·°C), phase transition temperature – 0.15 °C, wet soil density – 2000 kg/m^3, moisture content – 12%, initial temperature – 4.85 °C.

Inlet gas temperature – 30 °C, inlet pressure – $7.6\cdot10^6$ Pa, hydraulic resistance coefficient – 0.02, specific heat of the gas at constant pressure – 2300 J/(kg·°C), critical temperature – 205.022 °C, critical pressure – $47.213\cdot10^5$ Pa, gas constant – 449.4 J/(kg·°C), flow rate – 500 kg/s. An extruded polystyrene foam with a thermal conductivity of 0.031 W/(m·°C) is considered as the heat-insulating material of the pipeline. Thermal insulation thicknesses of 1 cm, 5 cm, 10 cm and 15 cm are studied.

Climatic data on air temperature, radiation balance of the surface and height of the snow cover are taken from Fedorov et al [13] for the conditions of the city of Yakutsk. Data on snow density are taken from Pavlov [14], data on wind speed – from Gavrilova [15].

All the monthly and ten-day averages data were interpolated using cubic splines.

3. Results

As output of the simulation, the temperatures of the gas and the surrounding soils were determined for several versions of the thermal insulation. Fig. 1 and Fig. 2 show, respectively, the distributions of gas temperature and pressure along the pipeline for different thicknesses of the thermal insulation layer.

The pressure distribution depends little on the thermal insulation of the pipeline (Fig. 2). The gradual decrease in temperature along the pipeline is due to heat exchange with the ground and the throttling effect. In the case where the pipeline is not heat-insulated, the gas cools to the point when its temperature is compared with the surrounding ground (Fig. 1).

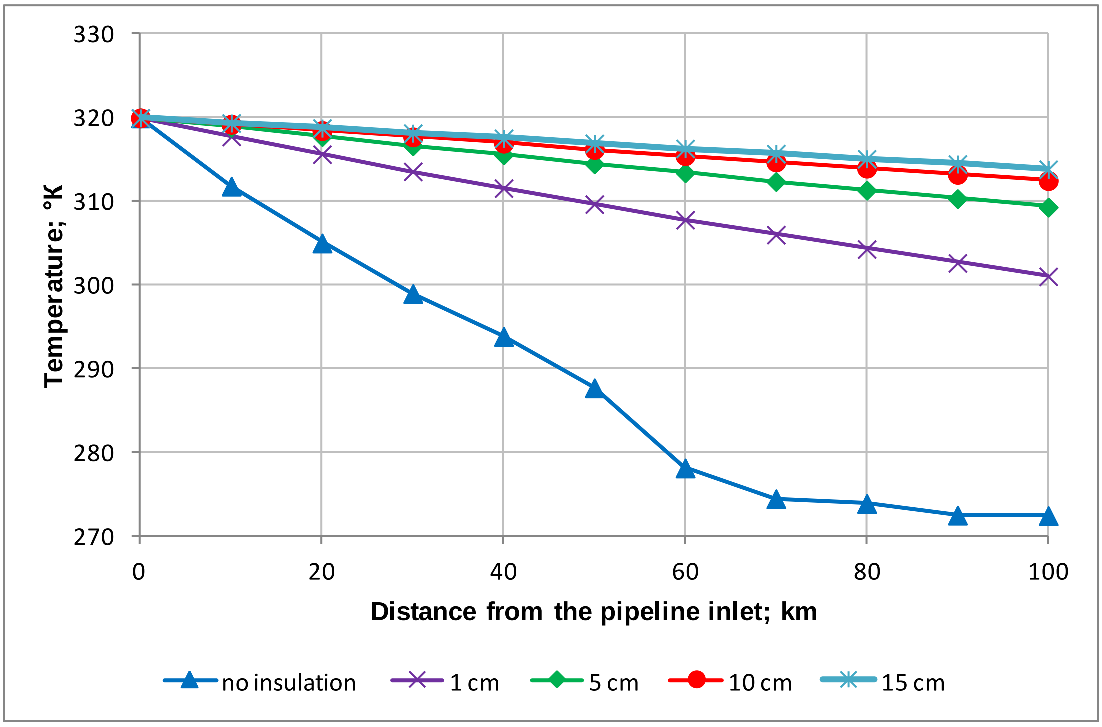

Figure 1. Distribution of the gas temperature along the pipeline for various thicknesses of thermal insulation.

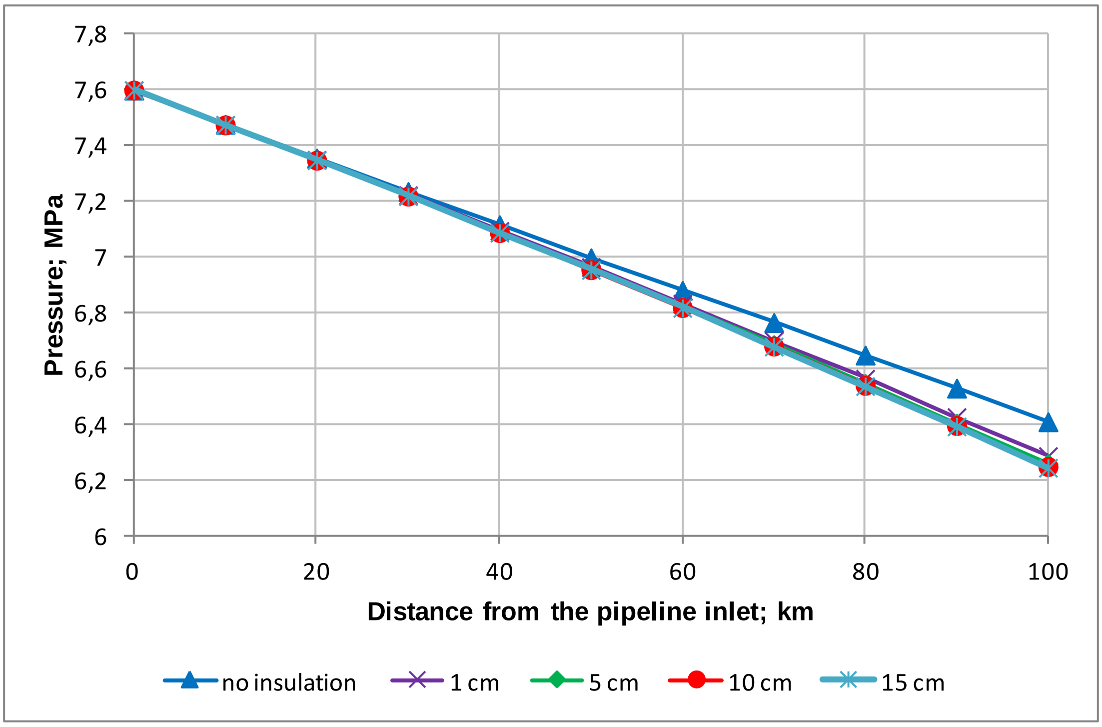

Figure 2. Distribution of the gas pressure along the pipeline for various thicknesses of thermal insulation.

Fig. 3 shows the behaviour of the radius of thawing under the gas pipeline near its inlet with different thicknesses of thermal insulation for 2 years of operation. It can be seen that a 1-centimeter layer of extruded polystyrene foam does not show significant effect on the thermal regime of the surrounding soil. With an increase in the thickness of the heat-insulating layer to 5 cm, the radius of thawing decreases by a factor of approximately two, and with further increase in thermal insulation to 10 cm, it again decreases by a factor of two. Further bringing the thickness of the heat-insulating layer to 15 cm does not reduce the radius of thawing substantially.

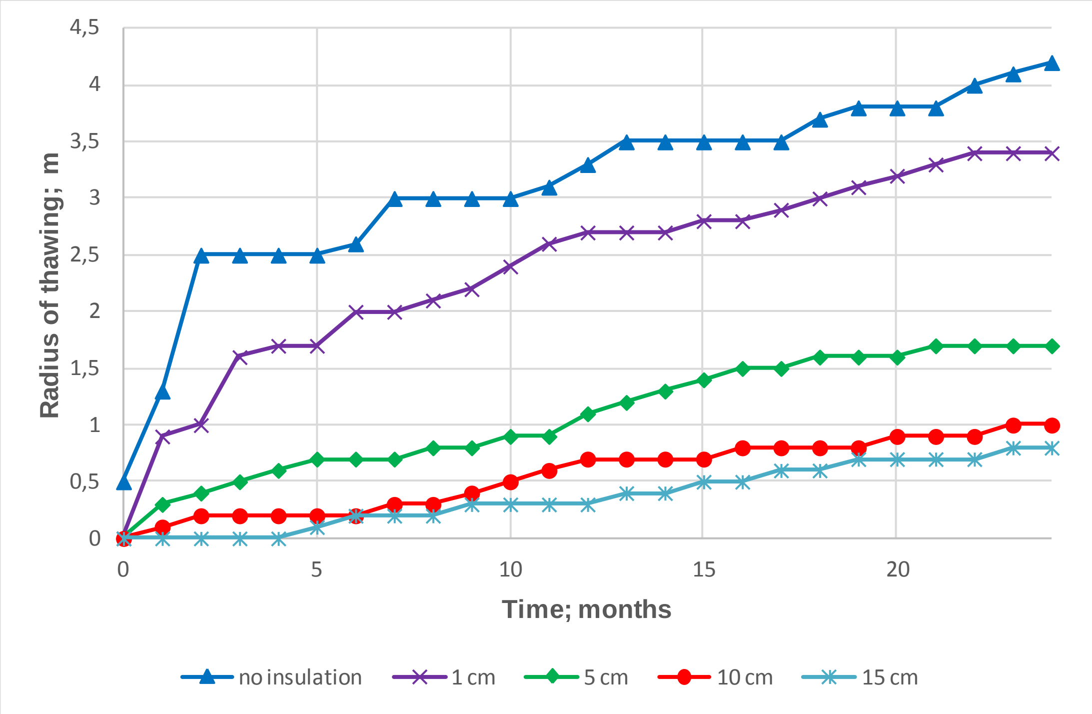

Figure 3. 2-year forecast for the radius of thawing under the gas pipeline on its initial interval for different thicknesses of thermal insulation.

4. Conclusion

Numerical simulation of the thermal interaction of an underground main gas pipeline with surrounding permafrost is carried out. It was revealed that in the course of flow through the pipeline, the heated gas is cooled and its pressure is reduced due to the throttling effect and the heat exchange with frozen soil. If there is no thermal insulation on the gas pipeline, then the gas temperature after some distance is compared with the ground temperature.

It is established that a layer of extruded polystyrene foam more than 5 cm on the main gas pipeline can significantly reduce the warm gas's heating effect on frozen ground.

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