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Modeling heat transfer processes in heating systems for surface of highways

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Modeling heat transfer processes in heating systems for surface of highways

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Abstract. At present, icing of the road surface has a significant impact on traffic safety, which reduces the coefficient of adhesion of tires by 5–10 times. In order to reduce this negative effect in winter, frictional, chemical, physical-chemical and combined methods of struggle are used. In this case, one of the most promising ways to combat icing is to use a hydraulic system for snow melting. This is due to the possibility of laying not only individual systems of snow melting under the road surface, but also urban heat communications on road sections subject to frequent ice formation. In this regard, the modeling of heat transfer processes in heating systems for road surfaces is relevant. The proposed mathematical description, as well as its implementation in the Abaqus software package based on finite element calculations, makes it possible to determine the temperature on the surface of the highways taking into account the coolant supply, the location of pipes, their diameter and depth, air convection temperature and a number of other parameters. In this regard, the developed simulation model of the hydraulic system for heating the surface of highways will be widely used in the reconstruction of road surfaces, as well as for the optimization of heating network laying systems.

1. Introduction

The formation of winter slipperiness is one of the winter factors that most adversely affects the road situation. With the formation of slipperiness, the coefficient of adhesion to the road decreases from the normative 0.7–0.8 to 0.08–0.15 [1], and because of this, the number of road accidents increases. This reduces the mobility of the vehicle and interferes with the optimal functioning of the overall transport systems. According to official figures, more than 1.5 million accidents occur due to bad weather conditions, resulting in about 7,000 deaths and 800,000 injuries annually. This leads to losses for the economy up to 3% of GDP [2], hence, the fight against winter slipperiness is one of the important problems of the road sector.

In Russia, namely in the Far East, in a region with cold, long winters, the operation of road transport infrastructure in the winter period of the year is an urgent problem that requires constant attention of road specialists and scientists who study and research new effective technologies for the operation and maintenance of highways in winter.

Winter conditions are characterized by snowfalls and blizzards, which form snow deposits, in addition, in winter there is a short daylight and low air temperature [3–5].

Clearing snow in winter conditions is of paramount importance for the safe operation of vehicles and pedestrian traffic. Anti-icing is carried out mainly by chemical methods, therefore large masses of chemical reagents enter the water bodies and the earth's surface, leading to significant changes in the chemical composition of the main components of the environment (soil, water, air), causes a change and destruction of the species composition organisms living in them [6–11, 19, 20].

2. Existing technologies for removing snow and ice from surface of highways

The main type of snow removal from roads is patrol snow cleaning, in which periodic passes of plow or plow-brush snowplows are made during the entire blizzard or snowfall. Patrol snow removal is carried out by single machines or by a detachment of plow-brush snowplows, moving at intervals of 30–60 m with the movement of snow from the axis of the road to the side of the road with overlapping the clearing strip of 0.3–0.5 m.

In the state members of the Customs Union, as well as abroad, the following methods of dealing with winter slipperiness are distinguished: frictional, chemical, physicochemical, combined.

Combined, chemical and frictional methods are aimed at increasing the frictional properties of the coating or melting snow-ice deposits with chemical reagents. There is a fairly extensive classification of deicing materials (DIM), but we will only consider its main provisions.

Friction DIMs should increase the coefficient of adhesion with snow and ice deposits on the surface to ensure safe driving conditions; have high physical and mechanical properties that prevent the destruction, wear, crushing and grinding of DIM, and should have properties that prevent an increase in dust content in the air and pollution of the roadside.

Chemical DIMs are used in solid, liquid and moisten form. The raw materials for obtaining these materials are most often natural reserves of bischofite, halite or industrial waste, for example, sylvinite or carnolite waste. According to the chemical composition DIMs of this group are divided into four subgroups. The first subgroup is chlorides. It includes DIMs based on $NaCl$, $CaCl_2$ and $MgCl_2$. The second subgroup is acetates, the third subgroup is carbamides and the fourth is nitrates.

The main purpose of using anti-ice reagents is to reduce the freezing point of snow and ice. Deicing reagents do not use heat to physically or chemically melt, these chemicals are usually applied before snowfall to prevent the road from freezing by lowering the freezing point of the water and therefore making it easier to remove the slush.

Combined DIMs have at the same time the functions of friction and chemical materials and consist of a mixture of sand and chemical DIMs. Solid salts are used as chemical additives: technical sodium chloride, salt of sylvinite dumps and calcium chloride.

The physico-chemical method is to impart deicing properties to the road surface by introducing deicing fillers into the asphalt concrete mixture. This method is used on sections of roads subject to frequent ice formation (sections in mountainous areas, near water bodies, thermal power plants, on bridges, overpasses, overpasses).

To prevent the formation or eliminate winter slipperiness, the following measures are taken:

- preventive treatment of coatings with anti-icing materials before the appearance of winter slipperiness or at the beginning of snowfall, in order to prevent the formation of a snow run;
- elimination of snow and ice deposits using chemical or combined DIM;
- processing of snow and ice deposits with friction materials.

The experience of the municipalities of Canadian cities (Montreal, Ottawa, Toronto) in cleaning streets in winter is of considerable interest [12, 13, 17].

Recycling of the snow mass taken out from the urban area is carried out on "dry" snow dump sites. These snow dumps are fenced areas where snow is transported and moved by bulldozers and powerful augers into a stack 20–30 meters high. Melting is carried out by natural heat. The base of the site is made of compacted asphalt granulate cut off during the repair of asphalt road surfaces.

All existing thermal methods for removing snow-ice mass from the surface of the road surface by melting it when exposed to a flow of thermal energy can be divided in the direction of this flow into two types:

- the heat flow is directed from the heat source to the upper boundary of the snow layer – outer;
- the heat flow is directed from the heat source to the lower boundary of the snow layer – internal.

The basis of any thermal system for snow melting or anti-icing is the heating medium distribution system (pipelines for heat transfer fluids, steam pipelines for steam and air ducts (or gas ducts) for gaseous media), that is, a system for heating the surface of road. Thermal snow melting systems are used to heat runways, difficult road sections, bridges, snow melting areas, sidewalks and garage entrances.

3. Snow melting hydraulic systems

One of the advantages of using a hydraulic system is that many heat sources can be used: gas boilers, fuel oil boilers, electric heaters [14]. Unlike electrical systems, hydraulic systems use pipes or heated pipes. The hydraulic pipes are embedded in the concrete slab so that the heat transfer medium in these pipes generates heat energy. Heat is transferred from the coolant to the pipes and then from the heated pipes to the concrete. Consequently, the temperature of the concrete increases, resulting in snow melting on the surface [18].

The hydraulic system includes four main components: a heat source, a circulation pump, a heating medium and a piping system. The most important element is the piping system.

The main idea behind a hydraulic system for melting snow is that the pipelines have a closed loop, which allows the fluid to circulate in the pipe and transfer heat equally throughout the system, without creating any "streaks" on the road surface at low temperatures. The circulating pump is designed to make the heating medium flow in the pipes at an appropriate speed and direction. When the liquid leaves the inlet, it has a higher pressure, after the liquid has passed through the closed circuit of the pipes, it returns to the inlet with a lower pressure.

Deciding what type of piping to use in a hydraulic system is extremely important. Typically, there are two main types of arrangements: back-return and serpentine.

Figure 1 shows a typical hydraulic system for melting snow. This system includes a concrete slab or sidewalk and hydraulic pipes (for simplicity, there is no need to model the insulation as the slab is in the ground). In this case, the heated pipes embedded in the concrete slab are U-shaped.

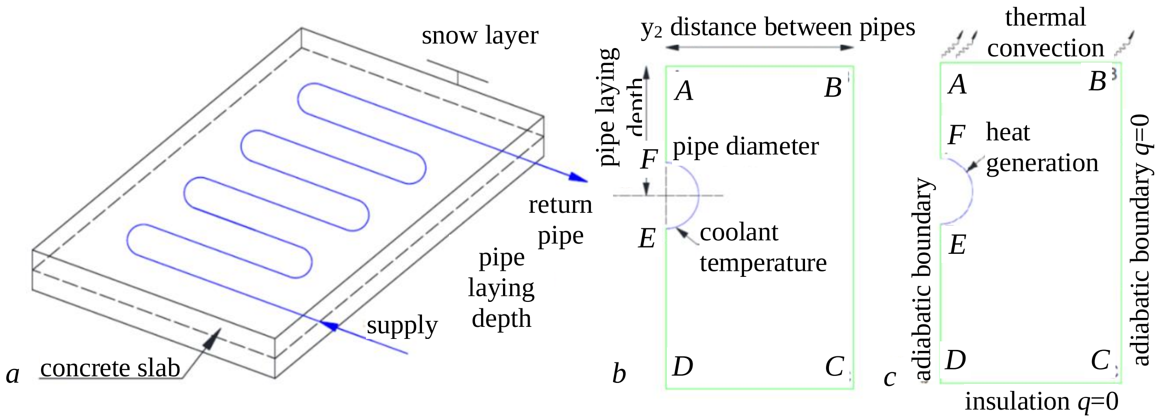

Figure 1. Scheme of the hydraulic system of snow melting (*a*), view of the symmetrical section (*b*) and boundary conditions (*c*).

In the final model, for simplicity and convenience, the following assumptions are given [23–25]:

- the concrete cover is homogeneous and isotropic;

- the effect of thermal deformation is not taken into account;
- pipe wall thickness is insignificant;
- convection between pipe and liquid is not considered;
- ice evaporation and snow melting are not taken into account;
- liquid consumption is not taken into account;
- heat losses inside the pipe are not included in the analysis.

4. Mathematical modeling of the hydraulic snow melting system

The top surface of a concrete slab is exposed to the fluid and ambient temperature, which means that as the fluid moves, heat will be transferred from one place to another. In other words, heat energy will be transferred from the surface to the environment. Consequently, convection occurs between the concrete surface and the liquid or air. The heat transfer rate by air convection is determined by the convection coefficient, and the convection coefficient depends on the wind speed [16]:

$$\beta = 9{,}6 + 1{,}12\upsilon , \tag{1}$$

where υ is wind speed.

An essential boundary condition T = T_{fl} (fluid temperature) is imposed along the curved EF. Natural boundary conditions are imposed along BC, AF, DE. Due to symmetry, these lines are set in adiabatic boundary conditions. In other words, there will be no heat flux on these surfaces. In addition, there is an insulated layer underneath the bottom surface of the concrete slab (along the CD), hence there is no heat flux.

The main differential equation for stationary heat transfer in a flat system is described by the expression:

$$-\frac{\mathrm{d}}{\mathrm{d}x}\left(k_x\frac{\mathrm{d}T}{\mathrm{d}x}\right)-\frac{\mathrm{d}}{\mathrm{d}y}\left(k_y\frac{\mathrm{d}T}{\mathrm{d}y}\right)=f\left(x,y\right)\ to\ \Omega \tag{2}$$

For a convective boundary, the natural boundary condition is the balance of energy transfer across the boundary due to conduction and convection, as discussed above:

$$k_x\frac{\mathrm{d}T}{\mathrm{d}x}n_x+k_y\frac{\mathrm{d}T}{\mathrm{d}y}n_y+\beta\left(T-T_\infty\right)=q_n \tag{3}$$

Where the first term is the transfer of thermal energy due to heat conduction; the second is the transfer of heat due to convection; the third is the transfer of thermal energy due to heat flow (if any); Ω is a two-dimensional area; T is the temperature inside a concrete slab or sidewalk; k_x, k_y are the thermal conductivity of concrete along the directions x and y; $f(x, y)$ is the internal heat release per unit volume; q_n is the heat flux (in this case, there is no internal heat); β – convection coefficient and T_∞ – ambient temperature on the top of the plate.

Expression for Ω_e:

$$0=\int_{\Omega^e}\left(k_x\frac{\mathrm{d}w\mathrm{d}T}{\mathrm{d}x\mathrm{d}x}+k_y\frac{\mathrm{d}w\mathrm{d}T}{\mathrm{d}y\mathrm{d}y}-wf\right)\mathrm{d}x\mathrm{d}y-\oint_{\Gamma^e}w\left(k_x\frac{\mathrm{d}T}{\mathrm{d}x}n_x+k_y\frac{\mathrm{d}T}{\mathrm{d}y}n_y\right)\mathrm{d}s$$

$$=\int_{\Omega^e}\left(k_x\frac{\mathrm{d}w\mathrm{d}T}{\mathrm{d}x\mathrm{d}x}+k_y\frac{\mathrm{d}w\mathrm{d}T}{\mathrm{d}y\mathrm{d}y}-wf\right)\mathrm{d}x\mathrm{d}y-\oint_{\Gamma^e}w\left(q_n-\beta\left[T-T_\infty\right]\right)\mathrm{d}s \tag{4}$$

Where w is an arbitrary function commonly used in finite element analysis.

The finite element model is obtained by substituting the finite element approximation:

$$T=\sum_{j=1}^{n}T_j^{\mathrm{e}}\psi_j^{\mathrm{e}}\left(x,y\right) \tag{5}$$

$$w = \psi^{\mathrm{e}}\left(x, y\right) \tag{6}$$

We expand the equation (5), then:

$$\sum_{j=1}^{n}\left(K_{ij}^{\mathrm{e}} + H_{ij}^{\mathrm{e}}\right)T_{j}^{\mathrm{e}} = F_{i}^{\mathrm{e}} + P_{i}^{\mathrm{e}} \tag{7}$$

The above coefficients can be determined:

$$K_{ij}^{\mathrm{e}} = \int_{\Omega^{\mathrm{e}}}\left(k_x \frac{\mathrm{d}\psi_i \mathrm{d}\psi_j}{\mathrm{d}x\mathrm{d}x} + k_y \frac{\mathrm{d}\psi_i \mathrm{d}\psi_j}{\mathrm{d}y\mathrm{d}y}\right)\mathrm{d}x\mathrm{d}y \tag{8}$$

$$H_{ij}^{\mathrm{e}} = \beta\oint_{\Gamma^{\mathrm{e}}} \psi_i \psi_j \mathrm{d}s \tag{9}$$

$$F_{i}^{\mathrm{e}} = \int_{\Omega^{\mathrm{e}}} f\psi_j \mathrm{d}x\mathrm{d}y + \oint_{\Gamma^{\mathrm{e}}} q_n \psi_j \mathrm{d}s \tag{10}$$

$$P_{i}^{\mathrm{e}} = \beta\oint_{\Gamma^{\mathrm{e}}} \psi_j T_{\infty} \mathrm{d}s \tag{11}$$

There are two new conditions (*H^eij* and *P^ei*). These additional values are due to the convection boundary condition and can be calculated by extracting the above integrals. These coefficients can be calculated only for those elements and boundaries that are subject to the boundary condition of convection (by setting the heat transfer coefficient, a thermal conductivity model is obtained without taking into account convection) [15, 21].

The coefficients $H^{e}{}_{ij}$ and $P^{e}{}_{i}$ for a linear three-sided element are determined:

$$H_{ij}^{\mathrm{e}} = \beta_{12}\oint_{0}^{h_{12}} \psi_i \psi_j \mathrm{d}s + \beta_{23}\oint_{0}^{h_{23}} \psi_i \psi_j \mathrm{d}s + \beta_{31}\oint_{0}^{h_{34}} \psi_i \psi_j \mathrm{d}s + \beta_{41}\oint_{0}^{h_{41}} \psi_i \psi_j \mathrm{d}s \tag{12}$$

$$P_{i}^{\mathrm{e}} = \beta_{12}T_{\infty}^{12}\oint_{0}^{h_{12}} \psi_j \mathrm{d}s + \beta_{23}T_{\infty}^{23}\oint_{0}^{h_{23}} \psi_j \mathrm{d}s + \beta_{34}T_{\infty}^{34}\oint_{0}^{h_{34}} \psi_j \mathrm{d}s + \beta_{41}T_{\infty}^{41}\oint_{0}^{h_{41}} \psi_j \mathrm{d}s \tag{13}$$

Where β_{ij} is the convection coefficient (assumed to be constant) for the side connectors i and j and the Ω_{e} element; $T^{\infty}{}_{ij}$ is the ambient temperature on the side, and h_{ij} is the side length.

For linear rectangular elements, matrices are of the form:

$$\left[H^{\mathrm{e}}\right] = \frac{\beta_{12}h_{12}}{6}\begin{bmatrix} 2 & 1 & 0 & 0 \\ 1 & 2 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} + \frac{\beta_{23}h_{23}}{6}\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 2 & 1 & 0 \\ 0 & 1 & 2 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} + \frac{\beta_{34}h_{34}}{6}\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 1 \\ 0 & 0 & 1 & 1 \end{bmatrix} + \frac{\beta_{41}h_{41}}{6}\begin{bmatrix} 2 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 2 \end{bmatrix} \tag{14}$$

$$\left[P^{\mathrm{e}}\right] = \frac{\beta_{12}T_{\infty}^{12}h_{12}}{6}\begin{Bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{Bmatrix} + \frac{\beta_{23}T_{\infty}^{23}h_{23}}{6}\begin{Bmatrix} 0 \\ 1 \\ 1 \\ 0 \end{Bmatrix} + \frac{\beta_{34}T_{\infty}^{34}h_{34}}{6}\begin{Bmatrix} 0 \\ 0 \\ 1 \\ 1 \end{Bmatrix} + \frac{\beta_{41}T_{\infty}^{41}h_{41}}{6}\begin{Bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{Bmatrix} \tag{15}$$

The initial data for software modeling of thermophysical processes is: a slab of concrete pavement (bridge crossing [22]), which is exposed to an ambient temperature of minus 27°C, and is also subjected to a convective boundary condition on the upper surface. There is no internal heat generation. A complete list of initial data is presented in table 1.

Table 1. Initial data.

Specifications	Unit of measurements	Values	Specifications	Unit of measurements	Values
Slab thickness	cm	15.0	Specific heat of concrete	J/(kg°C)	1090
Thermal conductivity of concrete	W/(cm°C)	0.062	Density of concrete	kg/m^3	2400
Convective heat transfer coefficient	W/(cm^2°C)	0.009	Ambient temperature	°C	-27
Heat carrier temperature	°C	30	Distance between pipes	cm	25.0
Pipe laying depth	cm	10.0	Pipe diameter	cm	2.5

Analysis of the temperature distribution in the concrete pavement is carried out in ABAQUS. The results are presented in figures 2, 4.

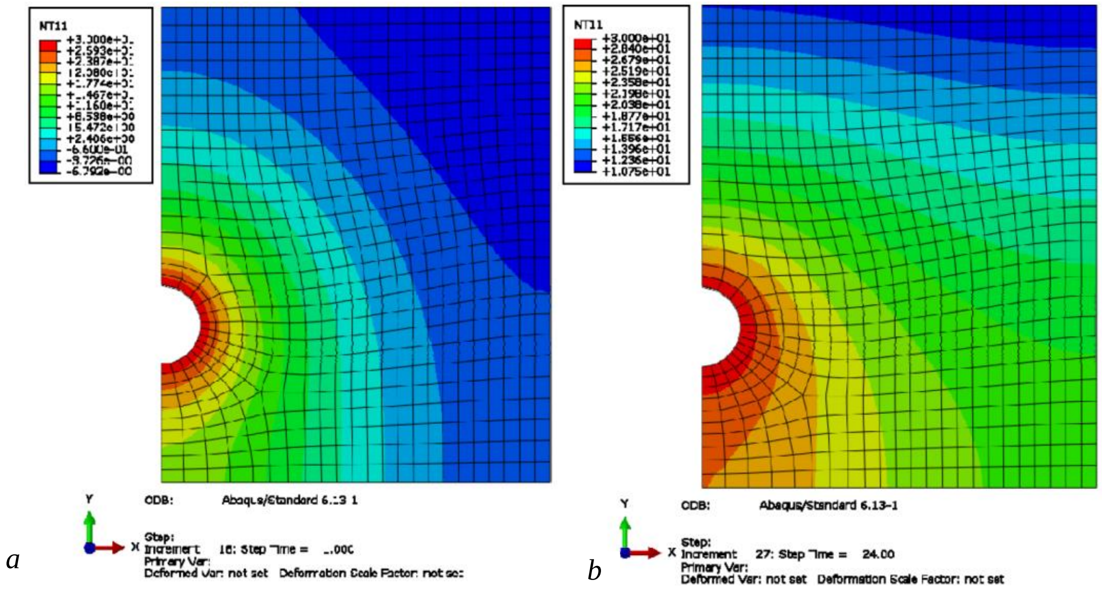

Figure 2. Temperature distribution during system operation 1 hour (*a*) and 12 hours (*b*).

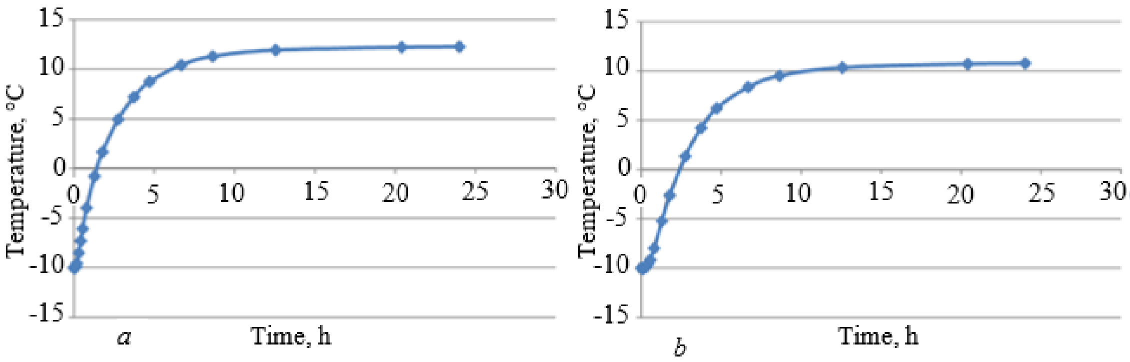

Figure 3. Distribution of temperature at point A (*a*) and B (*b*) during system operation 24 hours.

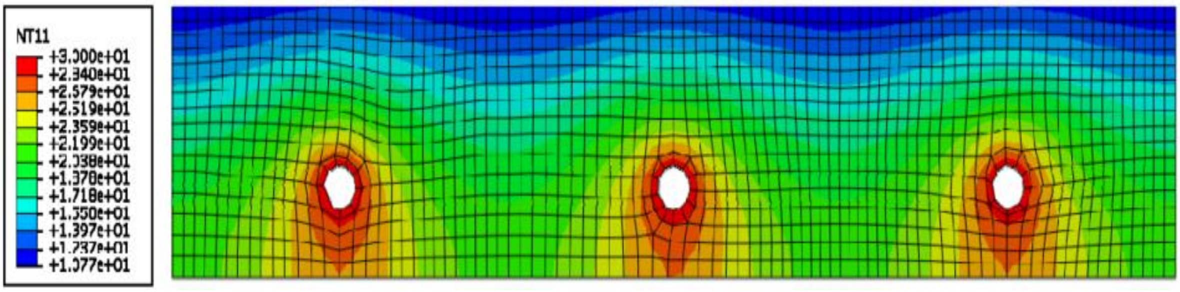

Figure 4. Temperature distribution in a concrete slab when the system is operating 24 hours.

5. Conclusions

The temperature distribution over the surface is not uniform as it shows a sine or cosine shape. The maximum surface temperature is higher than the heated pipe (point A), while the minimum temperature is half the distance between two adjacent pipes (point B). The deicing surface of the coating is achieved when the lowest temperature was above 0 degrees.

From the transient analysis (Figure 2–5), the melting rate is surprisingly high in the initial stages and then becomes slow. This may be due to the fact that heat transfer gradually passes from a non-stationary state to a steady state after a heating period. In general, the change in temperature of the concrete surface can be divided into four stages: initial stage, linear stage, accelerated stage and stable stage.

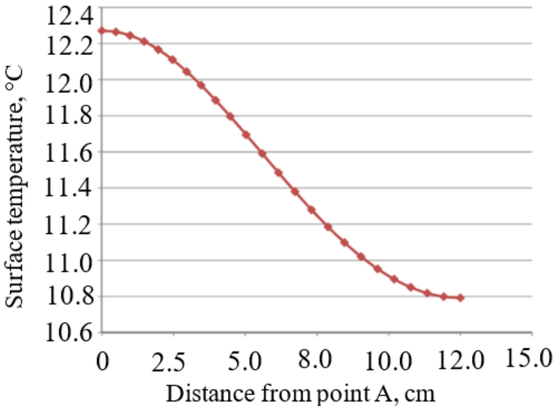

Figure 5. Temperature distribution over surface.

When the surface temperature reaches a relatively high temperature, an accelerated period begins and the surface temperature rises exponentially. This can be explained by the fact that the thermal energy generated by conduction is significantly higher than the energy dissipated by convection. In other words, the absorbed thermal energy due to conduction dominates the dissipated energy due to convection. The heat transfer process develops to a steady state where the concrete surface absorbs most of the heat energy transferred from the heating source.

The slope of the temperature curve at point A is higher than point B, indicating that the temperature change at point A is faster than at point B. Point A is closer to the heat source than point B, resulting in higher absorbed energy. Consequently, the surfaces near the pipe first melt due to the higher surface temperature. Then the surface temperature in some places remote from the pipe (i.e. at point B) rises after a while and, therefore, the snow melts completely.

The implementation of the research allows us to say that the simulation model of hydraulic snow melting can be adequately applied on stationary road objects, the coating of which is not subject to vertical vibrations. To use the method of snow melting on bridge crossings, it is necessary to provide for an additional system for draining water from the road surface.

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