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METHOD OF DETERMINING CHARACTERISTICS FOR AIR HEATING SYSTEM IN RAILWAY TUNNELS IN HARSH CLIMATIC CONDITIONS

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The article describes climatic and mining-technical conditions influencing frost formation process. It was noted that the radical tools for preventing frost formation in winter periods is creation of positive temperature in tunnels by heating the incoming outside air. We formulated tasks, which solution will promote development of engineering calculation method for heating systems parameters. The article provides results of theoretical studies based on mathematical modelling and analytical solutions and data on field instrumental measurements, which were processed with similarity criteria. It compares mathematical modelling results on determining amount of tunnel incoming air flow with portal gates and calculations data from experimentally determined coefficient of local resistance. We proved the energy efficiency of placing the tunnel portal gates and validated the places of preheated air injection points and removal of cool air from this flow, which provides maximal energy effect.

Key words: tunnel, calorifer, air heating, frost formation, mathematical modelling, heat transfer between air and concrete tunnel surface, aero and thermal dynamic processes

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Introduction. The two thirds of Russia territory are regions with harsh and extreme climatic conditions [9]. These areas have most explored mineral resources and very significant for our country cultural, scientific and industrial centers. The logistics is mainly done through railways having inherent infrastructure of railway tunnels. One of the key safety provision aspects is creation of required conditions, preventing development of negative processes during contact with outside air coming in tunnels from construction elements (roof support, contact wire, trench drains, etc). Among negative processes there is frost formation [11]. They appear mainly because of water coming from workings and contacting with outside cold air, which finally leads to frost formation. The temperature conditions of railway tunnels as opposed to other types of mining workings are influenced by variable amount of outside air volume. Its dynamics is defined by piston action of coming train, which depends on mining conditions of workings, train characteristics, its speed and traffic volume [4, 8].

Current Russian experience confirms that a radical measure for preventing frost formation is creation of positive temperature conditions in tunnels during winter periods by heating outside air [2]. Methods of determining parameters of heating systems of mining companies do not take into account the variable air volume depending on presence or absence of a moving train in a tunnel, and complex spatial dynamics of velocity and temperature fields accompanying the mixing of outside cold air and heated air near tunnel portals [6].

Researches of heat and mass exchange processes in railway tunnels during creation of positive temperature conditions were considered in works of scientists of the Saint-Petersburg Mining University [2, 9], where they developed main principles of working temperature conditions management during periodic movement of transportation vehicles and heating of outside air. The more detailed researches were carried out by scientists from Austria, Finland (V.Langner, B.Hagenah, T.Gronwel), Japan and Canada [13, 16, 17].

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Analysis of exploitation [14] of outside air heating systems coming into railway tunnels showed their comparatively low energy efficiency, irrational use under conditions of harmful gaseous substances emitting from rocks (for example, radon), and difficult application of these systems in emergency ventilation modes.

Transition to air heating systems of new generation, which do not have the abovementioned disadvantages, is possible only in case of developing scientific-methodic tools for selecting parameters of heating-ventilating systems, which should be based on the present experience and modern methods of mathematical modelling enabling studying complex processes of heat transfer in air medium – rock mass environment.

The development based on theoretical and experimental researches of engineering methods enabling determination of air heating systems parameters in railway tunnels and thus providing improvement of their energy efficiency, is of key importance now.

In order to implement this task we should:

• define main factors influencing processes of frost formation and roof support deterioration in haulage workings;

• perform a theoretical research of heat and mass exchange in air medium – rock mass environment depending on changes of temperature and air volume in time;

• carry out theoretical research of velocity and temperature fields dynamics when outside cold air and heated air move along the haulage working;

• define efficiency of tools for reduction of amount of outside cold air in workings and power of iar heating calorifers.

Theoretical researches are based in mathematical modelling of heat exchange in air medium-rock mass system and air-thermal dynamic processes when outside cold air comes into the tunnel due to natural draft and its heating from heated air flow from calorifers and are done with the help of Ansys-Fluent software package. Besides this theoretical researches included analytical solutions of simplified physical models, which practical validity was justified by comparison with computational results.

Mathematical modelling of heat exchange during contact of air and rock mass was done for assessment of stepped type of temperature and air flow rate movement changes influence on temperature of cement cover surface and heat flow volume. The stepped type of law is defined by periodic movement of trains along the tunnel (time τ_t), leading to increase of air volume at that time (Q_t), in the tunnel as compared to air volume during absence of trains (time τ_{ab}), and reduction of its temperature after heating (t_h) in comparison to temperature at τ_{ab} period (Fig.1).

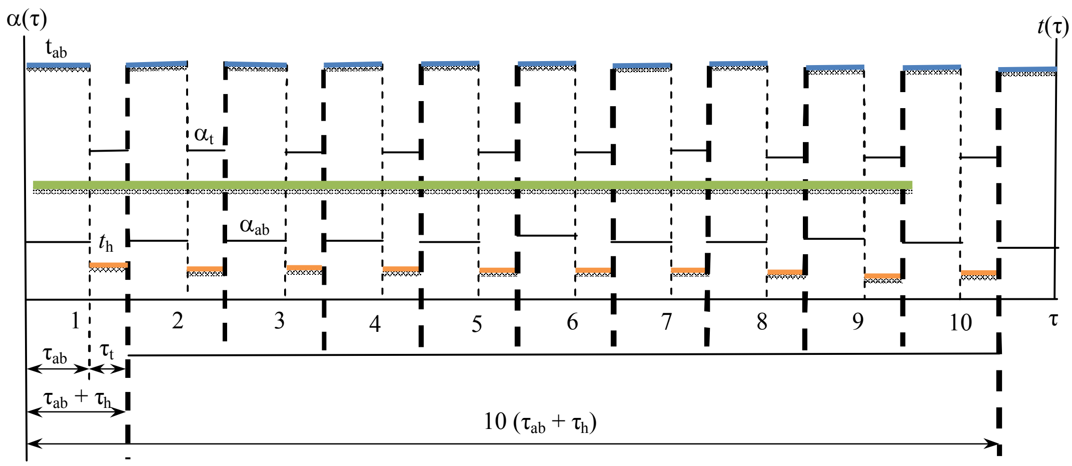

Fig.1. Temperature (solid lines) and heat exchange coefficient (dashes) changes at the incoming part of working during winter period

When formulating the mathematical model of the task we used the following suppositions (Fig.2):

• Inhomogeneous rock mass is replaced with isotropic mass with equivalent heat and physical characteristics and constant initial temperature T_0.

• Cross-section of working has rectangular shape with height and width of $2H$ and $2B$ (Fig.2).

• Temperature gradient along the direction perpendicular to working radius (parallel to z axis) is assumed to be zero.

• Air heat exchange of working surface is described with boundary conditions of third degree with stepped changes of heat exchange coefficient and air temperature.

• Heat exchange coefficients values are connected only to changes of air flow rate defined by movement or absence of trains and their piston effect.

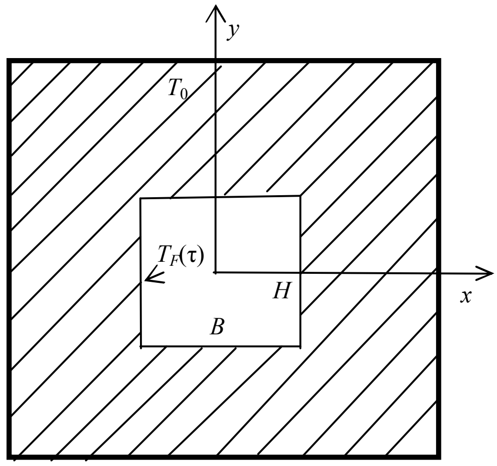

Fig.2. Calculation scheme for describing heat exchange process between air flow and roof support surface

• Oscillations of air temperature are determined by seasonal climate and weather changes (summer, winter) and heating of air during winter periods.

• During mixing of outside cold air within the considered cross-section the temperature is equalized within such a short period that air temperature in this cross-section could be considered as constant during periods of absence and presence of train in a working.

The mathematical formulation of the task under these suppositions has the following form:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = \frac{1}{\alpha_r}\frac{\partial T}{\partial \tau};$$

$$T(x, y, 0) = T_0; \qquad (1)$$

$$\alpha(\tau)\ [T_F(\tau) - t_\alpha(\tau)] = \lambda_r\,\partial T/\partial n \ \text{ at } \ x = B \ \text{ and } \ y = H;$$

$$\partial T/\partial n = 0 \ \text{ at } \ x \to\infty \ \ y \to\infty \ (x^2 + y^2 \to\infty),$$

where λ_r, α_r – heat and temperature conductivity of rock mass; $T(x, y, \tau)$ – rock temperature; n – normal line to working surface; $t_\alpha(\tau)$ – air temperature; $\alpha(\tau)$ – heat exchange coefficient.

To solve the task described by mathematical formulation (1) in one dimension with stepwise variation of heat exchange coefficient and constant air temperature we applied the calculation method introduced by I.R.Vengerov [1]. This method is based on usage of self-similarity principle for heat exchange task with thermal interference of air and unlimited rock mass. The solution has a form of relationship of coefficients of unsteady heat transfer k_τ in time, which is a specific heat flow under temperature difference of 1 degree. Unsteady heat transfer coefficients were introduced in mining and heat-physical calcualtions by A.N.Scherban and O.N.Kremnev and have been widely used [12]. In our case formulas for unsteady heat transfer coefficient calculation have the following form:

$$k_\tau\,(\alpha_{\text{ab}}) = \alpha_{\text{ab}}[1 - f(Z_{\text{ab}})]; \quad k_{\text{t}}\,(\alpha_{\text{t}}) = \alpha_{\text{t}}[1 - f(Z_{\text{t}})],$$

$$Z_{ab} = \left\{\frac{1}{\varepsilon}\sum_1^n\left[\left(1-\frac{1}{n}\right)\alpha_{ab}^2 + \alpha_t^2\delta\tau\right]n\tau_{ab}\right\}^{0,5}; \quad Z_t = \left\{\frac{1}{\varepsilon}\sum_1^n\left[\alpha_{ab}^2 + \alpha_t^2\delta\tau\right]n\tau_{ab}\right\}^{0,5}, \qquad (2)$$

where $\delta\tau = \tau_n/\tau_{\text{ab}}$; $\varepsilon = \lambda c\rho$, λ, c, ρ – heat conductivity, thermal conductivity and density of rocks; n – total amount of trains passing the working during the examined period of time.

When heat exchange coefficient and air temperature change in stepwise mode we used Duhamel theorem and Heaviside step function, which describe stepped law of temperature changes [3].

According to the law shown at Fig 1, the formula for calculation of heat flow with changing heat transfer coefficient and temperature has the following form:

$$q = k_\tau(\alpha_t, \Sigma\tau)(T_0 - t_{ab}) - k_\tau(\alpha_t, [\Sigma\tau - (\tau_{ab} + \tau_t)]\,\Delta t + k_\tau(\alpha_t, [\Sigma\tau - (2\tau_{ab} + \tau_t)]\Delta t + \ldots +$$

$$+ k_\tau(\alpha_t, [\Sigma\tau - ((n-1)\tau_t + n\tau_{ab})]\Delta t, \qquad (3)$$

where k_τ is calculated according to formulas (2).

The validity of the suggested approximation method of calculating air and rock mass heat transfer was confirmed by computational results made in Ansys software.

Fig.3 and 4 show the computational results for a case of changes of heat conductivity coefficients with constant air temperature (Fig.3), and a case of changes of heat conductivity coefficients and air temperature (Fig.4).

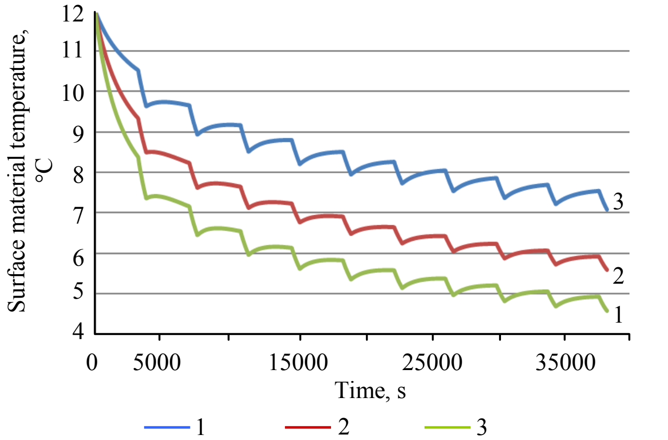

Fig.3. Concrete support surface temperature during periods of 3200 and 600 with corresponding heat transfer coefficients α_{ab} and α_t

1 – $\alpha_{ab} = 5$; $\alpha_t = 15$; 2 – $\alpha_{ab} = 10$; $\alpha_t = 20$; 3 – $\alpha_{ab} = 15$; $\alpha_t = 30$ W/(m·K)

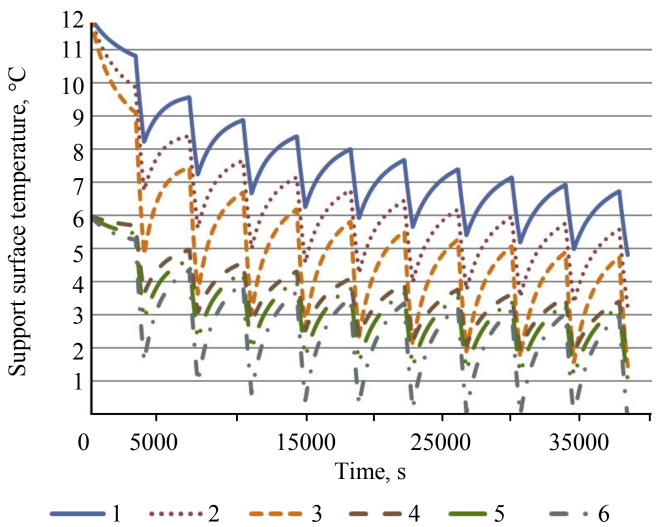

Fig.4. Support surface temperature in relation to time and heat transfer coefficient value

1, 2, 3 – $T_0 = 12$ °C; accordingly $\alpha_{ab} = 5$, $\alpha_t = 15$ W/(m·K); $\alpha_{ab} = 10$, $\alpha_t = 20$ W/(m·K); $\alpha_{ab} = 15$, $\alpha_t = 30$ W/(m·K);
4, 5, 6 – $T_0 = 6$ °C; $\alpha_{ab} = 5$, $\alpha_t = 15$ W/(m·K); $\alpha_{ab} = 10$, $\alpha_t = 20$ W/(m·K); $\alpha_{ab} = 15$, $\alpha_t = 30$ W/(m·K); $t_{ab} = 4$ °C; $t_t = 10$ °C

The comparison of calculations using approximation formula and results of mathematic modelling shows that when heat transfer does not exceed one year the two-dimension task can be considered as one-dimension.

To find relationship defining a condition of positive temperature of tunnel surface [7] after the end of piston effect action [5] at the end of n cycle of interstages with temperature t_f, heat transfer coefficient α_{ab} and temperature t_n, heat transfer coefficient α_t, it was assumed that air temperature can be presented in the form of average integral temperature of the period preceding the last $(n-1)$ cycle of temperature changes and heat transfer coefficient, and air temperature in n cycle, when it is changed in a stepwise mode from t_{ab} to t_t (see Fig.1).

The equation for calculation of tunnel surface temperature T_F has the following form:

$$\alpha_t(T_F - t_{av.t}) = k_\tau(\alpha_t, \Sigma\tau)(t_{av} - t_{av.t}) +$$

$$+ k_\tau(\alpha_t, (\tau_{ab} + \tau_t))(t_{av.t} - t_{av.t}), \qquad (4)$$

where $k_\tau(\alpha_t, \Sigma\tau)$, $k_\tau(\alpha_t, (\tau_{ab} + \tau_t))$ – coefficients of unsteady heat transfer determined in full interchange of time in n cycles of temperature and coefficient changes and last two values of temperatures $t_{av.ab}$, $t_{av.t}$ (formulas (2)).

Taking into account, that

$$t_{av.ab} = N_{cal}/c_p G_{ab} + t_{out}; \quad t_{av.t} = N_{cal}/c_p G_t + t_{out}, \qquad (5)$$

we have

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$$t_{av} = (t_{av.ab}\tau_{ab} + t_{av.t}\tau_t)/(\tau_{ab} + \tau_t), \quad (6)$$

where $G_{ab} = \rho_{out} Q_{ab}$ and $G_t = \rho_{out} Q_{out.t}$ are mass air flow rate during absence and presence of a train in a tunnel, kg/s; c_p is air specific heat, kJ/(kg·°C); N_{cal} – power of calorific units, kW.

By applying formulas (5) and (6) to equation (4) and solving it for power of calorific units N_{cal}, we have the following:

$$N_{cal} = \frac{(T_F - t_{out})}{\dfrac{1}{G_t} + \left(\dfrac{1}{G_{ab}} - \dfrac{1}{G_t}\right)Y} c_p, \quad (7)$$

where $Y = [k_\tau(\alpha_t, \Sigma\tau) - k_\tau(\alpha_t, (\tau_{ab} + \tau_t)\Delta\tau_t]/\alpha_t$, $\Delta\tau_t = \tau_t/(\tau_t + \tau_{ab})$.

The relationship (7) enables finding the power of calorifers heating the outside air providing the positive temperature in winter time and preventing frost formation.

The circulation air weight flow and its preheating temperature are calculated as:

$$G_c = N_{cal}/c_p(t_{heat} - t_{av.ab}); \quad t_{heat} = t_{av.ab} + N_{cal}/c_p G_c. \quad (8)$$

Thus, knowing the calorifers power and air temperature after heating we can calculate the circulation air flowrate and aerodynamic fan characteristics.

Based in relationship (2), (7), (8) we calculated calorifers power for preheating of outside air up to the temperature preventing frost formation in tunnels. The calculation was done with the following input data: tunnel length $L_t = 6700$ m, average cross-section area $S_t = 34$ m^2, outside air temperature –35 °C, number of trains in one day (24 h) -19, train speed 60 km/h, calculated train length 1100 m, value of natural draft 50-400 Pa. The calculation results (see the table below) showed that calorifers power could be up to 16,8 MW.

Air flow rate in tunnel *Q* and calorifers power *N* with portal tunnel gates and without them

Q, m^3/s N, kW	h_e, Pa					
	50	100	150	200	300	400
$Q_{ab.gate}/\ Q_{ab.no\ gate}$	12,2/95	17,2/134	21,1/165	24,3/190	29,8/233	34,27/270
$Q_{t.gate}/\ Q_{t.\ no\ gate}$	57,8/332	61,3/339	64,2/345	66,/352	71,2/365	75,1/380
$N_{gate}/\ N_{no\ gate}$	1030/7610	1380/9990	1640/11685	1850/12980	2200/15050	2470/16780

The power reduction is possible only in case of outside air flow rate decrease coming because of natural draft and train piston effect. The analysis of Severo-Muysky tunnel operation showed that the most efficient tool is portal tunnel gates (Fig.5). To assess the gates efficiency on amount of outside air coming into the tunnel due to natural draft we used the mathematical modelling.

The mathematical formulation of the task has a form of Reynolds averaged irregular equations of Navier-Stokes with k-ε-model of turbulence, written in the form of a system of two non-linear diffusion equations. The results of mathematical modelling (Fig.6, 7) showed that with fully closed gates (they have only holes for contact wires) the amount of air coming into the tunnel is about 10-40 m^3/s depending on natural draft strength, that is almost eight times lower than the amount of air coming when the gates are open. The experiments conducted by OAO «NIPIII Lenmetrogiprotrans» and Mining University at western portal of Severo-Muysky tunnel confirmed the calculation results and allowed finding the relationship between Euler number $\mathrm{Eu} = \Delta P/\rho V_т^2$ and area

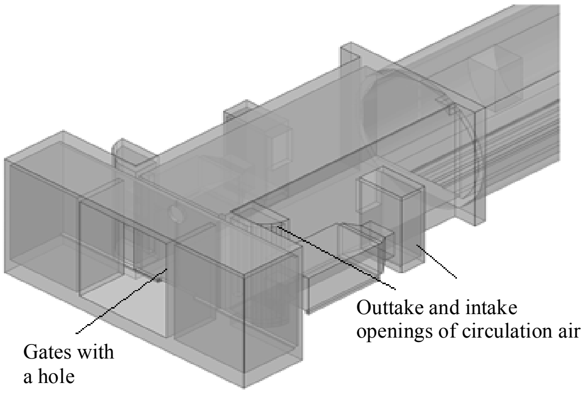

Fig.5. External view of Baikal tunnel portal with ventilation gates and air preheating and injection system

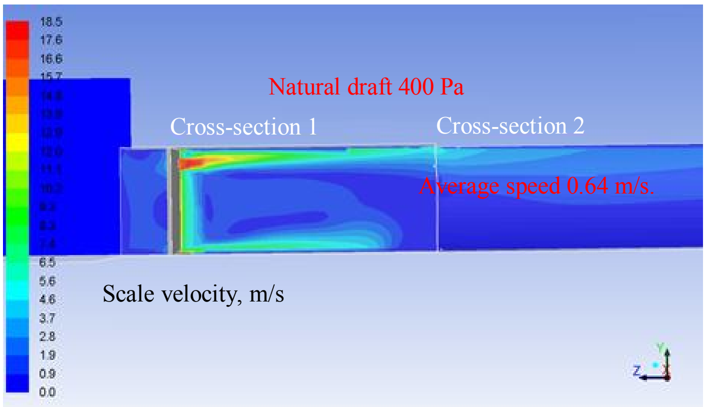

Fig.6. Distribution of air flow rate in cross-section near ventilation gates of western portal and with natural draft value of 400 Pa

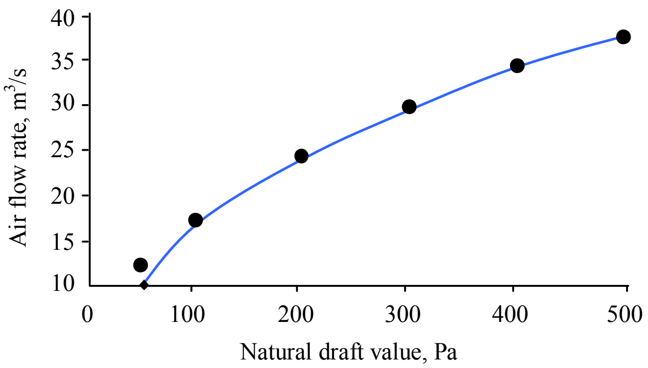

Fig.7. Relationship of tunnel incoming air rate from natural draft value (solid line – mathematical modelling results; dots – calculation results from experimental identification of local resistance coefficient)

of tunnel closure value $S_{cl} = (1 - S_{f.s} / S_T)$; $S_{f.s}$ is free cross-section for air passing). This relationship together with correlation ratio 0,97 and statistical reliability of 95 %, is described as the following equation

$$Eu = \exp\left(0{,}33e^{2{,}95S_{cl}}\right). \qquad (9)$$

And as a result of processing experimental data we determined the value of ventilation gates local resistance coefficient value ζ_{gate}. It appeared to be equal to double Euler number ($\zeta_{gate} = 2Eu$) and to 698 with fully closed gates.

The equation (7) calculations showed that in case of tunnel operation with periodically closed portal gates and absence of moving train the calorifers power can be reduced by more than 6,8-7,4 times (see the table).

When the gates are closed the air at the working entrance comes through the upper hole used for contact wire. The air flow velocity can be up to 17-18 m/s. As a result, there is an air flow at the tunnel arc moving with high speed and having temperature below zero. The required heating of the incoming air flow can be done only with such mixing of cold and pre-heated air providing maximal heat energy exchange between these flows.

The preliminary assessment based in the analysis of mathematical modelling of velocity fields showed that the formulated condition is met with a certain placement of holes for injecting the preheated air into the working. The validity of this condition was checked with mathematical modelling of aerodynamic processes with holes for preheated air being placed close to portal gates and at 8 m from them. The air flow rate at the air injecting unit was 10 m/s and 20 m/s accordingly.

To characterize the heat transfer process additionally to Reynolds averaged irregular equations of Navier-Stokes we sued the energy equation describing the change of ideal gas enthalpy depending on air flow pressure, its temperature and effective heat conductivity calculated according to previously accepted turbulence model [10].

The calculation results are presented in the form of temperature fields charts along the working cross-section, placed at different distance from tunnel entrance, and dynamics of temperature changes at cross-section control points placed at 8 m from entrance (Fig.8, 9).

The analysis of mathematical modelling results confirmed the assumption about influence of preheated air injection places and its velocity on temperature fields formation process.

In case of placing the preheated air injection points at 8 m from tunnel entrance provide positive average temperature at these injection places that is explained by increased efficiency of heat transfer between outside cold and heated air flow connected with significant reduction of velocity of air flow coming from hole in gates.

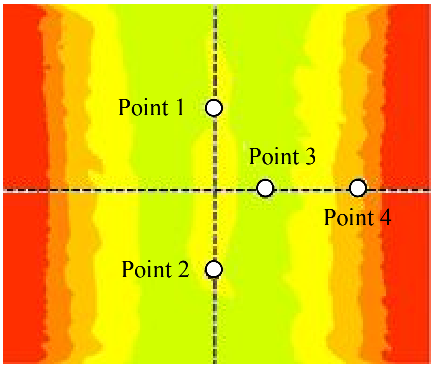

Fig.8. Placement of control points in working cross-section with injection if preheated air and distribution of temperatures

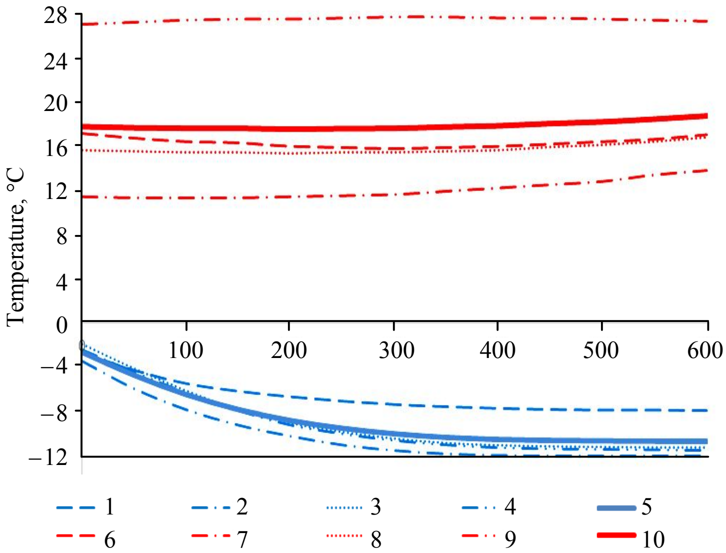

Fig.9. Dynamics of air flow temperature in control cross-section pints and its averaged values along the working cross-section (blue – temperature of preheated air at tunnel entrance, red – at cross-section, where the preheated air is injected)

1-5 – experiment 1; 6-10 – experiment 2; 1, 6 – point 1, cross-section 2; 2, 7 – point 2, cross-section 2; 3, 8 – point 3, cross-section 1; 4, 9 – point 4, cross-section 2; 5, 10 – averaged values

Conclusions

1. The main reasons of frost formation in workings with railway transportation vehicles are processes of heat transfer between incoming outside cold air and ground water found in it.

2. When defining the characteristics of outside air heating system in workings with railway vehicles we should take into account the stepped law of air temperature and its speed movement changes, determining the heat transfer coefficient values.

3. Method of defining the characteristics of outside air heating system should take into account the incoming air flow changes rate when a train moving is present or absent in the working as well as different intensity of heat transfer between air flow and rock mass.

4. The installation of ventilation gates at tunnel portals leads to reduction of amount of incoming air flow and decrease of air preheating calorific units power in 6,8-7,4 times.

5. It was shown that increase of air heating system efficiency is reached by placing openings for injection of preheated air at the distance not less than 8 m from the tunnel entrance gates and increasing the preheated air injection velocity up to 20 m/s.

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