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Heat and hygroscopic mass exchange modeling for safety management in tunnels of metro

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Abstract

Thanks to modern technologies of construction and operation of transport tunnels, it is assumed in the present work that drainage of water does not occur inside the membrane in the volume of reinforced coating of the tunnel and here takes place a non-stationary process of transfer of hygroscopic mass (moisture) together with a similar process of heat transfer between the ventilation stream and the surrounding mining massif. Thus, we have to deal only with the sorption mass content in the pores of the massif and the water in the explicit form in the tunnels can only be in exceptional cases as local sources and therefore, their influence on the ventilation flow should be considered separately. In addition, based on the principle of Onsager reciprocal relations, this article assumes that the heat flux is affected not only by the direct driving force-the temperature gradient, but also by the gradient of the mass transfer potential that is indirect in relation to this flow. Consequently, in the process of heat transfer is taken into consideration of the effect of Sore. Similarly, the mass (moisture) transfer is taken into consideration of the addition effect Dufour, when the cause of the mass transfer is not only the direct driving force - the gradient of the mass transfer potential, but also the indirect driving force in relation to this flow - the temperature gradient.

Keywords: Non-stationary heat and mass transfer, temperature gradient, mass transfer potential gradient, modeling.

1. Introduction

For the determation of changing of climatic parameters of the ventilation air of tunnels, it is necessary to considerate with naturally magnitudes of temperature and natural mass (moisture) transfer potential of surrouding rock massif. Due to seasonal fluctuations in the temperature and relative humidity of the atmospheric air, heat and mass transfer between the massif and the air is non-stationary. The nonstationary nature of the processes is more abundant by the formation of cooled zone and decreased moisture content zone in the massif around the tunnels. Therefore, the exchange of heat and matter between the massif and the ventilation flow occurs through the marked zones and the rate of marked exchanges decreases steadily over time.

Thus, the ventilation flow due to heat and mass transfer, through tunnel coating and liner, forms perturbed zones in the surrounding mining massif, which leads to a decrease in the natural values of the temperature and the mass transfer potential in these zones. As a result of this, the natural values of the marked physical quantities will be observed only in the depth of the massif. In classic papers non-stationarity considered by means of appropriate ratio when applyed the natural temperature of the massif. For example works of (Shcherban et al., 1977), (Oniani, 1973), (Kuzin et al., 1979) and (Kremnev and Zhuravlenko, 1980). But non-stationary of heat and moisture transfer may be considered by means of dimensionless temperature and dimensionless mass transfer potential on the dividing surface of the "tunnel wall - airflow" and of stationary appropriate ratio of transfer. Among similar works it is necessary to note papers (Lanchava and Ilias, 2017), (Lanchava, 1982; 1985), (Petrilean, 2013) and (Petrilean et al., 2014; 2017). In this approach, the entire complexity of changing physical fields in a massif is, as it were, transferred to the surface of the tunnel and the variable values are the dimensionless temperature and the potential of mass transfer of the walls of the tunnel.

For the circular shape of the tunnel, hypsometrically located below the first waterproof layer, the scheme of the natural temperature fields and the mass transfer potential is shown in Fig. 1. The noted scheme is typical for tunnels located at great depth, in which the width of the cooled and drained zones increases with time. The equations of fields of the temperature and of the mass transfer potential in surrounding rock massif, respectively, have the form

$t=f(R,\tau)$; $\vartheta=F(R,\tau)$ where τ is the time. For an infinite length of the cylindrical coordinate, the values of the temperature and the mass transfer potential take their natural magnitudes. Similar nonstationary heat and mass transfer processes are considered in (Lanchava, 1982; 1985).

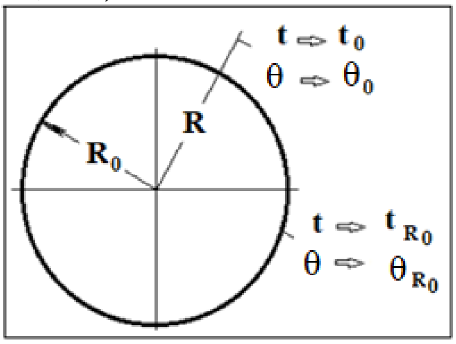

Fig. 1. Distributions of temperature and of mass (moisture) transfer potential on the tunnel surface and the surrounding rock massif on the tunnel axis: R - cylindrical coordinate; R_0 - equivalent radius of tunnel; 0 and R_0 indexes show the temperature and mass transfer potential values in the surrounding isotropic environments and on the dividing surface

As for the tunnels located at low depths, in particular transport tunnels and especially the tunnels of the metro, here the hygroscopic mass exchange behind the membrane in depth of massif does not occur, because the membrane is waterproof. Similar membranes are widely used in modern tunnelling. Thus, inside the membrane, within volume of the reinforced coating takes place moisture-equalizing. The mentioned volume has absorbed moisture from the air or gives moisture to the air depending on the season of the year. The moisture content of this volume is about the maximum hygroscopic index. Consequently, in the tunnels of the metro, non-stationary heat exchange takes place, during which the cooled zone in the massif spreads beyond the boundaries of the membrane. Mass transfer takes place only spread within a volume of reinforced coating.

2. Materials and methods

Non-stationary heat transfer coefficient for tunnels with reinforced coating is determined by formula

$$K_\tau = K_1\bar{t} \qquad (1)$$

Where K_τ - non-stationary heat transfer coefficient, W/(m^2.^0C); $\bar{t}=t(\tau,R_0)$ - dimensionless surface temperature of the tunnel, in parts of the one, $0\le\bar{t}\le1$; K_1 - coefficient of heat transfer from the massif to the ventilation flow, with consideration the influence of reinforced coating of the tunnel, which is determined by the formula

$$K_1=\left(\frac{1}{\alpha}+\frac{\delta_1}{\lambda_1}\right)^{-1} \qquad (2)$$

Where α - stationary heat transfer coefficient from surface of the tunnel, W/(m^2.^0C); δ_1,λ_1 - respectively, the thickness of reinforced coating of the tunnel and the coefficient of thermal conductivity of the coating material, m; W/(m.^0C).

Non-stationary mass transfer coefficient for tunnels with reinforced coating is determined by formula

$$K_{\tau m} = K_2\overline{\Theta} \qquad (3)$$

Where $K_{\tau m}$ - non-stationary mass transfer coefficient, kg.mol/(J.m^2.s); $\overline{\Theta}=\Theta(\tau,R_0)$ - dimensionless mass transfer potential of the tunnel surface, in parts of the one, $0\le\Theta\le1$; K_2 - coefficient of mass transfer from the massif to the ventilation flow, with consideration the influence of reinforced coating of the tunnel, which is determined by the formula

$$K_2 = \left(\frac{1}{\alpha_m} + \frac{\delta_1}{\lambda_{m1}} \right)^{-1} \quad (4)$$

Where α_m - stationary mass transfer coefficient from surface of the tunnel, kg.mol/(J.m^2.s); λ_{m1} - the coefficient conductivity of mass transfer potential of the coating material, kg.mol/(J.m.s).

Hygroscopic mass transfer potential can be calculated with the following formula (Tsimermanis, 1971)

$$\Theta = RT \ln \varphi \quad (5)$$

where Θ - hygroscopic mass transfer potential, J/mol; R - universal air constant; J/(mol.K), R = 8.3144; T - absolute temperature, *K*; ℓn – symbol of natural logarythm; φ – equilibrium relative humidity of air, balanced with a sorbent, $0 \leq \varphi \leq 1$. In which, apart from explained dimensions Θ - hygroscopic mass transfer potential, J/mol;

In this formula, $\ell n\varphi = 0$, when φ = 1, in the rest of the cases, for hygroscopic area φ <1 and value of the potential determined by the formula (5) is of negative sign.

The potential calculated with formula (5) is acceptable in order to evaluate hygroscopic mass transfer in mining massive. As commonly known, increasing temperature causes decrease of van der Waals powers of sorption field, which is resulted in decrease of isothermal specific mass factor (this factor of the capillary-porous body c_m = 0 on the critical temperature for water that equals of 647K, because at this temperature water vapor sorption is impossible). In such a case, the power of sorption field and its characteristic size – transfer potential should be necessarily decreased. Formula (9) permits to establish inversely proportional addiction between Θ and T as well c_m , T couples, while between Θ, c_m couples it arises directly proportional addiction. This not contradicts neither to existing theoretical views nor to experimental results of determining isothermal specific mass factor.

Calculating mass transfer potential for mining massif is also possible with the formula offered below:

$$\Theta = RT\ell n \left(\frac{U}{U_{\max}} \right) \quad (6)$$

Where U - hygroscopic moisture content of mining massif on the temperature T , kg/kg; $U_{\max}$ – maximum hygroscopic moisture content of mining massif on the same temperature, kg/kg.

3. Results and discussion

3.1. Thermophysical and Mass-physical characteristics of rocks

Thermophysical and mass-physical coefficients of rocks (or soils) (λ, a, c, λ_m, a_m, c_m δ_θ, γ_0), which are related to each other with a known law (Dzidziguri et al., 1966)

$$\lambda = ac\gamma_{0,} \quad (7)$$

Where λ is the heat conductivity coefficient of the rock, W/(m. K); a - coefficient of thermal diffusivity of the rock, m^2/s; c - specific heat, J/(kg. K); γ_0 - the rock density, kg/m^3.

Mass-physical characteristics of rocks are related to each other by analogical formulation, thus confirming the analogy of these processes (Lanchava, 1998)

$$\lambda_m = a_m \, c_m \, \gamma_0 \quad (8)$$

Where λ_m mass conductivity factor of the rock, kg.mol/(J.m.s); a_m – the mass transfer potential diffusivity factor for the rock, m^2/s; c_m - the isothermal specific mass factor for the rock, mol/J.

In the case of ventilation of tunnels, thermal exchange in a binary system "mining massif - ventilation flow" is not only under the influence of the temperature gradient but also of the gradient of mass transfer potential. The ultimate thermal flow consists of two elements: one is caused by the temperature gradient and the second by mass transfer potential gradient. Similarly, the mass flow consists of two elements. In this case the direct driving force is a gradient of mass transfer potential, and the temperature gradient is additional driving force. This is reflected in the mathematical expression of the principle of Onsager (1931) reciprocity that express the equality of certain ratios between flows and forces in not equilibrium thermodynamic systems

$$J_i = \sum_{k=1}^{n} L_{ik} X_{k(i=1,2,\ldots,n)} \tag{9}$$

Where J_i - the generated flows by thermodynamic driving forces; $L_{i,k}$ - the physical environment in which energy or substance is transmitted (in our case thermo physical and mass-physical characteristics of rocks); X_k - potential gradients that originated streams.

For the thermodynamic driving forces, such are a gradient of thermodynamic temperature and a gradient of mass transfer, the principle of Onsager's reciprocity has a form

$$J_1 = L_{11}X_1 + L_{12}X_2 \tag{10}$$

$$J_2 = L_{21}X_1 + L_{22}X_2 \tag{11}$$

Where J_1 is a thermal flow density, which is determined by the Fourier law in a private case; J_2 - the mass flow density, which is determined by the Fick's law or Luykov law, in the private case, in according what is the nature of the forces X_2, the gradient of concentration, or the mass transfer gradient.

3.2. Criteria for the similarity of heat and mass-exchange processes

Equations (10), (11), for the circuit depicted in Fig. 1, in the case of an isotropic and homogeneous mining massif, have the following differential form (Luikov, 1978)

$$\frac{\partial t}{\partial \tau} = a\Delta^2 t + \varepsilon r \frac{c_m}{c}\frac{\partial \Theta}{\partial \tau} \tag{12}$$

$$\frac{\partial \Theta}{\partial \tau} = a_m \Delta^2 \Theta + a_m \delta_\theta \Delta^2 t \tag{13}$$

Where ε - criterion for the phase transition of moisture in the mining massif. The rest of the symbols were determined previously.

Initial and boundary conditions have the form

$$\tau = 0,\ R = R_0:\ t_{(R_0,0)} = t_0,\ \Theta_{(R_0,0)} = \Theta_0 \tag{14}$$

$$\tau > 0,\ R = \infty:\ t_{(R,\tau)} = t_0,\ \Theta_{(R,\tau)} = \Theta_0 \tag{15}$$

$$\tau > 0,\ R = \infty:$$

$$-\lambda \frac{\partial t}{\partial R} + \alpha(t_k - t_h) + \alpha_m r(\Theta_k - \Theta_h) = 0 \tag{16}$$

$$-\lambda_m \frac{\partial \Theta}{\partial R} - \lambda_m \delta_\theta \frac{\partial t}{\partial R} + \alpha_m(\Theta_k - \Theta_h) = 0 \tag{17}$$

Where t_k, Θ_k - temperature and mass transfer potential of the walls of tunnel, ^0C, j/mol; t_h, Θ_h - the same for ventilation flow. The rest of the symbols were determined previously.

From these equations, initial and boundary conditions follow criteria for the similarity of heat and mass-exchange processes: Bio, Fourier, Kosovich, mass transfer criteria Fourier, Bio and Posnov that respectively have the form

$$Bi = \frac{\alpha R_0}{\lambda};\ Fo = \frac{a\tau}{R_0^2};\ Ko = \frac{rc_m}{c}\frac{\Delta\Theta}{\Delta t} \tag{18}$$

$$Bi_m = \frac{\alpha R_0}{\lambda};\ Fo_m = \frac{a_m \tau}{R_o^2};\ Pn_m = \delta_\theta \frac{\Delta t}{\Delta \Theta} \tag{19}$$

Where τ time, s; R_0 – equivalent radius of the tunnel, m; Δt, $\Delta\theta$ – temperature and potential increments respectively; δ_θ – thermal gradient factor showing additional mass transmission in the system in the form of Soret effect, J/mol. *K*);. The rest of the symbols were determined previously.

Equation (16) is an expression of the energy conservation law for the mentioned system. To analyse it, application of a new similarity criterion is needed. According to the π -theorem, in this formula the number of dimensional quantities, primary dimensions and dimensionless quantities (similarity criteria) are 9, 5 and 4, respectively (Kutateladze, 1982). These criteria are the dimensionless temperature, the Bio and Posnov criteria. The definition of a dimensionless temperature is given below. We note that, according to the π -theorem, there must be four criteria, but there are only three of them.

$$\frac{\Delta_\tau t}{\Delta_R t} = t_{(R,\tau)} = \frac{t - t_2}{t_0 - t_2} \tag{20}$$

Where t_0 – natural temperature of mining massif, ${}^0C$.

After insertion of limited proportional quantities according to L'Hopitale's rule and multiplication by $R/\lambda\Delta_\tau t$, equation (16) will transform as

$$\frac{\Delta_\tau t}{\Delta_R t} = \frac{\alpha R}{\lambda} + \frac{\alpha_m r R}{\lambda}\frac{\Delta_\tau \theta}{\Delta_\tau t} \tag{21}$$

For the tunnel wall, i. e. when $R = R_0$ after simple transformations equation (21) will get the following form

$$\frac{\Delta_\tau t}{\Delta_{R_0} t} = Bi + La\frac{Bi}{Pn_m} \tag{22}$$

Where a new criterion is introduced

$$La = \frac{\delta_\theta \alpha_m r}{\alpha} \tag{23}$$

As it is seen from equation (22), dimensionless temperature of a tunnel wall is combination of the appointed complexes. Thus, criterion expressed by formula (23) is the fourth dimensionless complex that is necessary for the process analysis according to π -theorem.

The new criterion relates thermal resistance $1/\alpha$ with mass transfer analogical resistance $1/\alpha_m$ within the limits of corresponding boundary layers. Thus, estimation of the ventilation air flow by it appears to be possible as both of those values are the current characteristics.

The first impression is that the same result can be obtained by Lewis, Kosovich, or Posnov criteria separately. This is not quite correct as each of them taken separately characterizes just the massif showing only a rate of increase of cooled and dried up layers thicknesses.

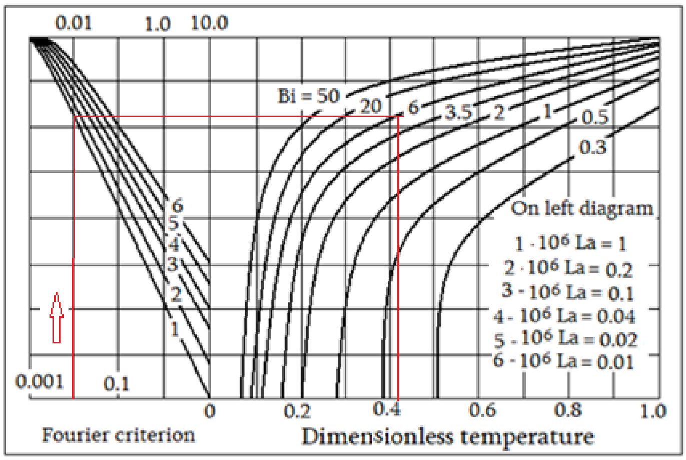

Fig. 2. Changing of dimensionless surface temperature of the tunnel $\bar{t} = f(Fo, Bi, La)$

Use the nomogram as follows according to the red lines (beginning on the left diagram): $Fo = 0.01; 10^6 La = 1$; $Bi = 6$; Dimensionless temperature $\bar{t} = t(\tau, R_0) = 0.42$

In fact, temperature gradient always causes additional mass flow and vice versa – gradient of mass transfer potential causes additional thermal current, but there are cases in practice, when consideration of these additional currents is not necessary for calculation of ventilation flow temperature, mass transfer potential and relative humidity. The said is corroborated by the critical value of the new criterion $10^6 La = 1$. Consideration of interference of these two processes for solution of multiparametric tasks is needed when this equality fails.

Using formula (1) and the dimensionless temperature from Fig. 2, it is possible to determine the non-stationary heat transfer coefficient with or without additional heat flow and accordingly perform thermal calculation.

4. Conclusions

Thus, heat and mass fluxes in the two-component system "mountain massif-ventilation air" are the result of the influence of two gradients-the temperature potential and the mass transfer potential. The additional threads initiated by the effects of Sore and Dufour tend to amplify the main flows, but in practice, there is a case where there is no need to consider the effect of additional flows. Based on the analysis of processes, the criteria that determine their numerical values show that accounting for additional flows of Sore and Dufour is mandatory. Marked effects can be ignored when $10^6 La = 1$. By means of the presented results can definite of non-stationary heat transfer coefficient for any cases of mentioned processes.

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