SEPARATION AND EVALUATION OF SIMULTANEOUS HEAT-MASS EXCHANGE IN SUBWAY TUNNELS

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Summary: *During simultaneous heat and mass transfer between a ventilation flow and a surrounding massif, the heat flow is supported by the mining massif, and the moisture flow is due to hygroscopic processes occurring only within the tunnel's concrete support. This is result of using moisture resistant membranes between the mining massif and the underground space. The simultaneous heat and mass transfer processes in the presented paper considered on the basis of* π*-theorem and established a new criterion by means of it is possible to divide processes heat and mass transfer at the two-component system "massif-air". The new criterion relates a thermal resistance* $1/\alpha$ *with mass transmission analogical resistance* $1/\alpha_m$ *within the limits of corresponding boundary layers. Thus, estimation of a ventilation air flow by it appears to be possible as both of those values are the current characteristics. As a result, it may be concluded that separation and evaluation of simultaneous heat mass exchange processes using the criterion introduced in this paper is possible.*

Key Words: *Subway tunnels; Non-stationary heat and mass (moisture)exchange; Heat and mass flows*

Introduction. According to modern technologies of transport tunnels' construction, there are the installation of various moisture resistant membranes between the mining massif and the underground space, therefore drainage of water does not occur through the concrete fastening of the tunnel inside the underground space. The appearance of the water in an explicit form here is local in its nature and should be consider separately. Consequently, in the area of tunnel's concrete fastening takes place a non-stationary process of transfer of hygroscopic moisture together with a similar process of heat transfer. Therefore, during simultaneous heat and mass transfer between the ventilation flow and the surrounding massif, the heat flow is supported by the massif, and the moisture flow is due to hygroscopic processes occurring only within the tunnel's concrete support.

The considerable practical interest has the separate assessment of heat and mass fluxes for jointly occurring processes, as well as the comparison of the numerical values of the coefficients of unsteady heat and mass transfer taking into account the mutual influence of temperature and mass transfer potential on the values of heat and mass fluxes. The great interest has also the establishment of cases when the noted effect should be taken into account and when it can be neglected without compromising the accuracy of the results obtained. The joint processes of heat and mass transfer also take place in karst caves [1], as well as into the tunnels of mines [2-5].

Study area, material and methods. Thus, in underground tunnels heat and mass transfer between the rock massif and the ventilation stream is non-stationary, which is due, on the one hand, to a periodic change in air speed in all sections of the tunnel depending on the movement of trains. and, on the other hand, with the conditions of heat and mass transfer in the rock massif, in the concrete fastening of the tunnel and the conditions of heat and mass transfer at the interface of the two-component thermodynamic system "massif – air". The temperature of surrounding rock massif is equal to the neutral layer temperature for Tbilisi metro conditions – 12.3 ^{0}C [6]. Mentioned temperature does not actually change over the year. In the area of the tunnel's concrete mount takes place maximum hygroscopic mass content, it also does not actually change during the year and from the point of view of mass exchange, this element of tunnel plays the role of a damper and equalizes the relative humidity [7]. The standard theoretical research methods are used, including the π-theorem.

Results and discussion. Let us assume that mountain massif is characterized by temperature and mass transmission potential force fields, kinetic coefficients describing the environment do not change by time within the range of temperature and potential variations and also the current temperature, mass exchange potential and relative humidity are invariable. In such conditions, the mutual heat mass exchange can be described by Luikov-Mikhailov's differential equation system [8].

In order to get an unambiguous solution to this system, it is necessary to observe the boundary conditions of the third kind at the interface of the mentioned binary system "massif – air". The boundary conditions of the third kind in this case are of the form

$$-\lambda\frac{\partial t}{\partial R}+\alpha(t_1-t_2)+\alpha_m r(\theta_1-\theta_2)=0 \tag{1}$$

where λ – the heat conductivity coefficient of the massif, W/m. ^{0}C; t, t_1, t_2 – temperatures of the body, the tunnel walls and the air respectively, ^{0}C; α – heat emission factor, W/m^2.^{0}C; α_m – mass emission factor, kg·mol/J·m^2·s; r – specific heat of the phase change, kJ/kg; θ_1 – mass transmission potential of the wall, J/mol; θ_2 – mass transmission potential of the air, J/mol; R – cylindrical coordinate, m.

Equation (1) is an expression of the energy conservation law for the mentioned system. To analyze it, application of a new similarity criterion is needed. According to π-theorem, similarity criterions for dimensional, primary dimensional and dimensionless quantities in this equation are 9, 5 and 4 respectively [9]. These criteria are dimensionless temperature, Bio- and mass-transfer Posnov complexes, which respectively have the form

$$\frac{\Delta_\tau t}{\Delta_R t}=t_{(R,\tau)}=\frac{t-t_2}{t_0-t_2}\,,\ Bi=\frac{\alpha R_0}{\lambda}\,,\ Pn_m=\delta_\theta\frac{\Delta t}{\Delta\theta}\ , \tag{2}$$

where τ – time, s; t_0 – the natural temperature of undisturbed mining massif, ^{0}C; R_0 – an equivalent radius of the tunnel, m; δ_θ – thermal gradient factor in the mass transmission potential scale showing additional mass transmission in the system in the form of Soret effect, J/mol.^{0}C; Δt, ΔQ – temperature and mass transfer potential increments respectively. The rest of the symbols were determined previously.

After insertion of limited proportional quantities according to L'Hopitale's rule and multiplication by $R/\lambda\Delta_\tau t$, equation (1) will transform as

$$\frac{\Delta_\tau t}{\Delta_R t}=\frac{\alpha R}{\lambda}+\frac{\alpha_m rR}{\lambda}\frac{\Delta_\tau\theta}{\Delta_\tau t}\,. \tag{3}$$

For the tunnel wall, when R=R_0 after simple transformations equation (3) will get the following form

$$\frac{\Delta_\tau t}{\Delta_{R_0} t}=Bi+La\frac{Bi}{Pn_m} \tag{4}$$

where a new criterion

$$La=\frac{\delta_\theta\alpha_m r}{\alpha} \tag{5}$$

is introduced. As it is seen from equation (4), dimensionless temperature of a tunnel wall is combination of the appointed complexes. Thus, criterion expressed by formula (5) is the very fourth dimensionless complex that is necessary for the process analysis according to π-theorem.

The new criterion is a synthesis of Lewis, Kosovitch and Posnov criteria. To prove it, let us consider heat and mass densities on the binary system interface according to the basic Fourier conduction law and Newton law, which are expressed as

$$\alpha(t_1 - t_2) = -\lambda \ grad \ t \ \ \alpha_m(\theta_1 - \theta_2) = -\lambda_m \ grad \ \theta \tag{6}$$

respectively. In addition to already defined values there is a new one – λ_m denoting mass conductivity factor of the massif, kg·mol/J·m·s.

The basic relations of heat and mass physical characteristics of rocks are

$$\lambda = ac\gamma_0 \ \ \lambda_m = a_m c_m \gamma_0 \tag{7}$$

where α - heat conductivity factor of the rock, m^2/s; α_m – conductivity factor of the mass transfer potential, m^2/s; c – specific heat, $J/kg \cdot {}^0C$; c_m – specific isothermal mass capacity, mol/J; γ_0 – the rock density, kg/m^3. Using simple transformations and considering (7) and (6) we get

$$\alpha = -ac\gamma_0 \frac{\Delta_\tau t}{\Delta_{R_0} t}, \ \alpha_m = -a_m c_m \gamma_0 \frac{\Delta_\tau \theta}{\Delta_{R_0} \theta}. \tag{8}$$

Taking into account expressions of Lewis and Kosovitch criteria, which are

$$Le = \frac{a_m}{a} \ \ Ko = \frac{rc_m}{c}\frac{\Delta\theta}{\Delta t} \tag{9}$$

respectively and inserting equation (8) in (5), after simple transformations we get

$$La = LeKoPn_m \tag{10}$$

that is the proof of our suggestion.

The new criterion relates thermal resistance $1/\alpha$ with mass transmission analogical resistance $1/\alpha_m$ within the limits of corresponding boundary layers. Thus, estimation of a 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, Kosovitch, 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.

The mentioned rate for a layer is what Lewis criterion shows in its classical form. Coefficient α shows temperature exchange rate in a massif caused by distortion introduced by an air flow energy impulse. Analogically, α_m is an indicator of potential exchange rate. It is impossible, to estimate air flow parameters by relation between them. Moreover, neither Kosovitch, nor Posnov criteria allow the correct thermophysical calculation of air flow as it requires knowledge of the desired quantities such as flow temperature and mass transfer potential in advance. The point is that temperature and potential increments in the first approximation are $\Delta t = t_1 - t_2$ and $\Delta\theta = \theta_1 - \theta_2$, where t_2 and θ_2 are the desired values.

In fact, temperature gradient always causes additional mass flow and vise versa – potential gradient causes additional thermal current, but there are cases in practice, when consideration of these additional currents is not necessary for calculation of 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.

In any case, dimensionless temperature by solution of the afore mentioned Luikov-Mikhailov's differential equations has the following form:

$$t_{(\tau, R_0)} = Bi(1 + LaPn_m^{-1}). \tag{11}$$

This equation makes it possible to determine nonstationary heat transmission factor considering an additional heat flow or without it.

Conclusions

– As a result, it may be concluded that separation and evaluation of simultaneous heat mass exchange processes using the criterion introduced in this paper is possible.

– The heat and mass fluxes in the underground space are the result of the influence of two gradients-the temperature 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. Marked effects can be ignored when $10^6 La = 1$.

References

1. Bolashvili N., Lanchava O., Tsikarishvili K. Tskaltubo (Prometheus) Cave System – Some Issues of Research. // Monograph, ISBN: 978-3-330-04974-1, LAP LAMBERT Academic Publishing, Gmbh & CO. Saarbrucken, Germany, 2017, 136 p.
2. Petrilean D.C.., Stanilă S., Irimie S.I., Study of variable heat exchange between a thickness limited cylindrical pipe and the rock massif for application in mine environment. // Environmental Engineering and Management Journal, 13(6), Iasi, Romania, 2014, pp. 1383-1388.
3. Petrilean D.C.., Stanilă S., Dosa I., A mathematical model for the determination of the dimensionless heat flux with application in mine environment. // Environmental Engineering and Management Journal, 16(6), Iasi, Romania, 2017, pp. 1331-1340.
4. Lanchava O.A., Heat and mass exchange in permanent mine workings. // Journal of Mining Science 1(6), Novosibirsk, 1982, pp. 87-92, (in Russian).
5. Lanchava O.A., Heat and mass exchange in newly driven mine workings. // Journal of Mining Science 1(5), 1985. pp. 99-104, (in Russian).
6. O. Lanchava, N. Ilias. Complex calculation method of temperature, mass transfer potential and relative humidity for ventilation flow in subway. // Journal of Engineering Sciences and Innovation. Volume 3, Issue 1, AGIR Publishing House, Bucharest, 2018, pp. 69-84.
7. O. Lanchava, N. Ilias. Some issues of thermal calculation of ventilation air for the metro. // Journal of Engineering Sciences and Innovation. Volume 2, Issue 2, AGIR Publishing House, Bucharest, 2017, pp. 92-105.
8. Luikov A. A. Teplomassoobmen. // Monograph, Moscow, 1978, 480 p. (in Russian).
9. Qutateladze C. C. Analiz Podobiya v Teplofizike, // Monograph, Novosibirsk, 1982, 308 p. (in Russian).