საქართველოს მეცნიერებათა ეროვნული აკადემიის მოამბე, ტ. 16, №2, 2022
BULLETIN OF THE GEORGIAN NATIONAL ACADEMY OF SCIENCES, vol. 16, no. 2, 2022

Mechanics

Determination of Non-Stationary Heat and Mass Transfer Coefficients in Tunnels

Omar Lanchava*, Teimuraz Kunchulia*, Zaza Khokerashvili*, Nino Arudashvili*, Davit Tsanava*

* *Occupational Safety and Emergency Management Department, Georgian Technical University, Tbilisi, Georgia*

(Presented by Academy Member E. Medzmariashvili)

The artificial and natural hollow underground structures, in which people are present, need to have inhabitable environment, which mainly implies sufficient ventilation. The ventilation air intensively exchanges heat and humidity with the rock massif surrounding the tunnels. As a result, the temperature and moisture content of both, the air and the rock massif change. The main heat and mass currents rising from the massif are due to the gradients of the temperature and mass transfer potential, which, at the same time, cause additional transfers as Dufour and Soret effects. The paper, based on Onsager's theorem and by considering the Curie's principle, shows that these two gradients are the cause of all kinds of manifestations of the heat exchange process under the ground. It is shown that the heat exchange between the rock massif and the ventilation flow is caused by the tensors of the first order: the given gradients of temperature and mass exchange potential, which are direct driving forces for the flow with the same name and additional driving forces for the flow and the forces with different names. The currents caused by both, the main and additional forces have the same effect on the variability of such climatic parameters of the ventilation, as temperature and relative humidity inside the tunnel, which is seasonal. The coefficients of non-stationary heat and mass transfer from the rock massif are subject to seasonal variability, which must be taken into account during the thermophysical calculation of tunnel ventilation. *© 2022 Bull. Georg. Natl. Acad. Sci.*

heat and mass transfer, non-stationary coefficients, seasonal variability, tunnel

All artificial and natural underground structures where the underground technological processes take place, or which have transport, hydrotechnical, warehousing, defense, treatment, scientific, urban or other designation where people present, need to have proper ventilation systems. As the ventilation current causes an exchange of heat and moisture with the surrounding rock massif, its temperature and relative humidity change. Both parameters are important indicators of the underground micro-climate giving optimal and safe working conditions [1].

If the rock massif is located under the water-proof rock layer, or a membrane is used alongside the reinforcement, no water will flow into the tunnel and the increased air humidity is due to the mass exchange.

This term describes the moisture with a sorption association with the rock massif, it is transferred to the air by desorption, while the transfer potential in this case is called mass transfer potential, whose role may be played by a chemical potential.

Thus, the rock massif in the tunnel area under the water-proof layer is a heterogeneous and multi-component environment with stationery fields of temperature and mass transfer potential. Before the ventilation starts, the given environment is a balanced, irreversible and isolated thermodynamic system with maximum entropy. This system loses equilibrium under the impact of the external force, which is the ventilation flow induced by the fan operation, which can be described by different thermodynamic parameters, while the potential is determined by the formula $\vartheta = RTln\varphi$. R in this formula is a universal constant, J/(mol. *K*); *T* is the absolute temperature, *K*; and $ln\varphi$ is the natural logarithm of the equilibrium relative humidity. The numerical value obtained with the given formula is with a negative sign what is a mass transfer potential in the hygroscopic area. On the edge of the hygroscopic and hydroscopic areas $\vartheta = 0$, while it has positive values in the hydroscopic area making the potential scale resemble to the Celsius temperature scale [2].

Theory

Under the action of any thermodynamic driving force X_i, one of the extensive parameters of the system corresponding to this force will inevitably change. This parameter, under the influence of mechanical processes, is called generalized coordinate x_i, and all types of work are presented by an equation $dA_i = -\mathrm{X}_i dx_i$. If *X* is pressure, then its corresponding generalized coordinate is specific volume v, while *A* expresses the work needed to compress or expand the gas.

Clearly, not all extension parameters of the system are coordinates, but a generalized coordinate is necessarily an extension parameter that changes as a result of a potential impact. Not all generalized coordinates in the joint heat transfer process are easy to determine. An example is entropy *S*, which is a generalized coordinate of thermal impact, and the potential in this case is thermodynamic temperature *T*.

According to Onsager's theorem, which is valid in both, classical and relativistic terms, the thermodynamic driving forces are determined by the partial derivative of entropy variation depending on the magnitude of deviation of parameters from the equilibrium state [3]

$$\mathrm{X}_i = \partial\left(\Delta S\right) / \partial\vartheta_i, \tag{1}$$

where ΔS is the change of entropy in time unit corresponding to the change of the equilibrium state; and ϑ_i is the deviation of thermodynamic parameter Π_i from equilibrium state Π_i^0.

In the equilibrium state, when $\vartheta_i = 0$, when specifying the thermodynamic state, the following classical parameters may be Π_i value: pressure, temperature, concentration, partial pressure, etc., i.e., all the parameters that characterize the thermodynamic system in irreversible processes.

The basic ratio of irreversible processes, i.e., the Onsager system of linear equations is as follows

$$j_i = \sum_{k=1}^{n} L_{ik} \mathrm{X}_{k(i=1,2,\ldots,n)}, \tag{2}$$

where L_{ik} is the kinetic parameters of the variation of the state of the system.

In order to understand the physical essence of equation (2), let us look at the following example: if a system is characterized by two variable parameters (χ_1, χ_2), which vary under the influence of the relevant potentials (X_1, X_2), the currents are determined with the formula similar to formula (2)

$$j_1 = L_{11}\mathrm{X}_1 + L_{12}\mathrm{X}_2\,, \quad j_2 = L_{21}\mathrm{X}_1 + L_{22}\mathrm{X}_2\,. \tag{3}$$

The formula shows that current j_1 depends not only on its corresponding driving force X_1 but on other potentials of the same system. This condition is envisaged by the Curie's Principle, which was adapted to the thermodynamics of irreversible processes by de Groot. As the principle suggests, the current is subject to a simultaneous impact of thermodynamic forces with the same order of tensor or with the difference between the orders of tensors being an even number [4]. The driving forces to transfer heat and mass in a capillary-porous body: the temperature gradient and the gradient of the ratio between the mass transfer potential and the temperature are vectors and the tensors of the first order.

Thus, the thermodynamic driving forces to transfer heat and mass in a capillary-porous body are as follows

$$\mathrm{X}_q = -{}^{1}\!/_{T}\,\nabla T\,, \quad \mathrm{X}_m = -T\nabla\left({}^{\vartheta}\!/_{T}\right) \tag{4}$$

making it clear that the thermodynamic driving force of heat transfer is directly proportional to the temperature gradient, while the thermodynamic driving force of mass transfer is directly proportional to the gradient of the mass transfer potential and the temperature ratio. ∇ is Hamiltonian operator.

In case of a continuous body without pores, when the coefficient $L_{12} = 0$, then the coefficient $L_{11} = \lambda$ from the first equation of formula (3). In this case, the Fourier equation of heat conduction is obtained from the same equation

$$q = -\lambda\, gradT\,, \tag{5}$$

where q is the heat current, W/m^2; λ is the heat conductivity coefficient, W/(m.*K*); $gradT$ is the temperature gradient, *K*/m.

Similarly, under isothermal conditions, the temperature gradient $\mathrm{X}_1 = 0$ and Lykov's formulation is obtained from the second equation of formula (3)

$$q_m = -\lambda_m\, grad\,\vartheta\,, \tag{6}$$

where q_m is the mass current, kg.mol/(J.m^2.s); λ_m is the mass conductivity coefficient, kg.mol/(J.m.s); $grad\,\vartheta$ is the mass transfer potential gradient, J/(mol.m).

Thus, Onsager system of linear equations given by equation (3) considers heat and mass currents in a non-isothermal capillary-porous environment as follows: a heat current is caused by the temperature gradient (direct driving force), which is added by an additional heat current (induced by an additional force, the change of mass transfer potential in time). The mass flow is induced by the mass transfer potential gradient (component of the direct driving force), which is added by an additional mass flow (in the given case induced by an additional force, the temperature gradient). The additional heat current is called Dufur Effect and the similar mass current is called Soret Effect.

If a tunnel in the infinite rock massif has a shape of a circle with radius R_0, the heat and mass transfer through the rock massif along the tunnel will be ignored and the rock massif will be considered as isotropic and homogeneous, the heat and mass transfer between the rock massif and the ventilation current will be described by the following differential equations

$$\frac{\partial t}{\partial \tau} = a\nabla^2 t + \varepsilon r \frac{c_m}{c}\frac{\partial \vartheta}{\partial \tau}, \tag{7}$$

$$\frac{\partial \vartheta}{\partial \tau} = a_m \nabla^2 \vartheta + a_m \delta_\vartheta \nabla^2 t, \tag{8}$$

where t and ϑ are the potential of rock massif temperature and mass transfer potentials, respectively, °C and J/mol; a and a_m are the temperature conductivity and mass transfer potential conductivity coefficient, respectively, m^2/s; ∇^2 is the Laplace Operator; ε is the phase transformation criterion in the rock massif; r is the specific enthalpy of phase transformation, kJ/kg; c_m and c are the coefficients of the rock massif isothermal mass capacity and specific heat capacity, respectively, mol/J and kJ/(kg.°C); τ is the time, s; δ_ϑ is the thermogradient coefficient, J/(mol.K).

To establish the single-valuedness conditions, we support the view that following the turbulence of the ventilation flow, the flow temperature and potential are evenly distributed across the section, the flow is one-dimensional and the following equations are true on the dividing surface

$$\propto (t_2 - t_1) - \lambda\, grad t = 0, \tag{9}$$

$$\propto_m (\vartheta_2 - \vartheta_1) - \lambda_m grad \vartheta = 0, \tag{10}$$

where $\propto$ and $\propto_m$ are the surface heat and mass output coefficients, respectively, W/(m^2.°C) and kg.mol/(J.m^2.s); t_1 and ϑ_1 are the air current temperature and mass transfer coefficient, °C and J/mol; t_2 and ϑ_2 are the same values for the surface; and $gradt$ and $grad\vartheta$ are the gradients of temperature and mass transfer in the rock massif, grad/m and J/(mol.m).

Following the above-mentioned, the single-valuedness conditions are as follows

$$\tau = 0,\ R = R_0: \quad t_{Ro,0} = t_0,\ \vartheta_{Ro,0} = \vartheta_0 \tag{11}$$

$$\tau > 0,\ R \to \infty: \quad t_{R,\tau} = t_0,\ \vartheta_{R,\tau} = \vartheta_0 \tag{12}$$

$$\tau > 0,\ R = R_0: \quad -\lambda \frac{\partial t}{\partial R} + \propto (t_2 - t_1) + \propto_m r(\vartheta_2 - \vartheta_1) = 0 \tag{13}$$

$$\tau > 0,\ R = R_0: \quad -\lambda_m \frac{\partial \vartheta}{\partial R} - \lambda_m \delta_\vartheta \frac{\partial t}{\partial R} + \propto_m (\vartheta_2 - \vartheta_1) = 0, \tag{14}$$

where in addition to the explained values, R is a cylindrical coordinate; R_0 is the radius equivalent to the tunnel section, m.

Obtained Results and Discussion

Solving the problem using the theory of similarity and practical use of the obtained results will be convenient if the similarity criteria are used. During the simple heat and mass transfer processes in both, newly constructed tunnels and those with old ventilation system, the dimensionless potentials of the tunnel walls are given by functional dependencies [5, 6]

$$\bar{t}_{\tau,Ro} = f(Fo, Bi), \tag{15}$$

$$\bar{\vartheta}_{\tau,Ro} = f(Fo_m, Bi_m), \tag{16}$$

where $\bar{t}_{\tau,Ro}$ is the dimensionless temperature of the tunnel wall given as a decimal quantity; $\bar{\vartheta}_{\tau,Ro}$ is the dimensionless potential of mass transfer given as a decimal quantity; Fo, Bi, Fo_m and Bi_m are Fourier, Bio and Fourier mass exchange criteria, and bio exchange criteria, respectively, defined by the following formula

$$Fo = \frac{a\tau}{R_0^2},\ Bi = \frac{\propto R_0}{\lambda},\ Fo_m = \frac{a_m \tau}{R_0^2},\ Bi_m = \frac{\propto_m R_0}{\lambda_m}. \tag{17}$$

Temperature and mass transfer dimensionless potentials are defined by equations

$$\overline{t}_{\tau,Ro} = \frac{t - t_1}{t_2 - t_1},\ \overline{\vartheta}_{\tau,Ro} = \frac{\vartheta - \vartheta_1}{\vartheta_2 - \vartheta_1}, \tag{18}$$

where in addition to the explained values, t is the rock massif temperature, °C; and ϑ is the mass transfer potential of the rock massif, J/mol.

The problem given by the differential equations (7), (8) and the corresponding boundary conditions can be solved with the help of the numerical grid method, using elementary volumes. The obtained result shows the type of variability of the temperature and mass transfer potential of the rock massif on the tunnel walls, which can be used to provide the thermophysical calculation of ventilation.

It should be noted that the mentioned variability is due to both, non-stationary state and seasonal variability of air temperature and relative humidity what also has an impact on the numerical values of the said non-stationary coefficients. The non-stationary state is given as the attenuation and stabilization of the processes depending on the duration of tunnel ventilation, while the seasonal variability is permanent. A type of seasonal variability can be determined by analyzing the results of observations over the variability of the climatic parameters of the ventilation air in the tunnel: the temperature and the relative humidity. If considering that the ventilation flow temperature, relative humidity, moisture content, mass transfer potential and enthalpy change linearly in the tunnel where the experiments must be done, then it can be reasonably assumed that any change in the air internal energy can be assessed depending on the variability of enthalpy, a parameter characterizing its condition.

Air enthalpy is given by the equation

$$i = c_p t_1 + \left(2500 - 1.96 t_1\right) d\ , \tag{19}$$

where in addition to the explained values, *i* is the air enthalpy, kJ/kg; $\left(2500 - 1.96 t_1\right)$ is the specific enthalpy of vaporization at temperature t_1, kJ/kg; *d* is the air moisture content, kg/kg.

Enthalpy, in addition to the kinetic energy of the motion of air molecules, which is macroscopically expressed by temperature, characterizes the potential energy of the molecules interaction as well. In this case, potential energy depends on the number of water vapor molecules in the air, is macroscopically expressed by moisture content and incorporates the thermal effect of phase transformation.

In the three- and two-component thermodynamic systems: “Rock Massif- Groundwater-Ventilation air” and “Rock Massif-Ventilation air”, the energy in the tunnels located below the waterproof layer can be redistributed in any manner, such as convection, conduction, evaporation, or condensation. However, regardless of the type of energy transfer, the amount of heat and mass transferred by high-potential components is equal to the amount of heat and mass received by the low-potential elements.

Let us introduce the following notations

$$i_q = c_p t_1 \tag{20}$$

$$i_m = \left(2500 - 1.96 t_1\right) d\ , \tag{21}$$

where i_q is the specific kinetic energy of air, kJ/kg; and i_m is the specific potential energy, kJ/kg.

By multiplying both sides of formulas (19)-(21) by the average mass discharge of the ventilation air in the tunnel section we will receive

$$Q = Q_q + Q_m \tag{22}$$

$$Q_q = \bar{G} c_p t_1 \tag{23}$$

$$Q_m = \left(2500 - 1.96 t_1\right) d\bar{G}\,, \tag{24}$$

where Q, Q_q and Q_m are complete, explicit and implicit heat flows directed towards the air, respectively, kW; $\bar{G}$ is the average air mass discharge in the tunnel, kg/s.

Thus, complete enthalpy for any air quantity $\bar{G}$ can be represented with formula (22) as the sum of its explicit and implicit enthalpies.

Therefore, for a tunnel of any length, or for its area, the following formulas can be used to give the increments of explicit and implicit air heat currents based on formulas (23) and (24)

$$\Delta Q_q = \bar{G} c_p \Delta t \tag{25}$$

$$\Delta Q_m = \left(2500 - 1.96 t_1\right) \Delta d\bar{G} = \bar{G} r \Delta d\,, \tag{26}$$

where Δt is the air temperature increment in the tunnel areas, °C; t_1 is the air temperature within the same area, °C; Δd is the air moisture content increment within the same area, kg/kg; and r is the specific enthalpy of phase transformation at t_1 temperature, kJ/kg.

The heat currents given by formulas (25) and (26) can be determined for the same conditions according to equations (7) and (8) in order to evaluate the accuracy of the latter. The formulas to calculate the currents using non-stationery heat and mass output coefficients are as follows

$$\Delta Q_q = 0.001 K_\tau P_T l \left(t_0 - t_1\right) \tag{27}$$

$$\Delta Q_m = K_{\tau m} \left(P_T l - F\right)\left(\vartheta_0 - \vartheta_1\right) r\,, \tag{28}$$

where ΔQ_q is the energy transferred from the rock massif by convection and conduction, kW; K_τ is non-stationary heat output coefficient, W/(m^2.°C); P_T is the perimeter of the tunnel, m; l is the length of the tunnel or its area, m; t_0 is the average natural temperature of the rock massif, °C; ΔQ_m is the energy transferred from the rock massif due to the phase transformation, kW; F is the open water surface area, m^2; ϑ_0 is the mean value of the natural mass transfer potential for the rock massif, J/mol; ϑ_1 is the ventilation flow mass transfer potential, J/mol.

It should be noted that formula (27) does not differentiate heat transfer from an open water surface because its temperature is in fact equal to the temperature of the rock massif, from which it flows. Besides, formula (28) considers only the energy transferred as a result of phase conversion from a rock massif and does not take into account evaporation from an open water surface, which is well studied and should be considered separately. Therefore, if subtracting the increment of the moisture content from the amount of water evaporated from the open water surface, the remaining value $\left(\Delta d_m\right)$ will be the amount of mass received by the air from the rock massif. By considering the above-mentioned, formula (26) will be as follows

$$\Delta Q_m = \bar{G} r \Delta d_m\,. \tag{29}$$

With simple transformations of formulas (25), (27)-(29), we receive

$$K_\tau = 1000 \frac{\bar{G}\Delta t c_p}{P_T l\left(t_0 - t_1\right)} \tag{30}$$

$$K_{\tau m} = \frac{\bar{G}\Delta d_m}{(P_T l - F)\left(\vartheta_0 - \vartheta_1\right)}. \tag{31}$$

Direct measurement of the values given in these formulas is not difficult in real tunnels and therefore, we think that the given methods can be used to experimentally determine non-stationery heat exchange coefficient K_τ with experiments, as well as non-stationery mass exchange coefficient $K_{\tau m}$.

On the other hand, the numerical values of these quantities can be determined by taking into account the solutions of differential equations (7), (8) and corresponding boundary conditions (11)-(14), in accordance with the methodology given in paper [7].

For a tunnel with monolithic reinforcement, the non-stationery heat and mass output coefficients are respectively calculated using the formulas

$$K_\tau = K_1 \bar{t}_{\tau,Ro}, \quad K_{\tau m} = K_2 \bar{\vartheta}_{\tau,Ro}, \tag{32}$$

where heat transfer coefficient K_1 and mass transfer coefficient K_2 are calculated with formula

$$K_1 = 1 \Big/ \left(\frac{1}{\propto} + \frac{\sigma}{\lambda}\right) \quad K_2 = 1 \Big/ \left(\frac{1}{\propto_m} + \frac{\sigma}{\lambda_m}\right). \tag{33}$$

In addition to the explained values of the given formulas, σ is the thickness of the bracket, m.

Heat output coefficient is calculated with formula

$$\propto = \frac{\varepsilon_1 \bar{G}^{0.8} P_T^{0.2}}{302 S}, \tag{34}$$

where in addition to the explained values, ε_1 is the tunnel bracket thickness coefficient. For concrete reinforcement, $\varepsilon_1 = 1.0$; S is the tunnel cross sectional area, m^2.

Mass output coefficient is calculated with formula

$$\propto_m = 0.468 \frac{\lambda_{m1} V^{0.5}}{R_0^{0.5} \nu^{0.17} D^{0.33}}, \tag{35}$$

where: λ_{m1} is the air mass conductivity coefficient, kg.mol/(J.m.*K*); *V* is the air velocity, m/s; R_0 is the equivalent radius of the tunnel section, m; ν is the air kinematic viscosity coefficient, m^2/s; and *D* is the water vapor diffusion coefficient, m^2/s.

The annual variability of non-stationery heat and mass exchange coefficients, based on the theoretical calculations and experimental observations, is given in Fig.

As the Fig. shows, the experimental values of these coefficients show a pronounced seasonal variability, while the theoretically calculated values show slight seasonal fluctuations. As a result, the theoretical values of non-stationary heat transfer coefficients need correction depending on seasons. This is an accepted method in the thermophysical calculation practice. If the type of the annual variability of the climatic parameters in a given tunnel is known, it is possible to determine the season-based adjustment increments of the coefficients quiet accurately. In case of absence of such data, linear interpolation can be used taking into account the fact that the theoretical and experimental values of the coefficients in the transition period (spring and autumn) are equal to each other.

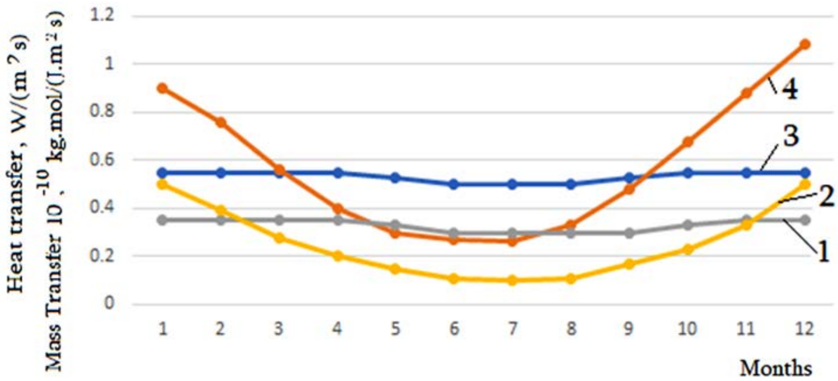

Fig. Annual variability of non-stationery heat and mass exchange coefficients based on the theoretical calculations and experimental observations: 1, 2 – Annual course of heat transfer coefficient: 1 – theoretical, 2 - experimental; 3, 4 - Annual course of mass transfer coefficient: 1 - theoretical, 2 - experimental.

Conclusion

According to the Onsager's theorem, by considering the Curie's Principle, the heat and mass transfer between the rock massif and the ventilation current is caused by the tensors of the first order: the temperature and mass transfer potential gradients, which are direct driving forces for the currents with the same name and additional driving forces in case the current and the forces have different names. The currents caused by both, main and additional forces act similarly on the variability of the climatic parameters of the ventilation flow: the temperature and the relative humidity within the tunnel, which is seasonal. The coefficients of non-stationary heat and mass transfer from the rock massif are subject to seasonal variability what must be taken into account during the thermophysical calculation of the tunnel ventilation.

This work was supported by Shota Rustaveli National Science Foundation of Georgia (SRNSF) [Grant number AR-19-1936, Project title "Development and Testing of Transformable System to Save Life in Road Tunnel in Case of Fire"].

მექანიკა

არასტაციონარული თბო- და მასაგადაცემის კოეფიციენტების განსაზღვრა გვირაბებში

ო. ლანჩავა*, თ. კუნჭულია*, ზ. ხოკერაშვილი*, ნ. არუდაშვილი*, დ. ცანავა*

* *საქართველოს ტექნიკური უნივერსიტეტი, შრომის უსაფრთხოებისა და საგანგებო სიტუაციების მართვის დეპარტამენტი, თბილისი, საქართველო*

(წარმოდგენილია აკადემიის წევრის ე. მეძმარიაშვილის მიერ)

ხელოვნური მიწისქვეშა ნაგებობები და სხვა ბუნებრივი ღრუ მოცულობები მიწისქვეშ, რომლებშიც საჭიროა ადამიანების ყოფნა, საჭიროებს სასიცოცხლო პირობების შექმნას, რაც ძირითადად გამართული ვენტილაციით გამოიხატება. სავენტილაციო ჰაერი გვირაბების გარშემომცველ სამთო მასივთან ინტენსიურად ცვლის სითბოსა და ტენს. აღნიშნულის შედეგად იცვლება როგორც ჰაერის, ისე მასივის ტემპერატურა და ტენშემცველობა. მასივიდან აღძრული თბური და მასის ძირითადი ნაკადები განპირობებულია ტემპერატურისა და მასაგადატანის პოტენციალის გრადიენტებით, რომლებიც იმავდროულად იწვევენ დამატებით გადატანას დიუფურისა და სორეს ეფექტების სახით. ნაშრომში ონზაგერის თეორემაზე დაფუძნებით, კიურის პრინციპის მხედველობაში მიღებით ნაჩვენებია, რომ აღნიშნული ორი გრადიენტი იწვევს თბომასაგაცვლის პროცესის ყველა გამოვლინებას მიწისქვეშ. ნაჩვენებია, რომ სამთო მასივსა და სავენტილაციო ნაკადს შორის თბომასაგადაცემას განაპირობებს პირველი რანგის ტენზორები – მითითებული ტემპერატურისა და მასაგადატანის პოტენციალის გრადიენტები, რომლებიც პირდაპირი მამოძრავებელი ძალებია იმავე დასახელების ნაკადებისათვის და დამატებითი მამოძრავებელი ძალები იმ შემთხვევაში, როცა ნაკადის და ძალების სახელები ერთმანეთს არ ემთხვევა. როგორც ძირითადი, ისე დამატებითი ძალებით განპირობებული ნაკადები ერთნაირად მოქმედებს სავენტილაციო ნაკადის კლიმატური პარამეტრების – ტემპერატურისა და ფარდობითი ტენიანობის ცვალებადობაზე გვირაბის ფარგლებში, რომელსაც სეზონური ხასიათი აქვს. სამთო მასივიდან სითბოსა და მასის არასტაციონარული გადაცემის კოეფიციენტები სეზონურ ცვალებადობას განიცდის, რაც მხედველობაში უნდა იქნეს მიღებული გვირაბების ვენტილაციის თბოფიზიკური გაანგარიშების შემთხვევაში.

REFERENCES

1. Racz M.D., Petrilean D.C. (2019) The influence of humidity on air temperature in underground mines as a factor of air quality assessment. *Quality-Access to Success,* **20**, S1: 371.
2. Oniani Sh.I., Lanchava O.A. (2020) Hygroscopic potential of mass transfer in rock mass. *Georgian Scientists,* **2**(2).
3. Onsager L. (1931) Reciprocal relations in irreversible processes. *Physical Review*, **37**: 405-426.
4. de Groot S.R., Mazur R. (2013) Non-equilibrium thermodynamics, 505, Dover Publications Inc., New York.
5. Lanchava O.A. (1982) O teplomassoobmene v kapital'nykh gornykh vyrabotkakh. *Soviet Rock Science*, **18**(6): 529-532 (in Russian).
6. Lanchava O.A. (1985) O teplomassoobmene v svezheproidennykh gornykh vyrabotkakh. *Soviet Rock Science,* **21**(5): 460-464 (in Russian).
7. Kuzin V.A., Velichko A.E., Khokhotva N.N. (2018) Edinaia metodika prognozirovania temperaturnykh uslovii v ugol'nykh shakhtakh,196. https://files.stroyinf.ru/Index2/1/4293744/4293744579.htm

Received March, 2022