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## **Complex calculation method of temperature, mass transfer potential and relative humidity for ventilation flow in subway**

**LAHCHAVA OMAR<sup>1,2</sup>, ILIAS NICOLAE<sup>3\*</sup>**

<sup>1</sup> 0186, Mindeli Street 7, G. Tsulukidze Mining Institute, Tbilisi, Georgia

<sup>2</sup> 0175, Kostava Street 77, Georgian Technical University, Tbilisi, Georgia

<sup>3</sup> Universității Street 20, University of Petroșani, Petroșani, Romania

**Abstract.** A complex method for calculating the atmospheric climate parameters of ventilation flow in the metro is proposed, which includes non-stationary heat exchange between the ventilation stream and the environment of the whole mountain massif, while the mass exchange process occurs only in zones of reinforcement and finishing areas of tunnels, since the effect of the moisture exchange process is limited to waterproof membranes. Placement of membrane between the mining and tunnel reinforcement is widely applied modern technology. Consequently, in case of tunnels we are facing only pores with sorption moisture and this moisture is in dynamic equilibrium with relative humidity of ventilation air and help to maintain latter's numeric value closest to average index throughout the year. Water in an explicit form in tunnel can be observed only in exceptional cases, in the form of local sources which is separately discussed in this paper in accordance with provided comprehensive method. This paper also considers the hygroscopic mass transfer potential in the mining massif and in the capillary-porous bodies. Calculation formulas for non-stationary heat and mass exchange coefficients are provided with and without consideration of tunnel reinforcement and finishing areas impacts.

**Key words:** metro, ventilation, complex method of thermal calculation.

### **1. Introduction**

According to modern technologies of construction and operation of transport tunnels, drainage of water does not occur inside the membrane in the area of reinforced coating of the tunnel and here takes place a non-

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\* Correspondence address: [iliasnic@yahoo.com](mailto:iliasnic@yahoo.com)

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. The essential nuance is that the heat exchange is spread on the all the surrounding mining massif and the mass transfer takes place only within the reinforcement and finish. Thus, we have to deal only with the sorption mass content in the pores of the reinforcement and finish 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.

The temperature of surrounding rock massif is equal to the neutral layer temperature that for Tbilisi metro conditions is 12.3 °C [1]. Mentioned temperature does not actually change over the year. In the area of reinforced coating takes place maximum hygroscopic mass content, it 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 of air all the year round. Because of this, when the average temperature of atmospheric air exceeds the neutral layer temperature and the air's absolute humidity is high in nature, then due to air cooling, in the places where the underground space is connected to the atmosphere takes place a local condensation of moisture. The air quantitatively drains, because the absolute humidity decreases, but is qualitatively moistened due to the increase in relative humidity. The condensation area is spread practically within all the length of tunnel between stations of metro. In this case the heat of the "liquid-vapor" phase transition is transferred to both components of the thermodynamic system "surrounding massif-cave air".

In the winter occurs the evaporation from the open surface of the mining array, and at this time the heat of steam or enthalpy of phase transformation "fluid-steam" is completely absorbed from massif and the air is heated. Quantitatively the air is moistened but since the growth rate of the temperature is greater than the rate of increase in the relative humidity, in fact there is a decrease in this value-the relative humidity.

In addition we think that:

- Air is a homogeneous binary mixture (dry air plus water vapor);
- During the movement, the air is incompressible;
- The characterize of this environment is possible by temperature, pressure and relative humidity (water steam partial pressure);
- In metro tunnels, the heat and mass exchange between the rock massif and the ventilation jet is non-stationary, which is caused on the one hand by the periodic change in the air velocity in all sections of the tunnel, depending on

the traffic of train, its speed and the piston effect, and on the other hand, from the change in the natural fields temperature and mass transfer potential in the surrounding massif, depending on the perturbations by means of ventilation flow.

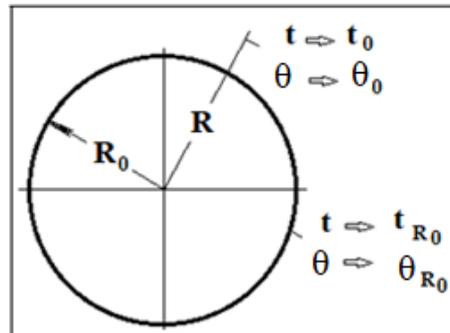


Fig. 1. Distribution of temperature and mass transfer potential capacity on the tunnel surface and the surrounding rockmassif on the tunnel axis:  $R$  - cylindrical coordinate;  $R_0$  - equivalent radius of tunnel; 0 and  $R_0$  indexes show the temperature and mass transfer potential values in the surrounding isotropic environments and on the dividing surface.

The equations of fields of the temperature and of the mass transfer potential in surrounding rock massif, respectively, have the form  $t = f(R, \tau)$ ;  $\theta = F(R, \tau)$ , where  $\tau$  is the time.

Thus, the ventilation flow involved in heat and mass transfer, taking into account the influence of the tunnel coating and liner, forms perturbed zones in the surrounding mountain mass, which leads to a decrease in the natural values of the temperature and the mass transfer potential of 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, while on the surface of the "tunnel wall - airflow" section the climatic parameters for these two components will be practically identical each other.

The average speed of ventilation flow is used in the calculation formulas of heat and mass transfer coefficients and by means of these formulas are calculated value of coefficients within the stationary conditions. Non-stationarity of processes is expressed in the reduction of the heat and mass amount transferred through the coating and liner area around the tunnel in comparison with the stationary process. Therefore, the use of medium speed of train motion in the tunnel is one of the proven ways to solve the problem of engineering. The calculation of non-stationary coefficients can be made according to the stationary coefficients calculated on the average speed [2].

Non-stationary heat transfer coefficient for tunnels without lining and with monolithic reinforcement and lining accordingly is determined by formulas

$$K_{\tau} = \alpha \bar{t} \quad (1)$$

$$K_{\tau} = K_1 \bar{t} \quad (2)$$

where  $K_{\tau}$  - non-stationary heat transfer coefficient, W/(m<sup>2</sup>.°C);  $\alpha$  - stationary heat transfer coefficient from surface of the tunnel, W/(m<sup>2</sup>.°C);  $\bar{t} = t(\tau, R_0)$  - dimensionless surface temperature of the tunnel, in parts of one,  $0 \leq \bar{t} \leq 1$ ;  $K_1$ - coefficient of heat transfer from the array to the ventilation flow, taking into account the influence of the lining of the tunnel, which is determined by the formula

$$K_1 = \left( \frac{1}{\alpha} + \frac{\delta_1}{\lambda_1} \right)^{-1} \quad (3)$$

where  $\delta_1, \lambda_1$  - respectively, the thickness of the lining of the tunnel and the coefficient of thermal conductivity of the lining material, m; W/(m.°C).

Non-stationary mass transfer coefficient for tunnels without lining and with monolithic reinforcement and lining accordingly is determined by formulas

$$K_{\tau m} = \alpha_m \bar{\vartheta} \quad (4)$$

$$K_{\tau m} = K_2 \bar{\vartheta} \quad (5)$$

where  $K_{\tau m}$  - non-stationary mass transfer coefficient, kg.mol/(J.m<sup>2</sup>.s);  $\alpha_m$  - stationary mass transfer coefficient from surface of the tunnel, kg.mol/(J.m<sup>2</sup>.s);  $\bar{\vartheta} = \vartheta(\tau, R_0)$  - dimensionless mass transfer potential of the tunnel surface, in parts of one,  $0 \leq \bar{\vartheta} \leq 1$ ;  $K_2$ - coefficient of mass transfer from the array to the ventilation flow, taking into account the influence of the lining of the tunnel, which is determined by the formula

$$K_2 = \left( \frac{1}{\alpha_m} + \frac{\delta_1}{\lambda_{m1}} \right)^{-1} \quad (6)$$

where  $\lambda_{m1}$ - the coefficient conductivity of mass transfer potential of the lining material, kg. mol/(J. m. s).

### 1.1. Hygroscopic mass transfer potential in mining massif

In hygroscopic area, in order to unambiguously define hygroscopic mass transfer potential of capillary-porous body we have to consider some perceptions related to this phenomenon. Similar to heat transfer in mining massif which origins under the influence of temperature gradient where temperature is potential of transfer, mass transfer direction and intensity in

massif is conditioned by mass transfer potential gradient. This potential serves as characteristic function of thermodynamic system of mining massif condition, which in the state of equilibrium is the same in all areas. It is noteworthy that moisture content of massif does not serve as transfer potential (despite the fact that some authors refer it as potential of mass transfer), because moisture content of different equilibrium soils is not equal. For example, sand (moisture content  $U = 0.1$  kg/kg) will not absorb moisture from peat (moisture content  $U = 0.3$  kg/kg), but on the contrary - moisture will transfer to higher levels of moisture content [3]. Thus, we can conclude that moisture content is not a potential of mass transfer. In the condition of isothermal equilibrium of above mentioned two soil components their potentials will be equal. Moisture content in mass transfer process is analogy to enthalpy characteristic to heat processes- it is possible for two components in isothermal massif to have similar temperature, however different enthalpy, if coefficient of heat capacity is different. We have the similar case in the given example for mass transfer process, when in isothermal environment potential of components is equal, but is different moisture content due to differences of isothermal mass factor.

Gibbs [4] has argued over the general principles of using phenomenological apparatus with thermodynamics functions, the concepts of chemical potential and free energy were introduced by him. In the thermodynamic method a transfer potential is a private production from the characteristic function of a thermodynamic system and is usually determined through interaction of the system with environment. In accordance with the interaction of the system with the environment, either internal energy ( $U$ ), or enthalpy ( $H$ ), or free energy ( $F$ ) or isobar-isothermal potential ( $Z$ ) are used as characteristic functions. At the same time, it is considered that the mass transfer is carried out under the influence of the chemical potential, which is determined by the partial derivative of the characteristic function according to the following formula

$$\mu_i = \left( \frac{\partial U}{\partial m_i} \right)_{v,s,m_j} = \left( \frac{\partial H}{\partial m_i} \right)_{p,s,m_j} = \left( \frac{\partial Z}{\partial m_i} \right)_{p,r,m_j} \quad (7)$$

The formula represents that the mass of  $i$  component is changeable, while the rest of the components in mass remains unchanged.

In the capillary – porous body (in sorbent), when the water steam is sorbat, chemical potential can be set in the following way:

$$\mu = \left( \frac{\partial Z}{\partial m} \right)_{r,p} = \left( \frac{\partial Z}{\partial m} \right)_{r,p} + \left( \frac{\partial \Delta Z}{\partial m} \right)_{r,p} = \mu_0 + \mu_1 \quad (8)$$

where  $\mu_0 = 0$  - chemical potential for maximal hygroscopic moisture content of sorbent, which is balanced with equilibrium relative humidity of air, when  $\varphi = \frac{P_u}{P_s} = 1$ . Potential  $\mu_1$  when  $\varphi < 1$ , is obtained with negative sign and the mass transfer is calculated similar to negative temperature of Celsius temperature scale.

This is also remarkable, that the formula (8) can be represented in the following way

$$\mu = \mu_0 + RT \ln \varphi \quad (9)$$

where  $\mu$  - thermodynamic potential, J/mol;  $R$ - universal air constant; J/(mol.K),  $R = 8.3144$ ;  $T$ - absolute temperature, K;  $\ln$  – symbol of natural logarithm;  $\varphi$  – equilibrium relative humidity of air relativity moisture content balanced with sorbent,  $0 \leq \varphi \leq 1$ .

Formula (9) conforms with that of Kelvin, while the second member on the right side  $RT \ln \varphi$  is the adsorbent potential of Polanyi  $\varepsilon$  taken with reverse sign. i. e.  $\varepsilon = -RT \ln \varphi$ . Polanyi refers water steam sorbent exclusively to adsorption power, while with Kelvin there is supposition that the steam phase of adsorbed moisture content is characteristic with ideal air features, liquid phase is none-compressible, while the enthalpy of the latter (i.e. that of liquid) and the heat of steam transformation are equal. This all causes error of about 20 per cent between hygroscopic and hydroscopic areas, that is to say when the balanced relativity moisture content is close to the size  $\varphi=1$ . The reason for error is also hysteresis appearing between sorption and desorption curves for similar samples of rock or another sorbent.

Similarly, to Celsius temperature scale A. V. Luikov has developed a scale of experimental potential, which is determined according to etalon filter paper moisture content, when the curves of sorption and desorption towards water steam are known. for absolutely dry filter paper is  $\theta = 0^\circ M$ , whereas when it is  $\varphi = 1$ , then there is  $\theta = 100^\circ M$ . The potential in hydroscopic area may exceed 100 degrees. For example, sand with moisture content of  $U = 0.1$  kg/kg, is characterised with the potential of  $\theta = 600^\circ M$  thus, it transfers moisture to peat with more moisture content, because the potential of the latter is approximately  $\theta = 350^\circ M$ , as it was mentioned above. It's evident enough that in order to determine any sorbent potential Mass transfer potential, the balance between filter paper and tested capillary - porous body should be established under isothermal conditions.

Based on thermo-dynamic laws of classic and inconvertible processes, L. Nikitina [6] has worked out thermo-dynamic potential. The author discusses

the mass transfer process on the basis of the formula uniting the first and the second laws. The potential, which has calculation formula respective the chemical potential, has been obtained based on the function of isochronous–isothermal condition – free energy by Helmholtz. The calculation formula of this potential appears like following:

$$\mu = -RT \ln \varphi \quad (10)$$

Using Boltzmann's law for water steam, who sets material fractions according to their potential energy, L. Tsimermanis [7] while calculating potential, has received the same formula, but with the reverse sign. Sorbed water vapor mentioned in this work is considered as an ideal air. Reasonability of such supposition has been proved with the so called distributing energy. This is an imaginary energy, which is spent in the entire space of sorption powers for equal distribution of molecules and overcoming molecule forces interaction in capillary – porous bodies as well as in ventilation air and on the separating surface of the sorbent and sorbate. As already proven, the distribution energy is transfer potential in the area of sorption forces and is quantitatively equal to chemical potential of balance sorbent with reversed sign. We recommend the aforementioned potential for further characterization of natural fields with hygroscopic moisture content under the first water proof layer of mining massif. This potential can most probably be used while evaluating hygroscopic moisture transfer process within the scope of the armature and the finishing of the subway tunnel. Another remarkable factor is that this particular area of tunnel is separated from the rest of the mining massif with waterproof membrane and as mentioned before, reinforcement and finishing of tunnel plays a kind of damper role from the view point of equaling ventilation air relative moisture throughout a year.

Thus, hygroscopic mass transfer potential can be calculated with the following formula:

$$\vartheta = RT \ln \quad (11)$$

In which, apart from explained dimensions  $\vartheta$  is hygroscopic mass transfer potential, J/mol.

In this formula,  $\ln \varphi = 0$ , when  $\varphi = 1$ , in the rest of the cases, for hygroscopic area  $\varphi < 0$  and size of the potential determined by the formula (11) is of negative sign.

The potential calculated with formula (11) 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 (11) permits to establish inversely proportional relationship between  $\vartheta$  and  $T$  as well  $c_m$  and  $T$  couples, while between  $\vartheta$  and  $c_m$  couples it arises directly proportional interaction. 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:

$$\vartheta = RT \ln \left( \frac{U}{U_{max}} \right) \quad (12)$$

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.

From the brief overview of mass transfer potential, it is evident that the potential calculated with  $RT \ln \varphi$  appears in literature with positive as well as with negative sign. Another remarkable factor is when determining quantitative size of isothermal specific mass factor experimentally, according to isotherm of sorption or desorption, increment of mass factor potential has been taken into consideration rather than its absolute value. Consequently, the potential sign is having no essence in case of increment. At the same time, Poytings equation, reflecting specific thermodynamic features of first phase transformation, assumes that in case of exceeded pressure of inert gas over the water surface, sorbent moisture content equilibrium to water steam quantitatively exceeds maximum sorption index. Starting from the above, the mass transfer potential figured out with the formula (12)  $U > U_{max}$  and  $\vartheta > 0$ , in hygroscopic area is featured with negative sign, while in hydroscopic area – with positive one like with the Celsius temperature scale.

These circumstances are also referred to in the work by De Boer [8], which describes sorbent “recharging” with water molecules in similar cases; similarly, also describes experiments mentioned in works by L. Tsimermanis.

## 2. Material and methods

For the elementary length of the tunnel  $dl$  ventilated by the throughflow shown in Fig. 2, the energy balance equation and the mass balance equation have the form

$$Gc_p dt + Gr dx = K_r \bar{U} (t_0 \pm \sigma l \sin \psi - t_i) dl + K_{pl} \bar{U}_{pl} (t_{pl} - t_i) dl \pm 9.81 G \sin \psi \quad (13)$$

$$Gc_m d\vartheta = K_{\tau m} \bar{U} (\vartheta_0 - \vartheta_i) dl \quad (14)$$

where  $G$  - air mass consumption in tunnel, kg/s;  $c_p$  - specific isobaric heat capacity of air, J/(kg. °C);  $dt, d\vartheta$  - increments of temperature and mass transfer potential as a result of heat and mass transfer;  $r$  - specific heat of the liquid-vapor phase transition, kJ/kg;  $dx$  - increment of mass content for air, kg/kg;  $\bar{U}$  - perimeter of the tunnel, m;  $t_0, \vartheta_0$  - accordingly natural temperature and natural mass transfer potential of rock massif, °C, J/mol;  $\sigma$  - geothermal gradient, °C/m;  $\psi$  - incline of the tunnel;  $t_i, \vartheta_i$  - temperature and potential of mass transfer of air flow at the beginning of the tunnel, °C, J/mol;  $t_{pl}, \bar{U}_{pl}$  - temperature and perimeter of pipeline in the tunnel, °C, m;  $K_{pl}$  - heat transfer coefficient of pipeline, W/(m<sup>2</sup>.°C);  $L$  - the total length of the tunnel, m.

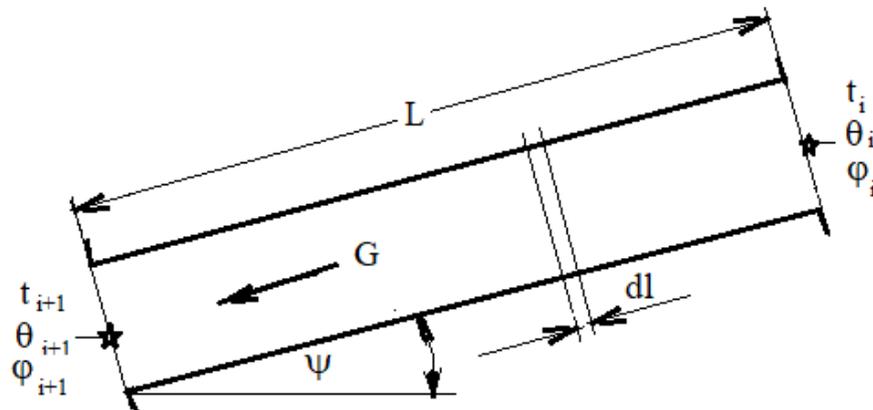


Fig. 2. The scheme for calculating climatic parameters of air in a tunnel.

For the equations (13), (14), the boundary conditions have the form

$$\tau > 0, l = l_i, t = t_i, \vartheta = \vartheta_i \quad (15)$$

where  $\tau$  – the duration of tunnel ventilation from the moment of opening to the time of calculation, c;  $i = 1, 2, 3, \dots, n$ .

By dividing equation (13) by the value of  $Gc_p$ , and equation (14) by an amount  $Gc_m$  and after simple transformations we obtain

$$\frac{dt + \frac{r}{c_p} dx}{M - \Pi t + K} = dl \quad (16)$$

$$\frac{d\vartheta}{A(\vartheta_0 - \vartheta)} = dl \quad (17)$$

where

$$M = \frac{1}{Gc_p} \left( K_r \bar{U} + K_{pl} \bar{U}_{pl} + \frac{\Sigma Q_{is}}{L} \right) \quad (18)$$

$$\Pi = \frac{1}{Gc_p} (K_r \bar{U} + K_{pl} \bar{U}_{pl}) \quad (19)$$

$$K = \frac{l \sin \psi}{c_p} \left( \frac{K_r \bar{U}}{G} \sigma + \frac{9.81}{L} \right) \quad (20)$$

$$A = \frac{K_{rm} \bar{U}}{Gc_m} \quad (21)$$

$$B = \frac{\Sigma W_{is}}{LGc_m} \quad (22)$$

In last formulas  $\Sigma Q_{is}$  – sum of local sources of warm on the length  $L$ , W;  $c_m$  – isothermal factor of specific mass, mol/J;  $\Sigma W_{is}$  – sum of local sources of water vapor on the length  $L$ , kg/s.

The approximated dependence of the temperature, pressure and relative humidity of the ventilation air on the moisture content has the form [9, 10]

$$x = \frac{83.1n'\varphi(t - \varepsilon')}{P - P_s} \quad (23)$$

where  $n'$ ,  $\varepsilon'$  - approximate coefficients;  $\varphi$  - relative humidity of air,  $0 \leq \varphi \leq 1$ ;  $t_a$  - air temperature, °C;  $P$  - air barometer pressure, Pa;  $P_s$  - medium pressure of saturated water vapor, Pa. Numerical values  $n'$ ,  $\varepsilon'$  and  $P_s$  are given in Table 1 according to the approximation levels.

Table 1. Numerical values of approximate coefficients and partial pressure

| $t, ^\circ\text{C}$ | $n'$  | $\varepsilon'$ | $P_s, \text{Pa}$ | $t, ^\circ\text{C}$ | $n'$   | $\varepsilon'$ | $P_s, \text{Pa}$ |
|---------------------|-------|----------------|------------------|---------------------|--------|----------------|------------------|
| 0-10                | 406.8 | -9.8           | 755.8            | 16-26               | 996.0  | 4.5            | 2168.0           |
| 2-12                | 459.0 | -7.5           | 864.5            | 18-28               | 1065.0 | 6.3            | 2460.5           |
| 4-14                | 511.0 | -5.9           | 997.5            | 20-30               | 1238.2 | 8.1            | 2726.5           |
| 6-16                | 571.6 | -4.3           | 1130.5           | 22-32               | 1367.8 | 9.7            | 3059.0           |
| 8-18                | 640.6 | -2.5           | 1263.5           | 24-34               | 1516.2 | 11.6           | 3458.0           |
| 10-20               | 718.7 | -0.8           | 1463.0           | 26-36               | 1662.6 | 13.1           | 3857.0           |
| 12-22               | 813.8 | 1.2            | 1662.5           | 28-38               | 1852.7 | 15.0           | 4256.0           |
| 14-24               | 908.8 | 2.8            | 1928.5           | 30-40               | 2009.0 | 16.5           | 4788.0           |

From the expression for the mass transfer potential,  $\varphi$  is determined, formula for calculating which has the form

$$\varphi = \exp \frac{\vartheta}{RT} \quad (24)$$

Taking into account the last formula, equation (19) takes the form

$$x = h_1(t - \varepsilon') \exp \frac{\vartheta}{RT} \quad (25)$$

where

$$h_1 = \frac{81.3n'}{P - P_s} \quad (26)$$

### 3. Theory/calculation

Substitution of the total differential from  $x$  from formula (24) into equation (16), taking into account equation (17), leads to expression

$$\left\{ 1 + h_1 \exp \left[ \frac{\vartheta_0 - C \exp(-Al) + B/A}{RT} \right] \left[ 1 + \left[ \frac{\vartheta_0 - C \exp(-Al) + B/A}{RT^2} \right] \right] \right\} = \\ = \left\{ \frac{h_1 \varepsilon AC}{RT} \exp \left[ \frac{\vartheta_0 - C \exp(-Al) + B/A}{RT} \right] \exp(-Al) + (M - \Pi t \pm K) \right\} dl,$$

which has no solution providing acceptable accuracy.

Therefore, in this paper was chosen another way. Since the numerical value of  $T(K)$  in this case is approximately an order of magnitude higher than  $T(^{\circ}C)$ , it is assumed that the temperature increment in the calculated region does not have a significant effect on the value of  $\vartheta$ , and  $\varepsilon$  for the chosen temperature variation interval is constant. Indeed, in real calculation, there is always the choice of the length of the tunneling calculation area that the increment of the flow temperature will does not exceed the pre-set size, say, 1 degree. In this case, as shown in Table 2 below, we make an error of 2.9% in determining the increment of relative humidity, which is quite acceptable taking into account the accuracy in determining the mass transfer potential. Proceeding from the foregoing, after substituting  $dx$  from formula (25) into equation (16) last formula takes the form

$$\frac{1 + \frac{r}{c_p} h_1 \exp \frac{\vartheta}{RT}}{M - \Pi t \pm K} dt = dl. \quad (27)$$

The general integrals of expressions (17) and (27), respectively, have the form

$$\vartheta = \vartheta_0 + \frac{B}{A} - C \exp(-Al) \quad (28)$$

$$\frac{1 + \frac{r}{c_p} h_1 \exp \frac{\vartheta}{RT}}{\Pi} \ln |M - \Pi t \pm K| = l + C \quad (29)$$

Taking into account the boundary conditions and after the introduction of the notation

$$\chi_{i,i+1} = \frac{\Pi}{1 + \frac{r}{c_p} h_1 \exp \frac{\vartheta_{i+1,i}}{RT_{i,i+1}}} \quad (30)$$

dependences are obtained for determining the mass transfer potential and the temperature of tunnel air in direct thermal calculation

$$\vartheta_{i+1} = \vartheta_0 + \frac{B}{A} - \left( \vartheta_0 + \frac{B}{A} - \vartheta_i \right) \exp[-A(l_i - l_{i-1})] \quad (31)$$

$$t_{i+1} = \frac{M \pm K}{\Pi} - \left( \frac{M \pm K}{\Pi} - t_i \right) \exp[-\chi_i(l_i - l_{i-1})] \quad (32)$$

For the inverse thermophysical calculation, these formulas respectively have the form

$$\vartheta_i = \vartheta_0 + \frac{B}{A} - \left( \vartheta_0 + \frac{B}{A} - \vartheta_{i+1} \right) \exp[-A(l_{i-1} - l_i)] \quad (33)$$

$$t_i = \frac{M \pm K}{\Pi} - \left( \frac{M \pm K}{\Pi} - t_{i+1} \right) \exp[-\chi_{i+1}(l_{i-1} - l_i)] \quad (34)$$

In formulas (32) and (34), the sign "+" before  $K$  refers to the case of a descending movement, and the sign "-" to the case of an ascending air movement.

The relative humidity of the ventilation air at the point  $i$  is calculated from the formula

$$\varphi_i = \exp\left(\frac{\vartheta_i}{RT_i}\right). \quad (35)$$

If the tunnel is not divided into computed sections, and we have only one section, then the formulas (31) and (32) accordingly take the form

$$\vartheta_2 = \vartheta_0 - (\vartheta_0 - \vartheta_i) \exp(-AL) \quad (36)$$

$$t_{i+1} = \frac{M+K}{\pi} - \left(\frac{M+K}{\pi} - t_i\right) \exp(-\chi_i L) \quad (37)$$

If the relative humidity of air does not change within the design section, that is,  $\varphi_1 = \varphi_2 = \varphi$ , then formula (30) takes the form

$$\chi_{i,i+1} = \frac{\pi}{1 + \frac{\gamma}{c_p} P \varphi}. \quad (38)$$

#### 4. Results and Discussion

Convenience of practical application of the proposed method will be considered on the example of direct calculation. In view of the fact that the potential for mass transfer of air is a function of two variables - temperature and relative humidity, when calculating the potential using formula (31), we only know the total effect of these two variables in the form  $\vartheta_{i+1}$ . Unlike other methods [9, 10], to calculate the temperature according to formula (32), is not required here the relative humidity at point  $(i+1)$ . It is sufficient to have the value of the mass transfer potential at this point (i.e., to have a total effect of  $\varphi$  and  $t$ ). Then, using the numerical value of the potential, by means of formula (30),  $\chi_i$  is calculated, and with numerical values  $\vartheta_{i+1}$  and  $t_{i+1}$  by formula (35), the relative humidity  $\varphi_{i+1}$ .

In this way, the presented method gives a complex calculation of the climatic parameters of the ventilation stream without using the Iteration method, which, as noted, significantly reduces the time required for calculation and increases the accuracy of the results obtained.

For the solve the equation, we used the assumption that, as noted above, causes an error in determining the increment of relative humidity. Depending on the temperature range and the increment of the same temperature, the error will have the values given in Table 2.

Table 2. Inaccuracy in determining the increment of relative humidity

| Temperature change interval<br>$t$ , °C | Increment of temperature<br>$\Delta t$ , °C | Increment of relative humidity<br>$\Delta \varphi$ , % |
|---|---|--|
| 10-50                                   | 1.0   | 2.9  |
| 10-50                                   | 2.0   | 4.8  |
| 10-50                                   | 3.0   | 6.8  |
| 10-50                                   | 4.0   | 8.5  |
| 10-50                                   | 5.0   | 10.0   |

As noted above, near the boundary of hygroscopic and hydroscopic mass transfer areas, when the equilibrium relative humidity approaches unity, the accuracy of the calculated determination of the mass transfer potential does not exceed 20% of its value. From Table 2 it can be seen that the proposed method allows the increment of relative humidity to be calculated as a minimum with the approximation of 10%.

## 5. Conclusions

Thus, the proposed complex method for the thermophysical calculation of the ventilation flow in subway tunnels differs favorably from other methods, since simultaneous determination of the temperature, the mass transfer potential, and the relative air humidity can be made by calculation. The accuracy of the method exceeds the accuracy of the calculation formulas for determining the potential of mass transfer in the hygroscopic area of mass transfer near of maximal sorption mass content of the surrounding mining massif.

Table N3. Physical values and coefficients

| Name  | Designation                              | Dimension                    |
|---|--|------------------------------|
| Non-stationary heat transfer coefficient                                      | $K_{\tau}$                               | W/(m <sup>2</sup> .°C)       |
| Stationary heat transfer coefficient  | $\alpha$                                 | W/(m <sup>2</sup> .°C);      |
| Dimensionless surface temperature of the tunnel                               | $\bar{t} = t(\tau, R_0)$                 | None                         |
| Thickness of the reinforcement and finishing of the tunnel                    | $\delta_1$                               | m                            |
| Thermal conductivity of the finishing material                                | $\lambda_1$                              | W/(m.°C)                     |
| Non-stationary mass transfer coefficient                                      | $K_{\tau m}$                             | kg.mol/(J.m <sup>2</sup> .s) |
| Stationary mass transfer coefficient  | $\alpha_m$                               | kg.mol/(J.m <sup>2</sup> .s) |
| Dimensionless mass transfer potential   | $\bar{\vartheta} = \vartheta(\tau, R_0)$ | None                         |
| Coefficient conductivity of mass transfer potential of the finishing material | $\lambda_{m1}$                           | kg.mol/(J.m.s)               |
| Moisture content of mining massif   | $U$                                      | kg/kg                        |

| Name  | Designation    | Dimension                         |
|---|----------------|-----------------------------------|
| Maximum hygroscopic moisture content of mining massif | $U_{max}$      | kg/kg                             |
| Thermodynamic potential                               | $\mu$          | J/mol                             |
| Universal constant of gas - $R = 8,3144$              | $R$            | J/(mol. $K$ )                     |
| Density (rock, soil)                                  | $\gamma_0$     | kg/m <sup>3</sup>                 |
| Heat conductivity (rock, soil)                        | $\lambda$      | W/(m. $K$ )                       |
| Specific heat (rock, soil)                            | $c$            | J/(kg. $K$ )                      |
| Thermal diffusivity (rock, soil)                      | $a$            | m <sup>2</sup> /s                 |
| Mass conductivity (rock, soil)                        | $\lambda_m$    | kg.mol/(J.m.s)                    |
| Mass transfer potential diffusivity (rock, soil)      | $a_m$          | m <sup>2</sup> /s                 |
| Isothermal factor of specific mass (rock, soil)       | $c_m$          | mol/J                             |
| Absolute temperature                                  | $T$            | $K$                               |
| Equilibrium relative humidity of air                  | $\varphi$      | $0 \leq \varphi \leq 1$           |
| Adsorbent potential of Polanyi                        | $\varepsilon$  | J/mol                             |
| Mass transfer potential by Luikov                     | $\theta$       | $^{\circ}M$                       |
| Mass transfer potential of surrounding massif         | $\vartheta$    | J/mol                             |
| Air mass consumption in tunnel                        | $G$            | kg/s                              |
| Specific isobaric heat capacity of air                | $c_p$          | J/(kg. $^{\circ}C$ )              |
| Specific heat of the liquid-vapor phase transition    | $r$            | kJ/kg                             |
| Natural temperature of rock massif                    | $t_0$          | $^{\circ}C$                       |
| Natural mass transfer potential of rock massif        | $\vartheta_0$  | J/mol                             |
| Geothermal gradient of rock massif                    | $\sigma$       | $^{\circ}C/m$                     |
| Incline of the tunnel                                 | $\psi$         | Gradus                            |
| Perimeter of the tunnel                               | $\bar{U}$      | m                                 |
| Temperature of pipeline in the tunnel                 | $t_{pl}$       | $^{\circ}C$                       |
| Perimeter of pipeline in the tunnel                   | $\bar{U}_{pl}$ | m                                 |
| Heat transfer coefficient of pipeline                 | $K_{pl}$       | W/(m <sup>2</sup> . $^{\circ}C$ ) |
| Time  | $\tau$         | s                                 |

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