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Mechanics

Aerodynamic and Thermophysical Calculation of Tunnel Ventilation Considering Traffic Effects

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(Presented by Academy Member Elguja Medzmariashvili)

Aerodynamic and thermophysical calculations were used to determine the total air discharge supplied under the action of vehicle movement piston effect on the example of a long gallery-type tunnel Marabda-Akhalkalaki railway in Georgia. It is established that for the conditions of the given tunnel, about 2/3 of the air discharge, driven by the piston effect, will move in the direction of the train and the rest will flow in the opposite direction and into the gap between the train and the tunnel perimeters. This induces strong air turbulent currents leading to the increased aerodynamic resistance. Despite this, all gallery-type tunnels of the said railway can be ventilated by natural traction driven by the piston effect of a train. It is necessary to provide ventilation openings in all chambers and recesses on both sides of the tunnel. The cross-sectional area of each opening should be 5.6 m^2. The mentioned measure will reduce the aerodynamic resistance created by the air flowing through the gap making it possible to supply the tunnel with the amount of air determined by the calculation. The results of the thermophysical calculation and the calculation method of the longest tunnel are given in the present paper. According to the calculations, 4.8 m^3/s in winter and 8.4 m^3/s of air flow rate in summer are sufficient to neutralize the heat generated by a rolling stock. These air discharges also ensure that the requirement for temperature maximum is met, and the temperature of the flow exiting the tunnel will not exceed 35°C at any time of the year. *© 2024 Bull. Georg. Natl. Acad. Sci.*

aerodynamic and thermophysical calculation, piston effect, natural resistance, tunnel depression

Transport tunnels are usually built on the most complex sections of highways to shorten distances and accelerate traffic flow. The movement of vehicles results in a piston effect of airflow, which, as a circulating stream, flows ahead of the moving vehicle. Part of the induced air current enters the space between the vehicle and the tunnel perimeters, causes strong local turbulent motion and should be considered as a negative effect that requires energy to overcome. Circulation flow is also characterized by hard-to-predict fluctuations in air velocity and flow rate, which causes dramatic changes in the aerodynamic characteristics of a tunnel, the determination of qualitative and quantitative indicators of which is an urgent task to ensure quality ventilation.

Along with this, the technical regulation standards require compliance with the regulated values of normal climatic parameters in tunnels. Of these, air temperature is always the target value, and sometimes the requirements include adherence to the relative humidity values. The above problems are closely related to the tunnel aerodynamics as well as the physical properties of the surrounding rock mass and the state of the physical fields. Physical properties mean first of all, thermophysical and mass-physical characteristics [1] and physical fields mean temperature and hygroscopic mass transfer potential fields of rock mass [2]. The nature of these issues is very complicated [3, 4], especially their combination [5, 6], that is clarified in the present work on the examples of specific tunnels, the working design of which was made and realized under our supervision.

Technical Data of the Tunnels

The methods and results of thermophysical and aerodynamic calculations of ventilation of Marabda-Akhalkalaki Railway tunnels and the results for the longest tunnel are given in the present paper. The same methodology can be successfully used for both railroad and one-way tunnels in case of large cargo transportation. It should be noted that 4 one-way gallery-type tunnels are constructed on the above-mentioned Railway, the technical data of which are given in Table 1.

Cargo and passenger trains moving in the tunnel are considered to be equal in terms of energy taken from the network, and so the thermal-physical calculation of ventilation is performed with certain reserve. On both sides of the tunnel, staggered chambers should be arranged every 300 m, and staggered niches between chambers should be provided every 60 m. The geometric dimensions of the cameras and niches are presented in Table 2.

According to the technical data, the power requirement to light the entire tunnel is 15 kW. It is important to consider that: 1. During the cold season of the year a longitudinal cooling system is used. 2. In all other cases a combined lighting system, which is closer to the longitudinal-transverse system, is used. A combined system is obtained by providing the ventilation windows of the appropriate cross-section in chambers and niches, as a result of which the amount of air supplied to the tunnel due to piston effect increases rapidly and the ventilation and climatic parameters are calculated for the longitudinal system.

Table 1. Technical data of Marabda-Akhalkalaki railway tunnels

Tunnel number	Picket	Altitude, m	Tunnels length, m	Average gradient, %	Cross section, m^2	Perimeter, m	Equivalent radius, m
3	990+27.24 1001+96.30	2150.85 2182.70	1170.0	2.722	63.12	31.78	3.97
4	1106+44.59 1109+53.51	2136.33 2135.88	308.9	0.146	63.12	31.78	3.97
5	1114+27.08 1118+52.88	2137.62 2133.85	525.6	0.717	63.12	31.78	3.97
6	1151+0.46 1156+33.094	2113.86 2105.71	533.5	1.526	63.12	31.78	3.97

Table 2. Technical data of cameras and niches of Marabda-Akhalkalaki railway galleries

Camera length, m	Camera width, m	Camera height, m	Niches length, m	Niches width, m	Niches height, m	Train movement time, up/down, s	
						between cameras	between niches
5.3	2.5	2.8	5.3	1.0	2.8	17.95/43.33	3.59/8.67

Calculation of heat generated by a rolling stock should be done for the case of uphill travel. This time, part of the energy taken from the network, which is not spent on increasing the potential energy of the train, is completely spent on overcoming all types of friction resistance and is eventually released as heat. To estimate the heat released by a train traveling downhill, the result obtained for uphill travel is used. The heat released during uphill travel can be determined by formula

$$q_1 = 860Mn(N_0 L - \frac{\Delta H}{102 \times 3.6}), \tag{1}$$

where q_1 is the heat released by the rolling stock, kcal/h; M is the mass of the rolling stock, t; n is the number of trains passing through the tunnel in 1 hour. As it can be seen from Table 2, the mass of the passenger train is less than the freight train. An assumption has been made about the equality of their masses. Consequently, the calculated air temperature will have reserve, because in reality less heat will be transferred on the air and the temperature increment will be less. Considering the above, let us take the average value of the number of trains n=2.17; N_0 is the average specific consumption of electric power by a train at double traction when traveling uphill, kW.h / (t.km); L is the tunnel length, m. The tunnel in this case is calculated as one calculation site; ΔH is the vertical distance between the levels of the tunnel portals, m.

All the power spent on lighting is transferred to the ventilation flow as heat, which is calculated by the formula

$$q_2 = 860N_1 m, \tag{2}$$

where N_1 is the required power of the lighting network, kW; m is the electrical loss ratio, m=1.0.

For the same ventilation system used in different seasons, the calculations are made only for summer conditions. In our case the calculation should be made separately for summer and winter seasons, because in winter we use a longitudinal ventilation system and longitudinal-transverse ventilation system at other times of the year.

Thermophysical Calculation Method

The air mass transfer potential, temperature and relative humidity are calculated by following formulas [2, 7]

$$\Theta_2 = \Theta_0 - \frac{B}{A} - \left(\Theta_0 - \frac{B}{A} - \Theta_1\right)e^{-L\sqrt{|A|}} \tag{3}$$

$$t_2 = \frac{M \pm K}{\Pi} - \left(\frac{M \pm K}{\Pi} - t_1\right)e^{-L\chi_1} \tag{4}$$

$$\varphi_2 = \exp\left(\frac{\Theta_1}{RT_1}\right), \tag{5}$$

where $\Theta_0, \Theta_1, \Theta_2$ are mass transfer potential of tunnel walls and ventilation flow, respectively, J/mol. Here and further index “0” corresponds to the tunnel walls, “1” corresponds to the beginning of the calculation site (one of the portals), “2” corresponds to the end of the calculation site; *A, B, M, K, Π* and χ_1 complexes are defined by formulas

$$A = \frac{K_{m\tau}P}{Gc_m}, \tag{6}$$

$$B = \frac{\Sigma W}{LGc_m}, \tag{7}$$

$$M = \frac{1}{Gc_p}\left(K_\tau P t_0 + \frac{\Sigma Q_d}{L}\right), \tag{8}$$

$$K = \frac{L\sin\psi}{c_p}\left(\frac{K_\tau P\sigma}{G} + \frac{9.81}{L}\right), \tag{9}$$

$$\Pi = \frac{K_\tau P}{Gc_p}, \tag{10}$$

$$\chi_1 = \frac{\Pi}{1 + \frac{r}{c_p} b_1 \exp\frac{\Theta_2}{RT_1}}. \tag{11}$$

L is the tunnel length m; e is the Napier number; t_0, t_1, t_2 are the temperature of tunnel walls and ventilation current, °C; R is the universal gas constant, J/(mol.degree); $K_{m\tau}$ is a non-stationary mass transfer coefficient, kg.mol/(J.m^2.s); P is the tunnel perimeter, m; G is the ventilation air mass flow rate, kg/h; c_m is the isothermal mass capacity coefficient, mol/J; ΣW is the sum of local moisture sources in the tunnel, mol; K_τ is the non-stationary heat transfer coefficient, kcal/(m^2.°C.h); c_p is the isobaric heat capacity coefficient, kcal/(kg. °C); σ

is the geothermal gradient of rock massif, degree/m; r is the enthalpy of evaporation, kcal/kg; $b_1 = \frac{1542n'}{P_A - \overline{p}}$; n', $\overline{p}$ is the approximation coefficient and partial pressure of saturated water vapor (Pa) taken from the source depending on the temperature increment [3]; P_A is atmospheric pressure, Pa.

Thermal and mass-physical characteristics of rocks, concrete and insulating material are given in reference below [1]. To determine the non-stationary heat transfer coefficients (K_τ) and non-stationary mass transfer coefficients ($K_{m\tau}$), it is necessary to take into account their mutual influence, according to the principles stated in the literature [2, 5, 6].

Heat transfer coefficient is determined by formula

$$K_1 = \frac{1}{\left(\frac{1}{\alpha_1} + \frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2} + \frac{1}{\alpha_2}\right)}, \qquad (12)$$

where α_1 and α_2 are heat transfer coefficients from the inner and outer walls of the tunnel, respectively, kcal/(m^2.°C.h); δ_1 and δ_2 are thicknesses of concrete and insulation, respectively, m; λ_1 and λ_2 are thermal conductivity coefficients of concrete and insulation, respectively, kcal/(m.°C.h).

Mass transfer coefficient is determined by formula

$$K_2 = \frac{1}{\left(\frac{1}{\alpha_{m1}} + \frac{\delta_1}{\lambda_{m1}} + \frac{\delta_2}{\lambda_{m2}} + \frac{1}{\alpha_{m2}}\right)}, \qquad (13)$$

where, except for the specified values, α_{m1} and α_{m2} mass transfer coefficients from the inner and outer walls of the tunnel, respectively, kg.mol/(J.m^2.s); λ_1 and λ_2 are mass conductivity coefficients of concrete and insulation, respectively, kgmol/(J.m.s). $Fo_m = \frac{a_m \tau}{R_0^2}$ is the Fourier mass exchange criterion used to determine the dimensionless potential by graph-analytical method; $Bi_m = \frac{\alpha_m R_0}{\lambda_m}$ is the Bios mass exchange criterion; a_m is the mass transfer potential coefficient, m^2/h.

Analysis of the Obtained Results

Air flows determined by thermophysical calculation by seasons of the year are shown in Table 3.

As it can be seen from Table 3, according to the calculations, 4.8 m^3/s in winter and 8.4 m^3/s of air flow rate in summer are sufficient to neutralize the heat generated by a rolling stock. These air discharges also ensure that the requirement for temperature maximum is met, and the temperature of the flow exiting the tunnel will not exceed 35°C at any time of the year.

Table 3. Air consumptions that meet the requirements of construction norms and regulations

Required air consumption in winter, m^3/h (m^3/s)	Required air consumption in summer, m^3/h (m^3/s)
17420 (4.8)	30200 (8.4)

The specified air flow rate in this tunnel can be provided by driving force induced by piston effect caused by the movement of a train. Note in advance that approximately 2/3 of air flow generated by piston effect will move in the direction of a train and the rest will flow in the opposite direction and into the gap between the train and tunnel perimeters. This causes air turbulence and is a component of the overall aerodynamic resistence. Despite this, all the galleries of Marabda-Akhalkalaki Railway can be ventilated by natural traction caused by the piston effect of a train.

This relationship can be clearly seen in Fig. 1, compiled from the data of numerical experiments for different coefficients of filling the tunnel cross-section with a train. Numerical tasks were performed with PyroSim computer software. On the ordinate, the sum of the 1st and 2nd curves is equal to the train speed, which induces the speed of the circulation flow moving in front of the train (Curve 1) and the speed of the flow flowing into the gap (Curve 2). The velocity shown by Curve 1 is almost always 2 times the velocity of the flow flowing into the gap, i.e. the specified 2/3 ratio is maintained.

The depression induced by the rolling stock can be calculated by formula

$$h = \frac{\rho V^2}{2}, \tag{14}$$

where h is the depression induced by a rolling stock, pa; ρ is air density, kg/m^3. Let us accept ρ=1.2 kg/m^3 as a proved value; V is speed of a rolling stock, m/s. It should also be noted that at a train speed in the range of 40-45 km/h air flow rate induced by piston effect may vary in the range of 90-100 m^3/s.

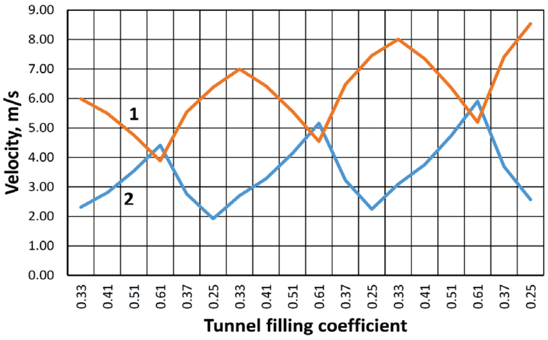

Fig. 1. Pattern of variation of average velocities of circulation current and the one flowing into the gap reduced to the tunnel area depending on the coefficient of filling the tunnel with a train: 1 - velocity of circulation flow in front of the train; 2 - velocity of current flowing into the gap.

According to the basic law of parallel ventilation networks the following expression is true

$$h_2 = h_3, \tag{15}$$

where h_2 and h_3 are the depressions of parallel networks, respectively.

Taking into account the formula for calculating tunnel depression and simple transformations, the following formula is obtained from (15)

$$\frac{R_2}{R_3} = \frac{Q_3^2}{Q_2^2}. \tag{16}$$

The latter formula shows that the amount of air passing through parallel networks is inversely proportional to their resistances, i.e. the equality of depressions in parallel networks is achieved by a corresponding change in air flow rate. It is obvious that the aerodynamic resistance of the gap between the train and the tunnel for data (S=49.2 m^2; P=45.8 m; ℓ=426 m) is 0.00052 N.s^2/m^3. After inserting the specified values and making simple transformations, the following formula is obtained from (16)

$$4.7Q_2 = 8.6Q_3. \tag{17}$$

This relationship can also be applied with great probability to the movement of rolling stock after-action when overflow no longer occurs and the additional amount of air is carried away by a stable flow having the same direction as the train.

The equation of air flow balance is as follows

$$Q_1 = Q_2 + Q_3, \tag{18}$$

where $Q_1 = 201707$ m^3/h and it is the maximum air flow rate in summer, when practically no opposite flow is generated. Let us solve equation (18) for air flow Q_2 parallel to the train direction by considering formula (17), when $Q_1 = 201707$ m^3/h. The solution is as follows: $1.546Q_2 = 201707$. Hence $Q_2 = 130470$ m^3/h.

It can be considered ascertained that in winter, with piston effect, it is possible to supply the tunnel with almost 2/3 of the summer flow rate, i.e. 130470 m^3/h of air. The presented material shows that the longest tunnel of Marabda-Akhalkalaki railway can be ventilated with great reserve due to natural traction caused by the movement of trains. Due to the relatively short length of galleries N4, N5 and N6 (see Table 1) the design air parameters are easier to achieve by piston effect of train movement.

For more efficient utilization of traction created by piston effect, it is necessary to provide ventilation openings in all chambers and niches on both sides of the long tunnel. To simplify the construction of prefabricated structures, it is desirable to build other shorter galleries with structures with ventilation openings (see Table 1), although their effective ventilation does not require the construction of the latter.

Conclusion

Aerodynamic resistance of Marabda-Akhalkalaki railroad tunnels is low, and therefore their effective ventilation is possible due to piston effect of train movement. The air flow rate to supply to the longest tunnel is 130500 m^3/h in winter and 201700 m^3/h in summer. In addition, the given air flows ensure that the maximum temperature requirement of the “Building Code” is met, and the temperature of the current leaving the tunnel does not exceed 35°C at any time of the year.

In Marabda-Akhalkalaki longest railway tunnel, at a train speed in the range of 40-45 km/h air flow rate induced by piston effect may vary in the range of 90-100 m^3/s.

In Marabda-Akhalkalaki longest railway tunnel about 2/3 of the air flow induced by piston effect moves towards the train, and the rest of the air flows in the opposite direction into the gap between the train and tunnel perimeters.

These regularities are also true for tunnels with one-way traffic with lengths of up to 400 m, the ventilation of which, according to current standards, should be provided by natural traction.

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მექანიკა

გვირაბის ვენტილაციის აეროდინამიკური და თბოფიზიკური გაანგარიშება ტრანსპორტის მოძრაობის გავლენის გათვალისწინებით

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(წარმოდგენილია აკადემიის წევრის ე. მეძმარიაშვილის მიერ)

აეროდინამიკური და თბოფიზიკური გაანგარიშების შედეგად, განსაზღვრულია ტრანსპორტის მოძრაობის დგუშის ეფექტის გავლენით მიწოდებული ჰაერის ჯამური ხარჯი მარაბდა-ახალქალაქის სარკინიგზო ხაზის, გალერის ტიპის გრძელი გვირაბის მაგალითზე. დადგენილია, რომ აღნიშნული გვირაბის პირობებისთვის, დგუშის ეფექტით აღძრული ჰაერის ხარჯის დაახლოებით 2/3 გადაადგილდება მატარებლის მოძრაობის მიმართულებით, ხოლო დანარჩენი გადაედინება საპირისპირო მიმართულებით მატარებლისა და გვირაბის პერიმეტ-

რებს შორის არსებულ ღრეჩოში. აღნიშნულის შედეგად, აღიძვრება ჰაერის ძლიერი ტურბულენტური ნაკადები, რაც იწვევს აეროდინამიკური წინაღობის გაზრდას. ამის მიუხედავად, აღნიშნული სარკინიგზო მაგისტრალის გალერის ტიპის ყველა გვირაბი შესაძლებელია განიავდეს მატარებლის დგუშის ეფექტით. აღძრული წევის ეფექტური გამოყენებისათვის საჭიროა სავენტილაციო ღიობების მოწყობა ყველა კამერასა და ნიშაში, გვირაბის ორივე მხარეს. ყოველი ღიობის განივი კვეთის ფართობი უნდა იყოს 5,6 მ^2. აღნიშნული ღონისძიება შეამცირებს ღრეჩოში გადადინებული ჰაერის ნაკადის მიერ გამოწვეულ აეროდინამიკურ წინაღობას და უფრო უტყუარად იქნება შესაძლებელი ჰაერის მიწოდება გვირაბში. გაანგარიშებების თანახმად, მოძრავი შემადგენლობის მიერ გამოყოფილი სითბოს გასანეიტრალებლად ზამთარში საკმარისია 4,8 მ^3/წმ, ხოლო ზაფხულში - 8,4 მ^3/წმ ჰაერის ხარჯი. ჰაერის აღნიშნული ხარჯები უზრუნველყოფს, აგრეთვე, ტემპერატურულ მაქსიმუმთან დაკავშირებული მოთხოვნის შესრულებას და გვირაბიდან გამომავალი ნაკადის ტემპერატურა, ნებისმიერი სეზონისათვის, არ იქნება 35°C-ზე მეტი.

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