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Ventilation of the Northern Mujsky Railway Tunnel

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ABSTRACT: The choice of ventilation schemes in the Northern Mujsky railway tunnel and definition of the necessary quantities of air ensuring regulated radiation conditions in the tunnel system has been accomplished. The influence of natural draught on the stability of tunnel ventilation has been estimated. The design of a portal ventilation gate allowing minimal influence from natural factors is described. The dependence of pressure loss in the sliding ventilation gates on their spanning value of the vehicle tunnel section has been determined. The selection of parameters for an atmospheric air heating system in winter has been carried out. The operation regimes of air heaters, dependent on the temperature of atmospheric air, have been established.

1 Introduction

The Northern Mujsky Railway Tunnel (NMT), located in the republic of Buryatia, is now the longest tunnel in Russia. One of the main problems is ensuring essential air quality in the tunnel, and the successful resolution of this problem, will make it possible to improve the safety of operations within the NMT. When discussing air quality, we propose a combination of thermodynamic, chemical and physico-chemical parameters, which allow the necessary level of safety to be achieved with minimum energy consumption. There are some factors, which hinder the safe operation of the NMT. They are the following: ice, corrosion of the tunnel concrete lining due to thermal deformation processes, fog formation, and the emission of radon from water and rock.

Irrespective of the season, the basic way of maintaining the essential air quality in the tunnel is to ensure that the ventilation and heating regimes assist the supply into the tunnel of a fixed amount of air at a positive temperature.

Engineering solutions, which create positive thermal conditions in railway tunnels, in order to minimize both ice formation processes and thermal destruction of the tunnel lining, have been developed before for the 6,7 km long Baikal tunnel /1,2,3/.

However, in the case of the NMT, satisfying the radiation conditions regulated by the Radiation Safety Standards (SRS-99) is of prime importance for the tunnel system /4/.

When choosing ventilation schemes for the NMT a satisfactory distribution of air should be provided throughout the tunnel system that satisfies the requirements of SRS-99.

2 The Characteristics of The Tunnel System

The NMT, which is 15343 m long, was built under the Angarakansky pass of the Northern Mujsky mountain range and has two-slope profiles, with the difference in height between the western and the eastern portal being 49 m. The highest point of the tunnel profile over the eastern portal is 65 m. The geometric configuration of the NMT is shown in Figure1

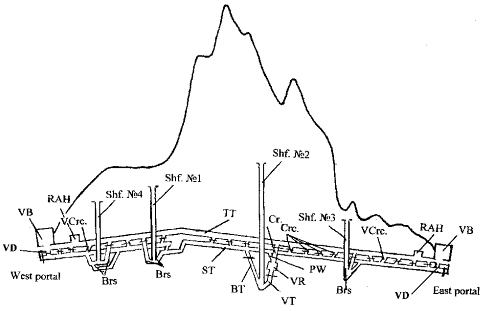


Figure 1 Geometry of the Northern Mujsky tunnel

The tunnel has four shafts №1, №2, №3 and №4 with their depths being 316 m, 356 m, 166 m and 200 m respectively. An arrangement of branches (PBW) and cross passages (Cr.) joined to the traffic tunnel (TT) are adjacent to every shaft. Parallel to the TT is the service tunnel (ST), which is approximately the same length as the TT. The ST is connected to the TT using a number of cross passages (Crc.). In addition, shaft N2 is connected to the ST using a bypass tunnel (BT). The base of Shaft №2 is 8753m from the western portal (western tunnel branch) and 6590 m from the eastern portal (eastern tunnel branch). The cross passage which runs from the base of Shaft №2 connects with the fan room (ventilation room – VR) and then descends to the ventilation tunnel (VT). The cross passage (Cr.) is connected with the ST by means of passageway (PW). Ventilation cross connecting ducts (VCrc.) are located 1190 m from the eastern portal and 1120 m from the western portal. These ventilation ducts connect the traffic tunnel to the ST. Ventilation buildings (VB) which house the ventilation and heating equipment for warming the air, are placed at the tunnel portals. These ventilation buildings are linked with the ST by means of ventilation duct (VD). Air from the ST can be supplied immediately to the main air heaters for warming up. There are special rooms for additional air heaters (RAH), which can be used for warming up air in the case of unusually low atmospheric air temperatures. These are located within 500 m of each portal in the traffic tunnel.

3 The influence of Radon on Air Quality in The Tunnel System

Radon forms during the decomposition of radium isotopes, which are contained in the rocks surrounding the tunnel system. The radon then penetrates through the pores and fractures of the rock mass into the tunnel air through gas diffusion and convection. Moreover, radon also enters the air from underground water, which is rich in radon and radium. Water can transport these elements for long distances from the place of their immediate occurrence, with the rock itself being the source of radioactive elements /8/.

When the radon enters the tunnel air, it begins to decay, forming by-products which, due to their minor half – cycle of decomposition, are the most harmful to the human organism /4,5/. In this case, the nearer the source of radon emission is to the place of fresh air supply into the tunnel system, the longer the period when the air will be in the working, and the larger the amount of decomposing radon by-products which will be contained in the air. To determine the dynamics of radon accumulation in the airflow, the use of a linear model of radon concentration growth C ($Bq \cdot m^{-3}$) is suggested as well as the exponential model for calculation of both the accumulation and decomposition **o**f radon by – products ($EEVA_{Rn}$) /4 /.

$$C = C_0 + \sigma \cdot U \cdot L/Q \tag{1}$$

$$\begin{aligned} EEVA_{Rn} &= \exp(-\lambda \cdot \sigma \cdot V / Q) + \\ & [C_0 + \sigma \cdot U \cdot Q / (2 \cdot V \cdot L)] \times [1 - \exp(-\lambda \cdot V \cdot L / Q)] \end{aligned} \tag{2}$$

Where:

U = working perimeter (m)

C_O = radon concentration in air, entering the tunnel system (Bq/m^3)

Q = volume flow of air in the tunnel section (m^3/s)

L = the length of the tunnel section (m)

λ = constant of radon decomposition ($3.33 \cdot 10^{-4}$ 1/s)

σ = the rate of radon emission per unit area from the tunnel surfaces ($Bq/s \cdot m$)

Software developed on the basis of these models permits the behaviour of $EEVA_{Rn}$ with distance along the tunnel to be determined given the air distribution along the tunnel, known topology of radon sources and the rate of radon emission from the surfaces. As a result of the mathematical simulation it is possible to minimize the air quantity required to meet the criteria for achieving acceptable radiation conditions in the tunnel.

4 The Technique of Mathematical Simulation of Ventilation in Tunnels

A numerical simulation method has been developed which models the flows, temperatures and behaviour of radon gas emission in tunnel networks on an unsteady basis. The basis of the methodology is given in refs. 5. A system of simultaneous equations is developed based on satisfying the flow continuity condition and the Bernoulli equation with allowance for pressure losses. The equations are solved using a method of successive approximations. The solution is advanced by small successive time steps to determine the variation of flow and pressure behaviour in the tunnel system with time. The effect of trains is modelled using a moving pressure source and the influence of meteorological effects is simulated by applying a pressure differential between the portals.

5 Methods to Choose The Air Heater's Parameters

Since 1988, technical solutions for the creation of air temperatures above 0°C in long railway tunnels during winter periods have been achieved in the Baikal tunnel. A recirculating scheme of ventilation located at the portal sections, provides the basis for these solutions. In this scheme, air heating is effected by means of air heaters located in bypass ducts near the portals /1,2/. The use of this scheme results in an increase in the temperature of air in the tunnel compared with the direct – flow scheme for the same consumption of energy for air heating. In the case of the Northern Mujsky tunnel, the utilization of the recirculating scheme of air ventilation can result in the deterioration of radiation conditions in the tunnel system due to the high level of radon emission from the rocks and infiltrating water. To overcome this problem, the method of heating the outdoor air at the portals was modified (Figure.2.) /6/.

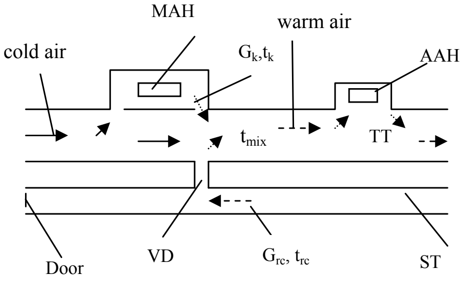


Figure 2 Arrangement for the heating of ambient air in winter

The required flow of cold outdoor air is directly supplied by fans into the main air heaters (MAH) located in the by pass duct adjacent to the portal and heated to the temperature required. This part of the air is directed to the tunnel, where it is mixed with a further part of cold outdoor air and relatively warm recirculated air supplied into the tunnel from the ST. If necessary, the temperature is increased using additional air heaters (AAH) located in one of the niches in the main tunnel. The power requirement for the air heaters is determined by the atmospheric air temperature, the quantity of air entering the tunnel both in the absence and presence of train movements, as well as by the frequency with which they pass through the tunnel. The prevention of ice formation involves keeping the temperature of the tunnel wall in the section behind the air heaters above freezing. (The section located near the portal is the most critical in term of ice formation). For the determination of the average air temperature in this section, t_{AV} , during the periods when traffic is absent and under the condition of piston effect action the following assumptions are made:

1. The heating effect arising from the train in the given section is taken to be zero. This is explained by the fact that the heat output from train depends on two factors. The first factor is that the energy input to the train is converted into heat. This factor is always positive. The second factor is that there is heat transfer between the train walls and air. This factor is negative in winter. It was shown in reference /1,3/ that these two factors compensate for each other under the given condition.
2. The heat transfer between the tunnel wall and air at the mixture temperature, $t_{mix.p}$,(see equation 4) during the period of piston effect action is determined using the heat transfer coefficient, α_p calculated from the average air flow velocity for the period of train transit.
3. During the absence of traffic, the heat transfer between tunnel wall and air is defined by the positive air temperature, t_{mix} ,(see equation 4) and the heat transfer coefficient, α, calculated from the air flow velocity.

$$v = \frac{(G_{ent} + G_{rc})}{S} \tag{3}$$

Where:
G_{ent} = the mass flow of air in the tunnel when the train piston action is absent (kg/s)
G_{rc}= the mass flow of recirculating air (kg/s)
S = the tunnel cross sectional area (m^2)

A formula for the calculation t_{AV} is derived in paper /2/. Calculations made with the formula indicate that, for an acceptable margin in the determination of the heating requirement, the minimum value of t_{AV} should be taken as 2 ^{0}C. In this case, the temperature of tunnel wall will not go down below 1 – 3^{0}C even with the maximum frequency of train movement through the tunnel /2/.

The relationship linking t_{AV} , $t_{mix.p}$ and t_{mix} may be given as /3/:

$$t_{av} = t_{mix} \cdot \Delta\tau_a + t_{mix.p} \cdot \Delta\tau_p \tag{4}$$

Where:
t_{mix} = the mixture temperatures of the air warmed up by the air heaters, cold ambient air supplied into the tunnel and recirculating air from the ST during the absence of traffic (^{0}C)
$t_{mix.p}$ = the mixture temperatures of the air warmed up by the air heaters, cold ambient air supplied into the tunnel and recirculating air from the ST during piston effect action (^{0}C)

$$\Delta\tau_a = \tau_a/\Sigma\tau \qquad \Delta\tau_p = \tau_p/\Sigma\tau \tag{5}$$

Where:
$\Sigma\tau$ = interval between train movements (s)
τ_p= total time of piston effect (s)
τ_a = time of absence of train piston action in seconds (s)

$$t_{mix.} = [(t_a + N/ G_{ent} \cdot c_p) \cdot G_{ent.} + G_{rc} \cdot t_{rc}]/(G_{ent} + G_{rc}) \tag{6}$$

$$t_{mix.p} = [(t_a + N/ G_{ent.p} \cdot c_p) \cdot G_{ent.p} + G_{rc} \cdot t_{rc}]/(G_{ent.p} + G_{rc}) \tag{7}$$

Where:
$G_{ent.p}$= the mass flows of air in the tunnel during piston effect action (kg/s)
$t_{a,}$ = temperature of ambient air (^{0}C)
t_{rc} = temperature of recirculating air (^{0}C)
N = the power requirements of the main air heaters at portals providing ambient air heating to t_{mix} temperature (kW)
c_p = the specific heat of air at constant pressure (kJ/kg·^{0}C)

Solving equation (5) for N, we get:

$$N = G_{ent} \cdot c_p \cdot [t_{mix} - t_a - (t_{mix} - t_{rc})/k_r] \tag{8}$$

Solving equation (4) in view of equations (6), (7), we get:

$$t_{mix} = \frac{t_{AV}}{\Delta\tau_a \left(1 + \frac{1+k_r}{1+k_p} \cdot \frac{\Delta\tau_p}{\Delta\tau_a} \right)} + \frac{t_a \cdot \Delta\tau_p}{\Delta\tau_a \left(1 + \frac{1+k_r}{1+k_p} \cdot \frac{\Delta\tau_p}{\Delta\tau_a} \right)} \cdot \frac{k_r - k_p}{1+k_p} \tag{9}$$

Where:
$k_r = G_{ent}/G_{rc}$; $k_p = G_{ent.p}/G_{rc}$.

The power requirement of additional air heaters can be determined in a similar manner.

6 Determination of The Necessary Air Quantity for The Normalization of Radiation Conditions in Tunnel System

A range of experiments preceded the determination of the quantity of air required for the achievement of acceptable radiation conditions. From investigations were carried out to determine the rate of radon emission into the tunnel workings. On the basis of the data obtained, conclusions were drawn concerning the emission rate during measurements and its behaviour with time was determined for the period of operation.

In particular, it was found that the rate of radon emission (σ) in the ST depends on the type of lining. Where there is a deficiency of concrete lining or shotcrete lining is used, the radon emission rate on the side surface of the ST is equal to that detected during measurements 0.1 – 2.7 Bq·m^{-2}·s^{-1}, while on the floor of the ST it is equal to 0 provided that water is diverted into enclosed drainage channels (the length of these tunnel sections is 8522 m). At the sections of ST with complete concrete lining sections (total length: 2010 m), the radon emission rate is approximately 0.05 Bq·m^{-2}·s^{-1}. Finally, at the sections of the ST with complete cast iron lining sections, the rate of radon emission can be taken as 0 (the length of the tunnel sections is 4346 m).

From measurements mentioned above, the distribution of the rate of radon emission per unit area (σ) along the ST is given in Figure 3. The total of radon emission in the ST per unit time (D) is also shown. It is evaluated at 100 kBq·s^{-1}.

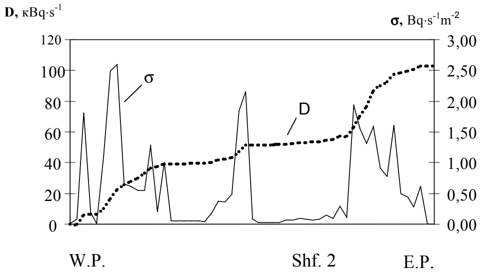


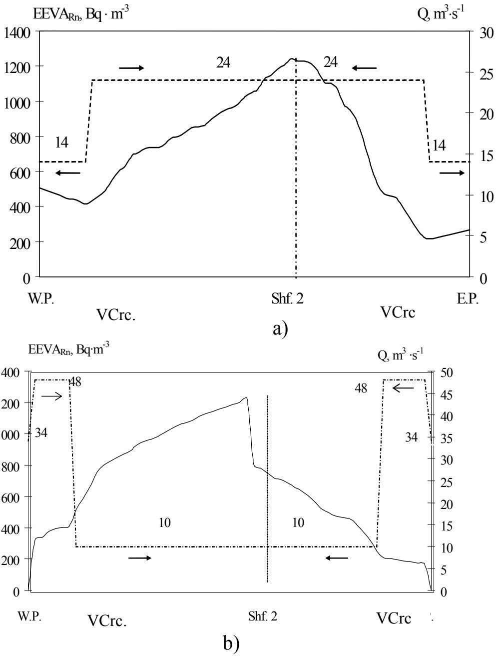
Figure 3 Distribution of both the rate of radon emission (σ) and the total of radon emission in the ST (D)

The rate of radon emission per unit area in the traffic tunnel, where the use of complete sections of tunnel lining is widespread, may be taken as constant and equal to 0.05 Bq·m^{-2}·s^{-1} in accordance with the measurement data.

A mathematical simulation of the formation process of radiation condition in the tunnel system was carried out for a series of possible ventilation schemes. In all, 14 feasible schemes of ventilation during the winter period and 6 schemes of ventilation for the summer period have been considered in selecting the most satisfactory arrangements.

The amount of air supplied during the periods considered and its distribution through the tunnel system varied. The basic guideline for the use of a specific ventilation scheme was the provision that the EEVA$_{Rn}$ value does not exceed 1200 Bq·m^{-3} for the lowest quantities of fresh air supplied.

The result of the simulation showed that the basic scheme of ventilation for the winter period may be considered as one which provides a supply of air through the portals of TT, organizes its movement along TT up to VCrc. followed by diversion of part of the air from the TT to the ST, from where it is directed both towards the shaft №2 and then back towards the ventilation building at the entry portal. Other portions of air in the TT, after passing through VCrc. flow from the western and eastern portals to the cross passage (Cr.) which connects with the shaft №2. At the end of Cr. these portions of air are mixed with air supplied through PW from the western and eastern portals along ST. The total amount of air supplied to VT through TT and ST from the western and eastern portals is removed to atmosphere through the shaft №2. When using this ventilation arrangement, the portals of the ST, BT and all the cross passages Crc., except VCcr. should be closed by ventilation gates (VG). The volume air flow rate and its distribution along the tunnel system for this ventilation scheme are shown in Figure. 4. From the analysis of the calculated data, shown in Figure. 4 it appears that for the achievement of acceptable radiation conditions in the tunnel system, the total amount of air supplied into the tunnel from each portal should be 34 m^3·s^{-1} (24 m^3·s^{-1} is directed to the shaft N2 along ST and 10 m^3·s^{-1} along TT). The total volume flow of air for the tunnel ventilation is 68m^3·s^{-1}. In this case, the amount of recirculating air in the sections between VCrc. and ventilation buildings (VB) is 14m^3·s^{-1}. In the majority of cases, the air quantity necessary for tunnel ventilation using this scheme ensures a reasonable level of energy consumption when creating acceptable thermal conditions.



a)

b)

Figure 4 Distribution of EEVA$_{Rn}$ along (a) ST and (b) TT and the corresponding air volume flow (arrows show the direction of air movement in tunnel system)

At the same time, if the atmospheric air temperature drops for a short period, the amount of air supplied into the tunnel may be reduced. It is apparent that such a reduction in the air flow will result in an increase in $\mathrm{EEVA_{Rn}}$.

In the summer period, the principal ventilation scheme should be based on a supply of fresh air through shaft №2 directed along the ventilation tunnel (VT), passageway (PW) and the cross passage (Cr) into ST and TT and its distribution in equal portions among the tunnel branches to the west and east. The results of the mathematical simulation of the $\mathrm{EEVA_{Rn}}$ distribution along the tunnel system obtained from the required air flow rate in the winter period (34 $m^3 \cdot s^{-1}$ of air is supplied to each tunnel branch, 24 $m^3 \cdot s^{-1}$ supplied into ST and 10 $m^3 \cdot s^{-1}$ into TT) suggest that, with the given ventilation scheme, $\mathrm{EEVA_{Rn}}$ in the tunnel system will not exceed 900 $Bq \cdot m^{-3}$.

Apart from the scheme mentioned above, it is possible to use a ventilation scheme with separate ventilation of the ST and TT. According to this scheme, TT is ventilated exclusively as a result of both natural air draught and the piston effect. ST is ventilated separately with fresh air supplied through the shaft №2 and directed along both the western and eastern branches. For this ventilation scheme, the cross passage to the shaft №2, as well as all other linking passages and the bypass tunnel should be closed using ventilation gates.

7 Characteristics of Ventilation Equipment Used for Ventilating the Tunnel System.

Fans and different damper arrangements must be used to supply the necessary amount of air into the NMT and distribute it through the branches of the tunnel system.

The use of two axial fans with a capacity of 30 – 90 $m^3 \cdot s^{-1}$ each and with a delivery pressure of 1400 – 4600 Pa installed in parallel in the ventilation room near shaft № 2 has been planned. Centrifugal fans with a capacity of 8 – 16 $m^3 \cdot s^{-1}$ and a pressure rise of 400 – 1300 Pa supply atmospheric air into the main air heaters to ensure heating of the recirculated air by - passed from the ST to the ventilation building. Axial fans with a capacity of 8 – 18 $m^3 \cdot s^{-1}$ and a pressure in the range 200 – 800 Pa are installed in cross passages to produce the preset air distribution between TT and ST.

The following damper arrangements are provided for securing the desired air distribution along the tunnel system: a ventilation gate with a damper (ventilation window with changing cross section for passing air), air doors, dampers and an adjustable ventilation gate. Ventilation gates with a damper are located in the cross passage leading to shaft № 2 and in the ventilation tunnel between shaft № 2 and VR. Air doors are located at the portals of the ST, in the BT, in cross passages (Crc.) connecting TT and ST, in the ventilation cross passages (VCrc) and in the ventilation duct (VD) connecting the ventilation building at the portals TT with the ST. A damper is located in the passageway (PW) and adjustable ventilation gates are located at the portals TT. A damper in the ventilation gate in VT is used for the regulation of the total air quantity entering in the tunnel system. A damper in the ventilation gate in Gr. ensures required air distribution between the western and eastern branches in winter. Ventilation doors in ST, VD, VCrc. have only two positions “open” and “closed”. Ventilation doors in Crc. are closed all the time. They are opened in the case of emergency.

In summer, the air doors at the portals of the ST are in the “open” position while the air doors in the BT, Crc., VCrc. and VD are “closed”. The ventilation gates in the Cr. and VT are “open”.

In winter, the air doors at the portals ST, in the Crc. and in the BT are “closed” and the air doors in the VD and in the VCrc. are “open”. The openings of the dampers in the ventilation gate in the Cr., in the VT and in the PW are adjusted to obtain the necessary air distribution in the tunnel system. Sliding ventilation gates at the tunnel portals serve to restrict the amount of outside air entering the TT as a result of natural draught and the piston effect in winter /7/.

When a train approaches one of the sliding ventilation gates at a tunnel portal, the gate opens and remains open until the train reaches the central part of the tunnel. As the train leaves the central part of the tunnel, the sliding ventilation gate at the entry portal closes, while the sliding ventilation gate on the exit portal opens.

8 The Results of Piston Effect Measurements

Accomplishment of this stage was connected with determination of the factual value of average air quantity entering the tunnel while trains were there, which is essential for calculating the air heaters capacity.

While measurements were being taken, the air temperature was 10,7^{0}C, relative humidity 66%, barometric pressure 91.3 kPa. Average air flow velocity was 1.54 m/s (air volume flow 59.1 m^3/s).

Analysis of instrumental measurement data shows that the full time of piston effect action is 22.82 minutes (Figure 5). During this, the stabilization time of air flow when a train is leaving the tunnel is 4.9 minutes. Average air velocity at the period when the train is in the tunnel is 3.97 m/s and air volume flow reaches 153 m^3 /s.

9 Determination of Pressure Loss in Sliding Ventilation Gates

The examination of pressure loss in the ventilation gates was taking place at the eastern portal. While taking air measurements the temperature in the tunnel was 12,5^{0}C (while outdoor temperature was 19^{0}C), atmospheric pressure was 91.37 kPa. During the examination procedure the gates’ shutters were successively placed in the following positions: the gates were fully open and the free cross-sectional area was 29.7 m^2 (the gates shutters extended 1 m); free section area - 22.5 m^2 (the gates spanned half of

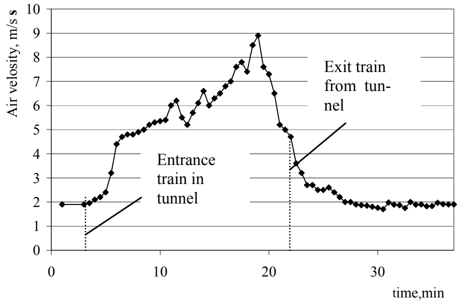


Figure 5 Air velocity (V_m) change during the piston effect

the tunnel section); 11.2 m^2 (75% of the tunnel section was spanned by the gates); free section area – 0.44 m^2 (the gates were fully closed) (Figure 6). At each position of the gates 3 to 5 series of pressure drop and air quantity measurements were taken which were averaged afterwards. The treatment of measurement results was based on the Eulerian number ($Eu = \Delta P / V_{av}^2 \rho$, ; ΔP – pressure loss, Pa; V_{av} – velocity of air, m/s; ρ - air density, kg/m^3) and dimensionless ratio $S_{rel} = S_h/S_t$ (S_h – section of blockage of the gate, m^2; S_t – section of tunnel, m^2), which is the blockage ratio of the free cross-sectional area of the tunnel (Figure.6.).

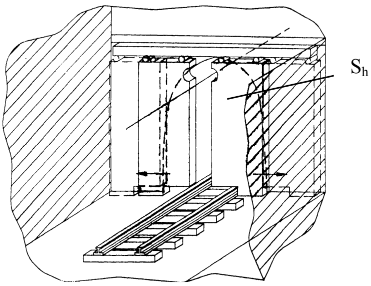


Figure 6 The configuration of the sliding gate

The experimental data lead to the following conclusion; if the spanning value is less than 0.75, the value of pressure loss of air flowing through gates is insignificant. At the same time, on the interval S_{rel} from 0.75 to 0.99 this value increases more than 10 times. Aerodynamic gates resistance increases by the same size. In this way, the effective regulation of the air quantity entering the tunnel can be reached only in the case of the ventilation gates being in position 'closed'

10 Choice of Operation Conditions of Air Heaters

In accordance with the technique set forth in section 5, the temperature dependence of the air, after being warmed up by the air heaters, has been established. The relationship between the capacity of the air heaters and both the atmospheric air temperature and the intensity of vehicle travel has been determined. Calculations are made for the condition presented in Figure 4. The volume flow of air of air

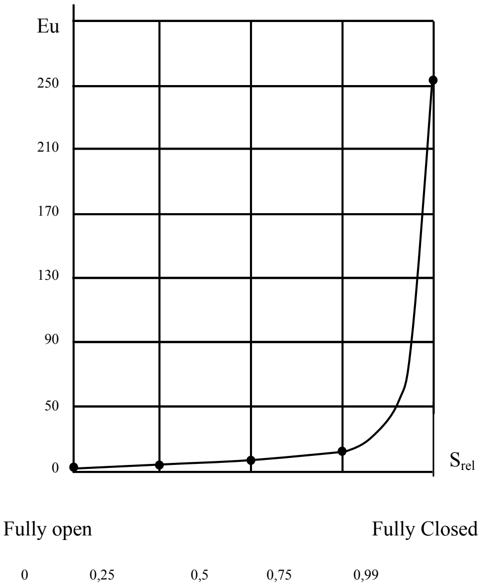


Figure 7. The dependence of pressure loss in ventilation gate on the spanning value of the free cross-sectional area

entering the tunnel when a train is travelling along it is determined from Figure5. (The average amount of air entering the portal during the transit of the train along the tunnel is also calculated).

The results of calculations for N with using formulas (7) – (8) to ensure value t_{AV} is equal to 2 ^{0}C are given in Figure 8.

On the basis of the calculated values presented in Figure 8 the analysis of the possibility of accommodating the air heaters in the ventilation buildings with their present construction dimensions, it is acceptable to use air heaters with a total power requirement of about 1440 kW. If one compares the present value of the total air heater capacity with the data from the diagrams in Figure.8, it is evident that when the traffic level corresponds to 8 trains in each direction per 24 hours, the main air heaters secure the necessary level of air heating for atmospheric air temperatures down to – 30^{0}C. However, when the travel level increases to 24 trains in each direction per 24 hours, the lowest atmospheric air temperature rises to – 24^{0}C. If the traffic level remains equal to 24 trains in each direction per 24 hours and heating capacity is 1440 kW then the drop in atmospheric air temperature below – 24^{0}C may result in t_{AV} falling below 0^{0}C. In this case, additional air heaters are required to heat the air.

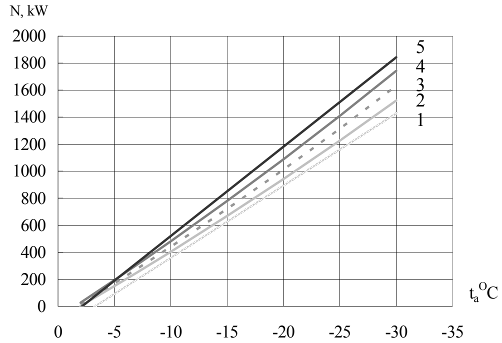


Figure 8 Dependence of capacity of basic air heaters when air heating is needed on outside air temperature and traffic level (Numbers 1-5 presented on the diagram correspond to traffic levels of 8, 12, 16, 20, 24 trains in each direction per 24 hours.)

11 Conclusion

The theoretical and experimental studies carried out have made it possible to choose a ventilation system for the NMT. The air flow requirements for the achievement of safe radiation conditions have been determined. Fan capacities, damper arrangements and operating modes have been established for effective operation of the ventilation system.

The capacity of air heating equipment and conditions of its use, depending both on atmospheric air temperature and intensity of trains travel, has been determined according to the quantity of air entering the tunnel, both when there is an absence of trains and when trains are travelling along the tunnel.

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