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Enhanced methodology for thermal management area assessment of metro lines

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Abstract. The article analyzes the operation of metro lines with double-track and single-track tunnels in the Russian Federation. Simultaneous activation of traffic on single-track and double-track tunnels affects the management of thermal and humidity parameters of the air environment on metro lines. Currently, there is limited experience in using shared lines. The study conducted an analysis of the features in the formation of thermal and ventilation regimes in double-track and single-track subway tunnels. It also examined the temperature regime of the station when mixing air flows from a double-track tunnel between stations and the flow from one of the stations. An algorithm has been defined for controlling the thermal and humidity parameters of the environment in underground structures. Measures are proposed to minimize the consequences of combining air flows and normalize microclimate parameters. The analysis of air mass movement revealed that the air temperature at the station located beyond the junction point of the double-track tunnel section and single-track tunnels is influenced by circulation flows in single-track tunnels, as well as the flow rate and temperature of the air coming from the double-track tunnel.

1 Introduction

An increase in population growth in large cities leads to a decrease in available space in the city, and the deterioration of the transport situation leads to the problem of the development of public transport [1, 2]. The main share of transportation is provided by underground transport – the metro [3, 4].

The urban off-street railway provides speed of movement with a large volume of passenger traffic with guaranteed safety during movement. One of the solutions to the problem of passenger transportation in large cities is the development of metro lines [1, 5].

Modern construction trends dictate new rules for the use of design solutions [3, 6, 7]. The use of single-track tunnel designs is gradually being replaced by the design of new generation double-track tunnels. The performance indicators of single-track and double-track metro tunnels vary and depend not only on design features, but also on the use of special ventilation schemes, which are significantly influenced by traffic intensity, engineering and geological conditions of occurrence, climatic parameters of the city, etc.

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The relevance of the topic is related to the modern construction of new double-track lines and stations, namely the joint operation of metro lines, including single-track and double-track tunnels [8-10]. The issues of managing thermodynamic parameters when monitoring normative parameters of the air environment on lines with single- and double-track tunnels have not yet been fully resolved, since there is not enough experience in Russia, and the climatic parameters and construction standards are different abroad [1, 3, 11].

2 Problem statement

An analysis of world experience in the construction of subways indicates that the construction of double-track tunnels leads to a reduction in costs by approximately 20 - 30% compared to traditional single-track tunnels while simultaneously reducing work time.

Construction time is reduced due to the construction of one tunnel instead of two; there is no need for expensive and labor-intensive construction of cross ramps, evacuation breaks, transitions from tunnel to tunnel and other related workings. To ensure the operation of subways, there are many engineering systems, one of the main ones is the ventilation system. The operation of this system should contribute to the creation and maintenance of normative air parameters in transport tunnels and stations under normal conditions, as well as the implementation of emergency modes that guarantee the safe evacuation of people in the event of an emergency (for example, a fire) and their subsequent liquidation (fire extinguishing).

Abroad, in operating metro lines with double-track tunnels, the ventilation scheme is similar to the scheme that is used for subways with single-track tunnels [12-14]. Fresh air is supplied to the tunnel through shafts located in the center of the stage, and the outgoing stream is removed from through the station shafts. Unlike parallel single-track tunnels, where air movement through the distillation tunnels is carried out mainly due to the piston effect from the movement of trains, in double-track tunnels the main source of thrust is fans, which are installed in the ventilation units of the distillation and station shafts [1, 3, 15].

Another distinctive feature of the aerodynamics of a double-track tunnel from single-track tunnels is that there are no air flows initiated by trains moving in opposite directions. During the operation of subway sections, including double-track and single-track running tunnels, the air flowing through the double-track tunnel to its junction with single-track tunnels is mixed with the circulation air flows that occur in areas adjacent to these junctions from stations with single-track tunnels. As a result of this mixing, the temperature of the air circulating between the junction of double-track and double-track tunnels and the station with single-track tunnels will be higher than with the traditional scheme, when the flows of external and circulating air are mixed [16, 17, 18]. This may lead to an increase in air temperatures at stations adjacent to junctions on the side of single-track tunnels above normative values.

The solution to the problem of normalizing the thermal regime during the joint operation of double-track and single-track distillation tunnels should be sought by selecting the required amount of air supplied to the double-track tunnel through a ventilation shaft located near the junction of the double-track and single-track tunnels.

3 Materials and methods

When solving the assigned problems, an integrated approach was used, consisting in the use of methods of mathematical statistics, methods of computational fluid dynamics, mining thermal physics, as well as computer modeling methods [1, 3, 19]. The research methods and the obtained initial data are based on theoretical and full-scale experimental studies at existing metro facilities [1, 20]. To a greater extent, when solving the problems, particular methods of computational fluid dynamics were used, namely the finite element and finite volume methods when solving the Navier-Stokes equation.

4 Results and discussion

The methodology is based on the requirements set out in the regulatory document of the Russian Federation "Code of rules 120.13330. 2012 METROPOLITEN" (hereinafter CR 120.13330).

Calculations of air temperatures were carried out at various points of the metro, such as the station and the middle of the section.

As an example, let's look at the method for calculating the temperature for the run from station "1" to station "2" (the actual locations of the stations are not disclosed for security reasons).

Tunnel parameters:

- Square: S=69,4 m^2
- Perimeter: P=29,53 m
- Stage length: L=1924 m
- Projected heat excess: N=1 712 513 kcal/h
- Air consumption in winter: Q_{w}=215 000 m^3/h
- Air consumption in summer: Q_{s}=400 000 m^3/h

Since air will be supplied through the ventilation duct in the middle of the stage, we will accept the assumption that an equal amount of air is distributed in both directions to the stations from the middle of the stage.

In accordance with the regulatory document of the Russian Federation "CODE OF RULES 131.13330.2012 BUILDING CLIMATOLOGY", the climatic parameters for the city "N" are as follows:

- Average annual air temperature: 5.4°C
- Average winter temperature: -4.6°C
- Average temperature for the coldest month: -5.5°C
- Temperature of the coldest five-day period: -24°C
- Average summer temperature: 12.6°C
- Average temperature for the warmest month: 18.8°C
- Hottest day temperature: 22.1°C

The following were taken into account: humidity and air density, coefficients from the approximation of the dependence of moisture content on temperature, supplied air flow rates, effective heat capacities, weight flow rates, heat transfer coefficients for different periods of the year, thermal conductivity and thermal diffusivity coefficients.

Equations required for calculation (average annual value t=5.4°C):

Effective heat capacity:

$$c_{ef} = c_a + s \cdot \varphi \cdot n_{app} \cdot \frac{0{,}101}{P_b},\ \text{J/kg·°C} \tag{1}$$

where:

c_a- heat capacity of air, J/kg·°C;

s - specific heat of condensation of water, kJ/kg;

φ - air humidity, fractions of units;

n_{app}- approximation coefficient, fractions of units;

P_b - barometric pressure, MPa.

$$\mathrm{c}_{ef} = 1006 + 2470 \cdot 0{,}7 \cdot 0{,}55 = 1956{,}95\ \text{J/kg·°C}$$

Table 1. Coefficients from the approximation dependence of air moisture content on temperature.

t,°C	from -30 to -20	from -20 to -10	from -10 to 0	from 0 to 10
n_{app}	0.045	0.95	0.19	0.40
t,°C	From 10 to 15	from 15 to 20	from 20 to 25	from 25 to 30
n_{app}	0.56	0.83	1.10	1.40

Air density:

$$\rho = 0{,}461 \cdot \mathrm{P_b}/\mathrm{T},\ \mathrm{kg/m^3} \tag{2}$$

where T-temperature, K

$\rho = 0{,}461 \cdot \frac{760}{5{,}4+273} = 1{,}2585\ \mathrm{kg}/m^3$

Weight consumption:

$$\mathrm{G} = \mathrm{Q} \cdot \rho,\ \mathrm{kg/s} \tag{3}$$

where Q- air consumption, m^3/h

Average annual air flow, ($\mathrm{Q}_{mid.ye}, m^3/h$):

$$\mathrm{Q}_{mid.ye} = 0{,}583 \cdot \mathrm{Q}_s + 0{,}417 \cdot (\mathrm{Q}_w + \mathrm{Q}_{cir}) \tag{4}$$

$$\mathrm{Q}_{mid.ye} = 0{,}583 \cdot \left(\frac{400000}{3600}\right) + 0{,}417 \cdot \left(\frac{215000}{3600} + 0\right)$$

$$\mathrm{Q}_{mid.ye} = 89{,}68\ m^3/h$$

$$\mathrm{G}_{mid.ye} = 89{,}68 \cdot 1{,}2585 = 112{,}86\ \mathrm{kg/s};$$

$$\mathrm{G}_s = \frac{400000}{3600} \cdot 1{,}2585 = 136{,}3053\ \mathrm{kg/s};$$

$$\mathrm{G} = \frac{(\mathrm{G}_{mid.ye} + \mathrm{G}_{cir}) \cdot 5 + \mathrm{Q}_s \cdot 7}{12} = 126{,}574\mathrm{m}^3/h$$

Heat transfer coefficient:

$$\alpha = 2{,}6 \cdot \left(\frac{\mathrm{Q}}{\mathrm{S1}}\right)^{0{,}8} \cdot \left(\frac{\mathrm{P1}}{\mathrm{S2}}\right)^{0{,}2} \tag{5}$$

$$\alpha = 2{,}6 \cdot \left(\frac{126{,}574}{14{,}6}\right)^{0{,}8} \cdot \left(\frac{18{,}4}{14{,}6}\right)^{0{,}2} = 15{,}324$$

Average annual coefficients of unsteady heat transfer:

$$\mathrm{k} = \alpha \cdot \left(\frac{\mathrm{R}}{\lambda}\right) \tag{6}$$

where R- twice the ratio of tunnel area to perimeter,
λ- coefficient of thermal conductivity, W/m·°C

$$R = 2 \cdot \left(\frac{\mathrm{S}}{\mathrm{P}}\right), \tag{7}$$

$$R = \frac{69{,}4}{29{,}53} = 4{,}7003\ m$$

$$\mathrm{k} = 15{,}324 \cdot \left(\frac{4{,}7003}{1{,}8}\right) = 40{,}0142$$

Biot number characterizing the relative intensity of heat transfer:

$$\mathrm{Bi} = \alpha/(1 + \mathrm{k} \cdot \ln\left(1 + \sqrt{2{,}5 \cdot \mathrm{a}}\right) \tag{8}$$

$$\mathrm{Bi} = 15{,}324/(1 + 40{,}0142 \cdot \ln\,(1 + \sqrt{2{,}5 \cdot 4{,}857 =}\ \ 0{,}251$$

The calculation is performed similarly for other Biot numbers.

Based on the results of the calculations, Figure 1 displayed the temperatures in various sections of the distillation tunnels, including stations.

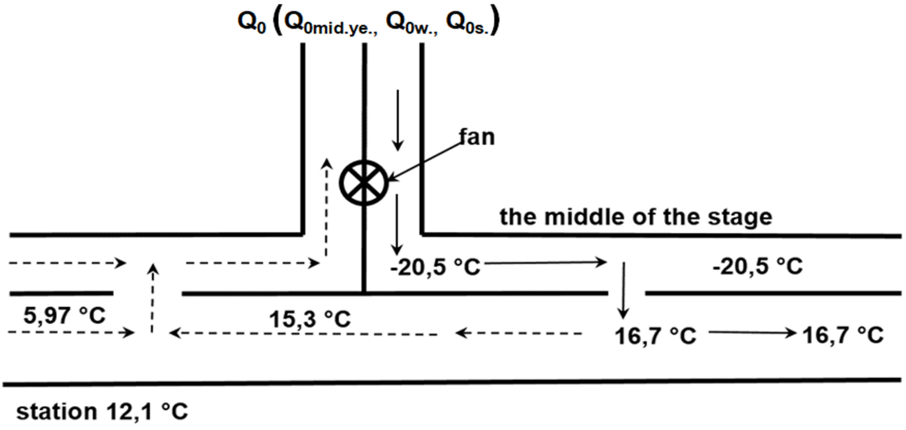

Fig. 1. Temperature distribution along the length of the tunnel during the coldest period: --------- for direction of air with a positive temperature after mixing the outside and tunnel air; ———— for direction of air with a negative temperature supplied from the surface.

As an example of combined lines, we considered the stretch between the stations "Station 1", which is located on a stretch with a double-track tunnel, and the station "Station 2", located on a section with single-track tunnels. To calculate the air temperature at the Station 2 station, the results of calculations of air temperatures in a double-track tunnel connecting with single-track tunnels were used, in particular the air temperature before connecting with single-track tunnels, and calculated dependencies to determine the temperature distribution in the circulation circuit of single-track tunnels.

When calculating the air temperature at the junction of double-track and single-track tunnels, the following dependence was used:

$$\mathrm{t} = \frac{\mathrm{G_{dtt}} \cdot \mathrm{t_{dtt}} + \mathrm{G_{stt}} \cdot \mathrm{t_{stt}}}{\mathrm{G_{dtt}} + \mathrm{G_{stt}}} \tag{9}$$

where $\mathrm{G_{dtt}}$- weight flow coming from the side of the double-track distillation tunnel, kg/s, $\mathrm{G_{stt}}$- weight flow coming from a single-track tunnel equal to the circulation air flow, kg/s; $\mathrm{t_{dtt}}$ and $\mathrm{t_{stt}}$ – air temperatures coming from double-track and single-track distillation tunnels, respectively, °C.

The calculations were carried out using software developed for the case of simultaneous operation of sections with double-track and single-track tunnels [1, 3, 5]. As a result of calculations, temperature values were obtained for various periods of the year: average annual temperatures, average winter temperatures, average summer temperatures, average January temperatures, temperatures of the coldest and hottest periods [3, 10, 11]. At the same time, the amounts of air supplied to the double-track distillation tunnel through the shaft located at the junction of the double-track and single-track tunnels were accepted as corresponding to the design ones, and increased taking into account the provision of normative parameters of the thermal regime.

The calculation data for the design ventilation scheme are presented in Table 2. In addition, based on the calculation results, graphs were constructed that determine the values of station air temperatures for the periods considered above (Fig. 2 a and 2 b).

Table 2. Temperature values at station “Station 2” at design air flow rates.

Period	Temperature coming from a double-track tunnel, °C	Temperature coming from a single-track tunnel, °C	Temperature at the metro station, °C
Winter period	27.2	21.5	24
Coldest month	27.8	18	22.2
The coldest five-day period	16.7	13.9	14.9
Summer period	30.7	22.9	26.3
Warmest month	30.9	25.8	28
Hottest day	31.3	27.1	28.8

Based on the data presented in Fig. 2a, there is an exceedance of the normative temperature values at "Station 2".

The most effective way to normalize the normative parameters of the microclimate at a station should be considered to be an increase in the flow rate of the supplied air. To confirm this statement, we calculated temperatures at a 1.5-fold increase in the amount of supplied air, in Fig. Table 3 shows the average temperatures at station “Station 1” with increased air flow.

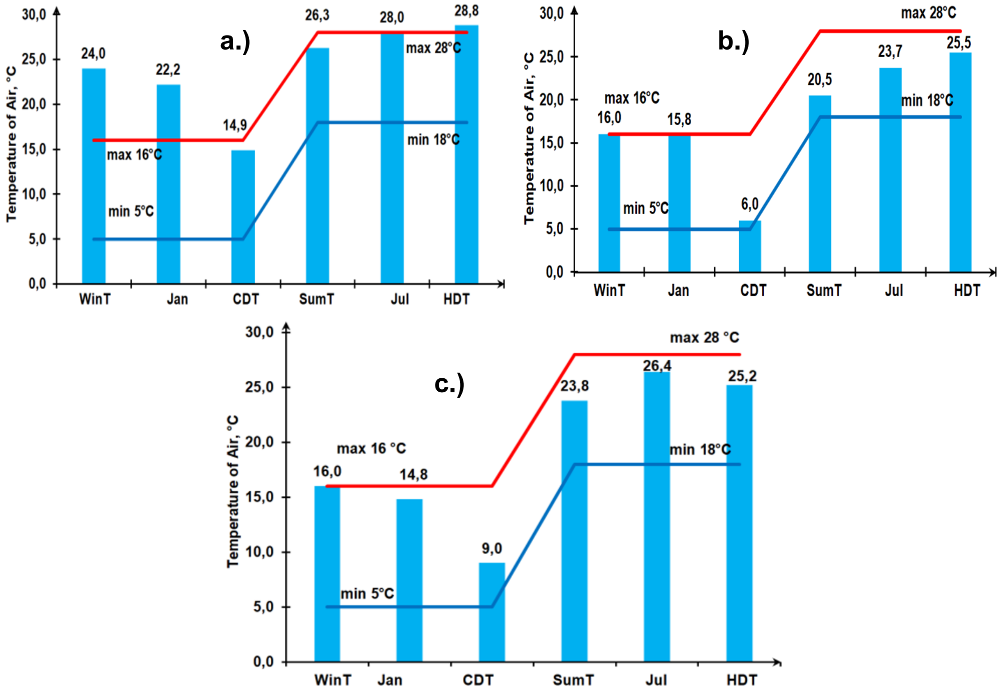

Fig. 2. Air temperature values at the station: a.) “Station 2” at design air flow rates; b.) “Station 1” at a 1.5-fold increase in air flow; c.) when redistributing the volumes of supplied air.
— min & max — normative value of temperature
WinT- winter temperature; Jan- Temperature of January; CDT - Colder Day Temperature; SumT – summer temperature; Jul - Temperature of July; HDT - Hottest Day Temperature

The graphs presented below in Figure (2 a) and (2 b) demonstrate that a 1.5-fold increase in the flow of supplied air directed through the suspended ceiling into a double-track tunnel, and then to interface with single-track tunnels, will ensure a reduction in it temperature at the interface, which will affect the microclimate parameters of the Station 2 station, which will correspond to normative values.

Another way to control the thermal regime of a section with double-track and single-track tunnels is to divide the supply air flow into two parts. One part of the outside air, similar to the design ventilation scheme, is pumped into the false ceiling and then transferred into the tunnel, and the other part is supplied directly to the junction of the double-track and single-track tunnels, where air flows from the double-track and single-track tunnels are mixed.

The temperature of the mixture of air flows from a double-track tunnel and circulating air from single-track tunnels will be calculated using the formula.

$$t = \frac{G_{dtt} \cdot t_{dtt} + G_{stt} \cdot t_{stt} + G_{shaft} \cdot t_{shaft}}{G_{dtt} + G_{stt} + G_{shaft}} \tag{9}$$

where G_{shaft} - weight flow rate of air entering the place of mixing air flows directly from the ventilation shaft adjacent to the junction point, kg/s.

The results of calculations performed similarly to previous calculations are shown in Table 3 and above in Figure 2 c.

Table 3. Temperature values at the station during air redistribution.

Period	Temperature coming from a double-track tunnel, °C	Temperature coming from a single-track tunnel, °C	Temperature at the metro station, °C	Temperature coming from a double-track tunnel, °C
Winter period	27.2	21.5	-4.6	16.0
Coldest month	27.8	18.0	-5.5	14.8
The coldest five-day period	16.7	13.9	-24.0	9.0
Summer period	30.7	22.9	12.3	23.8
Warmest month	30.9	25.8	18.8	26.4
Hottest day	31.3	27.1	22.1	25.2

5 Conclusion

An analysis of the temperature regime of the station was carried out when mixing air flows from a double-track tunnel between the stations “Station 1” - “Station 2” and the flow from the station “Station 2”. It has been established, as the processing of an array of experimental data has shown, that with such a mixing of air flows, the microclimatic parameters of the station “Station 2” have unfavorable values.

Several ways to solve the problem of normalizing microclimatic parameters have been proposed. To do this, it is necessary to increase the amount of air supplied to the tunnel space or to redistribute the supplied air due to partial dilution of the air in the center of mixing air flows.

It has been suggested that the thermodynamic parameters of the atmosphere of subway tunnels, both single- and double-track tunnels, should be established on the basis of the proposed method for calculating temperature distribution. The methodology is based on taking into account the average annual, average winter, average summer, average monthly and extreme (coldest five-day, hottest day) outdoor air temperatures for conditions.

It has been established that microclimatic parameters are best in two road tunnels. We assume that this is explained by the absence of circulation flows associated with the movement of trains, as a result of which heat accumulates, a significant part of which does not have time to be completely dissipated by the stream emanating from the subway tunnel.

It was revealed that the air temperature at the station located beyond the junction point of the double-track tunnel section and single-track tunnels is influenced by circulation flows in single-track tunnels initiated by moving trains, as well as the flow rate and temperature of the air coming from the double-track tunnel. At the same time, we believe that reducing the air temperature at the station to normative values of 28 °C can be achieved by increasing the amount of air coming from the double-track tunnel. The required additional amount of air is determined by aerodynamic calculations.

References

1. S.G. Gendler, M.S. Kryukova, MIAB. MiningInf.Anal.Bull. **9-1**, 248-269 (2023).
2. Z.A. Abiev, V.A. Rodionov, G.P. Paramonov, V.I. Chernobay, MIAB. Mining Inf. Anal. Bull. **5**, 26-34 (2018) DOI: 10.25018/0236-1493-2018-5-0-26-34
3. S.G. Gendler, M.S. Kryukova, News of TulSU. Earth sciences. **2**, 77-87 (2022).
4. A.A. Konstantinova, A.M. Merkulova, A.I. Pereladov, L.Yu Chavkina, MIAB. Mining Inf. Anal. Bull. **2-1,** 100-112 (2021).
5. V.A. Rodionov, G.N. Karpov, A.V. Leisle MIAB. Mining Inf. Anal. Bull., **6-1**, 198-213, (2022). DOI: 10.25018/0236_1493_2022_61_0_198.
6. Kongar-Syuryun Ch.B., Kovalski E.R. Geology and Geophysics of Russian South. 2023. **13(4)**: 177-187.
7. E.R. Kovalski, Ch.B. Kongar-Syuryun, D.N. Petrov, Sustainable Development of Mountain Territories, **15(2),** 349-364 (2023).
8. I.V. Klimova, Yu.G. Smirnov, V.A. Rodionov, Occupational Safety in Industry, **1**, 46–50 (2022) https://doi.org/10.24000/0409-2961-2022-1-46-50
9. Y.I. Vinogradov, S.V. Khokhlov, R.R. Zigangirov, A.A. Miftakhov, Y.I. Suvorov, Journal of Mining Institute, 1-15 (2024).
10. E.Yu. Kulikova, S.V. Balovtsev, O.V. Skopintseva, Sustainable Development of Mountain Territories, **15(1),** 7-16 (2023).
11. R.R. Vagapov, V.A. Rodionov, Oil Industry, **11**, 123–125 (2010)
12. B.Yu. Vasilev, M.G. Mustafin, MIAB. Mining Inf. Anal. Bull. **9**, 141-159, (2023). DOI: https://doi.org/10.25018/0236_1493_2023_9_0_141.
13. C.B. Kongar-Syuryun, A.V. Aleksakhin, E.N. Eliseeva, R.V. Klyuev, D.A. Petrusevich, Resources, **12(4),** 50 (2023).
14. V. Rodionov, I. Skripnik, Yu. Ksenofontov, et al. AIP Conference Proceedings **2467**, 080004 (2022); https://doi.org/10.1063/5.0093906
15. I.I. Raguzin, E.N. Bykowa, O.U. Lepikhina, Lomonosov geography journal, **78(3),** 92-103 (2023). DOI: https://doi.org/10.55959/MSU0579-9414.5.78.3.8
16. E. Bykowa, M. Skachkova, I. Raguzin, I. Dyachkova, M. Boltov, Sustainability, **14**, 9383 (2022). https://doi.org/10.3390/su14159383
17. S. Khokhlov, Z. Abiev, V. Makkoev, Appl. Sci. **12**, 1515 (2022). https://doi.org/10.3390/app12031515
18. Vladimir Khokhlov, Valery Lukin & Sergey Khokhlov, Annals of GIS, **29:1**, 143-161 (2023). DOI: 10.1080/19475683.2022.2064911
19. M.V. Tumanov, S.G. Gendler, E.I. Kabanov, V.A. Rodionov, E.A. Prokhorova, MIAB. Mining Inf. Anal. Bull. **6-1**, 230-247, (2022) DOI: 10.25018/0236_1493_2022_61_0_230.
20. S.V. Balovtsev, A.M. Merkulova, MIAB. Mining Inf. Anal. Bull. **3,** 170-181 (2024). DOI: 10.25018/0236_1493_2024_3_0_170.