sciendo

CIVIL AND ENVIRONMENTAL ENGINEERING REPORTS

E-ISSN 2450-8594

CEER 2022; 32 (4): 0259-0269
DOI: 10.2478/ceer-2022-0056
Case study

ANALYSIS OF TUNNEL VENTILATION DURING TUNNELLING - A CASE STUDY

Krzysztof SŁOTA[1], Zbigniew SŁOTA
Faculty of Mining, Safety Engineering and Industrial Automation, Silesian University of Technology, Gliwice

A b s t r a c t

In the case of tunnelling by mining methods, mining regulations apply to the design of ventilation. The most important criteria to be taken into account when calculating the minimum air flow rate in a tunnel are the air velocity, the multiple exchange of air during one hour, not exceeding the permissible concentrations of gases and dust, and ensuring appropriate climatic conditions. In this paper, an analysis of ventilation methods is carried out, taking into account the parameters of fans and ventilation ducts. Changing the diameter of the duct line from 1,000 to 1,400 mm results in a 3-4-fold reduction in fan power. Adding a second twin installation reduces the ventilation power requirement fourfold. Making the duct lines parallel increases the ventilation power requirement by about 30-50% compared to two duct installations.

Keywords: tunnel, ventilation, air monitoring

1. INTRODUCTION

Pressurised duct ventilation is most commonly used to ventilate tunnels during their excavation. Large electric fans and duct lines with a diameter of more than 800 mm are used for such ventilation. When calculating the air requirements at the face, the mining regulations [1] and the regulations for ensuring the right atmosphere (air composition) [2] must be used. On the other hand, when designing

[1] Corresponding author: Faculty of Mining, Safety Engineering and Industrial Automation, Silesian University of Technology, Gliwice, e-mail: krzysztof.slota@polsl.pl

the installation itself, it is necessary to calculate the minimum fan operating parameters - damming and air flow rate [3-8]. As the length and cross-section of the tunnelling increases, it is necessary to use high-power fans and large-diameter duct lines. These parameters can be ensured by using different duct ventilation systems.

2. MATERIALS AND METHODS

When designing the ventilation of tunnels excavated by mining methods, the relevant provisions of the Regulation of the Minister of Energy of 23 November 2016 on the detailed requirements for the operation of underground mining plants [1] must be applied. The necessary information is contained in Division III of the Regulation. They concern ventilation and related general requirements and ventilation by duct lines, auxiliary ventilation equipment or by diffusion.

In the works [9-12] a methodology has been developed for the design of auxiliary ventilation in roadways (excavations), where the necessary formulae for calculating the volume flow of air supplied to the face of an advancing tunnel are given. According to the Regulation [1], a minimum air velocity, one air exchange per hour, appropriate atmospheric composition (not exceeding the permissible concentrations of noxious gases and dust originating mainly from blasting, machinery, equipment used in the construction of the tunnel and mined rock), appropriate climatic conditions, etc. should be ensured in the tunnel.

The following parameters of the tunnelling and ventilation system were assumed for the calculation of the minimum air flow rate:

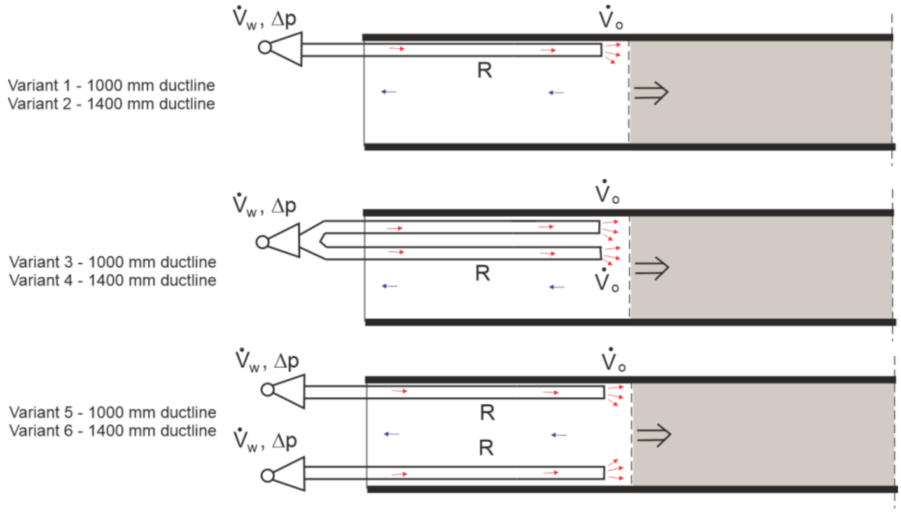
- L - length of the tunnel, duct line - 1000 m,
- S_t - cross-sectional area of the tunnel - 100 m^2,
- D - diameter of the duct line - 1.0 m and 1.4 m,
- Forcing ventilation system.

For the tunnelling, it was assumed that excavation machines - excavators and loaders (due to the fact that the tunnel will be tunneled in easily workable material, e.g. clay) and dump trucks, whose engines meet the minimum requirements of the EURO 4 emission standard, will be used.

Calculations were made for six variants:

- variant 1 - one duct fan with a 1000 mm diameter of the duct,
- variant 2 - one fan with a 1400 mm diameter of the duct,
- variant 3 - one fan with two 1000 mm ducts connected in parallel,
- variant 4 - one fan with two 1400 mm ducts connected in parallel,
- variant 5 - two fans with two separate ducts of 1000 mm diameter,
- variant 6 - two fans with two separate ducts of 1400 mm diameter.

A conceptual diagram of the design variants is shown in Fig. 1.



The legend:
Δp - total pressure of a duct-fun, Pa,
$\dot{V}_o$ - volumetric flow at the end of the duct line, m^3/s,
$\dot{V}_w$ - volumetric flow rate of the duct-fan, m^3/s,
R - aerodynamic resistance of the duct line, kg/m^7.

Fig. 1. Schematic diagram of the design variants [source: own elaboration]

3. RESULTS

For the assumptions given in section 2, the necessary calculations [1, 9-12] were made for the determination of the minimum air expenditures (volume flows) depending on the fulfilment of the legally required parameters.

The minimum airflow rate $\dot{V}_v$ in the tunnel due to ensuring the minimum air velocity:

$$\dot{V}_v = S_t \cdot v_{min} \;, \frac{m^3}{s}, \tag{3.1}$$

where:
S_t – cross-sectional area of the tunnel = 100 m2,
v_{min} – minimum air velocity determined for hazard control or required by legislation = 0,15 m/s.

$$\dot{V}_v = 100 \cdot 0{,}15 = 15{,}00 \frac{m^3}{s}$$

Minimum airflow rate $\dot{V}_{os}$ due to the working crew in the face zone of the tunnel:

$$\dot{V}_{os} = n \cdot q_n \;, \frac{m^3}{s}, \tag{3.2}$$

where:
n – highest number of workers in the tunnel at the same time = 20 workers,
q_n – required airflow per worker = 0,067 m^3/s.

$$\dot{V}_{os} = 20 \cdot 0{,}067 = 1{,}34\frac{m^3}{s}$$

Minimum airflow rate $\dot{V}_{wp}$ in the tunnel due to one air change per hour:

$$\dot{V}_{wp} = \frac{S_t \cdot L}{3600} \quad , \frac{m^3}{s}, \tag{3.3}$$

where:

L – tunnel length = 1000 m.

$$\dot{V}_{wp} = \frac{100 \cdot 1000}{3600} = 27{,}78\frac{m^3}{s}$$

Minimum airflow rate $\dot{V}_m$ in the tunnel due to machinery in operation [13]:

$$\dot{V}_m = \dot{V}_{max}(CO; NO_x; DPM) \ , \frac{m^3}{s}, \tag{3.4}$$

$$\dot{V}_{CO} = \frac{\dot{m}_{CO}}{NDS_{CO}} \quad , \frac{m^3}{s}, \tag{3.5}$$

$$\dot{V}_{NO_x} = \frac{\dot{m}_{NO_x}}{NDS_{NO_x}} \quad , \frac{m^3}{s}, \tag{3.6}$$

$$\dot{V}_{DPM} = \frac{\dot{m}_{DPM}}{NDS_{DPM}} \quad , \frac{m^3}{s}, \tag{3.7}$$

where:

N_m – machine power and combustion standards:

excavator, loader – 100-200 KM – STAGE IV
telescopic handler – 100 KM – STAGE IIIB
pump – 350 KM – EURO 4
concrete mixer – 400-500 KM – EURO 4
tippers – 1500 KM – EURO 5

$\dot{m}_{CO}$ – mass emission of CO due to the operation of machinery = 132,7 mg/s
$\dot{m}_{DPM}$ – mass emission of DPM due to the operation of machinery = 2,76 mg/s
$\dot{m}_{NO_x}$ – mass emission of NOx due to the operation of machinery = 57,86 mg/s
NDS_{CO} – the maximum permissible concentration of CO in the air = 23 mg/m^3
NDS_{DPM} – the maximum permissible concentration of DPM in the air = 10 mg/m^3
NDS_{NOx} – the maximum permissible concentration of NOx in the air = 3,5 mg/m^3

$$\dot{V}_{CO} = \frac{132{,}7}{23} = 5{,}77\frac{m^3}{s},$$

$$\dot{V}_{NO_x} = \frac{57{,}86}{3{,}5} = 16{,}53\frac{m^3}{s},$$

$$\dot{V}_{DPM} = \frac{2{,}76}{10} = 0{,}28\frac{m^3}{s}$$

$$\dot{V}_m = 16{,}53\frac{m^3}{s}$$

- Calculation for a 1000 mm diameter duct [14]

Actual unit resistance of the duct (per 1 m length of the duct):

$$r = r_o \cdot (1 + 0{,}01 \cdot \lambda)\ ,\ kg/m^8, \qquad (3.8)$$

where:
ro – specific aerodynamic resistance of new duct = 0,040 kg/m^8,
λ – damage intensity function of the duct based on the assumed smoothness quality = 15,38%.

$$r = 0{,}040 \cdot (1 + 0{,}01 \cdot 15{,}38)$$
$$r = 0{,}0462\ kg/m^8$$

Auxiliary size:

$$Q = \sqrt{(0{,}25 \cdot r \cdot \theta^2 \cdot 10^{-12})^2 + \left(\frac{16 \cdot \varepsilon \cdot \rho \cdot \theta^2 \cdot 10^{-12}}{3 \cdot \pi^2 \cdot D^4}\right)^3}\text{, m-3} \qquad (3.9)$$

where:
D – diameter of the duct = 1,0 m,
r – unit aerodynamic drag of used duct = 0,0462 kg/m^8,
ρ – air density = 1,2 kg/m^3,
ε – symbol indicating the type of duct ventilation system – for forcing ventilation = -1,
Θ – air mass exchange coefficient, for the assumed duct tightness quality = 2.

$$Q = \sqrt{(0{,}25 \cdot 0{,}0462 \cdot 2^2 \cdot 10^{-12})^2 + \left(\frac{16 \cdot (-1) \cdot 1{,}2 \cdot 2^2 \cdot 10^{-12}}{3 \cdot \pi^2 \cdot 1{,}2^4}\right)^3}$$
$$Q = 4{,}615 \cdot 10^{-14}\ m^{-3}$$

Organic growth parameter:

$$a = \sqrt[3]{0{,}25 \cdot r \cdot \theta^2 \cdot 10^{-12} + Q} + \sqrt[3]{0{,}25 \cdot r \cdot \theta^2 \cdot 10^{-12} - Q}\ \text{, m-1,} \qquad (3.10)$$

where:
Q – auxiliary size = $4{,}615 \cdot 10^{-14}\ m^{-3}$.

$$a = \sqrt[3]{0{,}25 \cdot 0{,}0462 \cdot 2^2 \cdot 10^{-12} + 4{,}615 \cdot 10^{-14}} +$$
$$+\sqrt[3]{0{,}25 \cdot 0{,}0462 \cdot 2^2 \cdot 10^{-12} - 4{,}615 \cdot 10^{-14}}$$
$$a = 4{,}51 \cdot 10^{-5}\ \text{m}^{-1}$$

Fan capacity for one fan with duct installation:

$$\dot{V_w} = \dot{V_o} \cdot e^{a \cdot L}\ ,\ m^3/s\ , \qquad (3.11)$$

where:
$\dot{V_o}$ – volumetric flow rate at the end of the duct line = 20,8 m^3/s,
a – organic growth parameter =4,51•10-5 m^{-1}.

$$\dot{V_w} = 20{,}8 \cdot e^{4{,}51 \cdot 10^{-5} \cdot 1000}$$
$$\dot{V_w} = 21{,}76 m^3/s$$

Fan capacity for two fans with duct installation:
$\dot{V_o}$ – volumetric flow rate at the end of the duct line = 10,4 m3/s,

$$\dot{V_w} = 10{,}4 \cdot e^{4{,}51 \cdot 10^{-5} \cdot 1000}$$
$$\dot{V_w} = 10{,}88 m^3/s$$

Fan capacity for one fan with duct installation connected in parallel:

$\dot{V}_o$ – volume flow at the end of the duct line = 21,0 m^3/s,

$$\dot{V}_w = 21{,}0 \cdot e^{3{,}46 \cdot 10^{-5} \cdot 1000}$$

$$\dot{V}_w = 21{,}97\ m^3/s$$

Aerodynamic resistance of a single duct line:

$$R = \frac{r}{2 \cdot a} + \frac{8 \cdot \rho}{\pi^2 \cdot D^4} \cdot (\zeta_w + \varepsilon) + \left[\frac{8 \cdot \rho}{\pi^2 \cdot D^4} \cdot (\zeta_o - \varepsilon) - \frac{r}{2 \cdot a}\right] \cdot e^{-2aL}\ \text{, kg/m}^7, \qquad (3.12)$$

where:

ζw – dimensionless resistance factor of the beginning of the duct line - forcing ventilation = 0,6,

ζo – dimensionless resistance factor of the end of the duct line - forcing ventilation = 1.

$$R = \frac{0{,}0462}{2 \cdot 4{,}51 \cdot 10^{-5}} + \frac{8 \cdot 1{,}2}{\pi^2 \cdot 1{,}0^4} \cdot (0{,}6 - 1) +$$
$$+ \left[\frac{8 \cdot 1{,}2}{\pi^2 \cdot 1{,}0^4} \cdot (1 + 1) - \frac{0{,}0462}{2 \cdot 4{,}51 \cdot 10^{-5}}\right] \cdot e^{-2 \cdot 4{,}51 \cdot 10^{-5} \cdot 1000}$$
$$R = 47{,}464\ kg/m^7$$

Aerodynamic resistance of two duct lines connected in parallel:

$$R_p = \frac{R_1 \cdot R_2}{R_1 + 2 \cdot \sqrt{R_1 \cdot R_2} + R_2} + R_r\ \ , kg/m^7, \qquad (3.13)$$

where:

R, R_1, R_2 – aerodynamic resistance of individual duct lines = 47,464 kg/m^7,

R_r – duct line branching resistance = 2,305 kg/m^7.

$$R_p = \frac{47{,}464 \cdot 47{,}464}{47{,}464 + 2 \cdot \sqrt{47{,}464 \cdot 47{,}464} + 47{,}464} + 2{,}305\ , kg/m^7$$
$$R_p = 14{,}171\ kg/m^7$$

Total fan pressure:

$$\Delta p = R \cdot V_w^2 \ \text{ or } \Delta p = R_p \cdot V_w^2\text{, Pa ,} \qquad (3.14)$$

where:

R_p – aerodynamic resistance of duct lines connected in parallel = 14,171 kg/m^7.

Fan pressure for one fan with duct installation:

$$\Delta p = 47{,}464 \cdot 21{,}76^2 = 22474\ \text{Pa}$$

Fan pressure for two fans with duct installation:

$$\Delta p = 47{,}464 \cdot 10{,}88^2 = 5619\ \text{Pa}$$

Fan pressure for one fan with duct installation connected in parallel:

$$\Delta p = 14{,}171 \cdot 21{,}97^2 = 6840\ \text{Pa}$$

Ventilation power of the fan:

$$N_w = R \cdot V_w^3 \ \text{ or } N_w = R_p \cdot V_w^3\text{, W ,} \qquad (3.15)$$

Ventilation power of the fan for one fan with duct installation:

$$N_w = 47{,}464 \cdot 21{,}76^3 = 489036\ W$$

Ventilation power of the fan for two fans with duct installation:

$$N_w = 47{,}464 \cdot 10{,}88^3 = 61130\ W$$

Ventilation power of the fan for one fan with duct installation connected in parallel:

$$N_w = 14{,}171 \cdot 21{,}97^3 = 150277\ W$$

- Calculation for 1400 mm diameter duct [14]

Actual unit resistance of the duct:

r_o – specific aerodynamic resistance of new duct = 0,010 kg/m^8,

$$r = 0{,}010 \cdot (1 + 0{,}01 \cdot 15{,}38)$$
$$r = 0{,}01154\ kg/m^8$$

Auxiliary size:

$$Q = \sqrt{(0{,}25 \cdot 0{,}01154 \cdot 2^2 \cdot 10^{-12})^2 + \left(\frac{16 \cdot (-1) \cdot 1{,}2 \cdot 2^2 \cdot 10^{-12}}{3 \cdot \pi^2 \cdot 1{,}4^4}\right)^3}$$
$$Q = 1{,}1538 \cdot 10^{-14}\ m^{-3}$$

Organic growth parameter:

$$a = \sqrt[3]{0{,}25 \cdot 0{,}01154 \cdot 2^2 \cdot 10^{-12} + 1{,}1538 \cdot 10^{-14}} +$$
$$+\sqrt[3]{0{,}25 \cdot 0{,}01154 \cdot 2^2 \cdot 10^{-12} - 1{,}1538 \cdot 10^{-14}}$$
$$a = 2{,}84 \cdot 10^{-5}\ \mathrm{m}^{-1}$$

Fan capacity for one fan with duct installation:

$\dot{V_o}$ – volumetric flow at the end of the duct line = 20,8 m^3/s,

a – organic growth parameter =2,84•10-5 m-1.

$$\dot{V_w} = 20{,}8 \cdot e^{2{,}84 \cdot 10^{-5} \cdot 1000}$$
$$\dot{V_w} = 21{,}40 m^3/s$$

Fan capacity for two fans with duct installation:

$\dot{V_o}$ – volumetric flow at the end of the duct line = 10,4 m^3/s,

$$\dot{V_w} = 10{,}4 \cdot e^{2{,}84 \cdot 10^{-5} \cdot 1000}$$
$$\dot{V_w} = 10{,}70 m^3/s$$

Fan capacity for one fan with duct installation connected in parallel:

$\dot{V_o}$ – volume flow at the end of the duct line = 21,0 m^3/s,

$$\dot{V_w} = 21{,}0 \cdot e^{2{,}84 \cdot 10^{-5} \cdot 1000}$$
$$\dot{V_w} = 21{,}62\ m^3/s$$

Aerodynamic resistance of a single duct line:

$$R = \frac{0{,}01154}{2 \cdot 2{,}84 \cdot 10^{-5}} + \frac{8 \cdot 1{,}2}{\pi^2 \cdot 1{,}4^4} \cdot (0{,}6 - 1) +$$
$$+\left[\frac{8 \cdot 1{,}2}{\pi^2 \cdot 1{,}4^4} \cdot (1 + 1) - \frac{0{,}01154}{2 \cdot 2{,}84 \cdot 10^{-5}}\right] \cdot e^{-2 \cdot 2{,}84 \cdot 10^{-5} \cdot 1000}$$
$$R = 12{,}100\ kg/m^7$$

Aerodynamic resistance of two duct lines connected in parallel:
R, R_1, R_2 – aerodynamic resistance of individual duct lines = 12,100 kg/m^7,
R_r – duct line branching resistance = 1,920 kg/m^7.

$$R_p = \frac{12{,}100 \cdot 12{,}100}{12{,}100 + 2 \cdot \sqrt{12{,}100 \cdot 12{,}100} + 12{,}100} + 1{,}920\ , kg/m^7$$

$$R_p = 4{,}945\ kg/m^7$$

Fan pressure for one fan with duct installation:

$$\Delta p = 12{,}100 \cdot 21{,}40^2 = 5541 \text{ Pa}$$

Fan pressure for two fans with duct installation:

$$\Delta p = 12{,}100 \cdot 10{,}70^2 = 1386 \text{ Pa}$$

Fan pressure for one fan with duct installation connected in parallel:

$$\Delta p = 4{,}945 \cdot 21{,}62^2 = 2312 \text{ Pa}$$

Ventilation power of the fan for one fan with duct installation:

$$N_w = 12{,}100 \cdot 21{,}40^3 = 118584\ W$$

Ventilation power of the fan for two fans with duct installation:

$$N_w = 12{,}100 \cdot 10{,}70^3 = 14823\ W$$

Ventilation power of the fan for one fan with duct installation connected in parallel:

$$N_w = 4{,}945 \cdot 21{,}62^3 = 49973\ W$$

4. SUMMARY AND CONCLUSIONS

For tunnelling with a cross-section of 100 m^2 and a length of 1,000 m, the minimum airflow rate at the face of the tunnel will be 20.8 m^3/s. Calculations of the duct line parameters and fan operation parameters were carried out for this size. The results are summarised in Table 1.

Table 1. Summary of calculation results

Calculation variant	Duct diameter	Fan volume flow rate	Fan pressure	Fan ventilation power
	ø	$\dot{V}_w$	Δp	N_w
	mm	m^3/s	Pa	W
1	1x1000	21,76	22474	489036
2	1x1400	21,40	5541	118584
3	2x1000	21,97	6840	150227
4	2x1400	21,62	2312	49973
5	2x1000	2x10,88	2x5619	2x61130
6	2x1400	2x10,70	2x1386	2x14823

Source: own elaboration

A single 1000-duct diameter lute installation with one fan (variant 1) requires a fan with a ventilation power of almost 490 kW. Changing the diameter of the duct line to 1400 mm (variant 2) will reduce the ventilation power requirement of the fan to about 120 kW - about 25% of the power compared to the first solution.
Enlarging the installation with a second duct line and connecting them in parallel (variant 3 and 4) will reduce the ventilation power demand from 490 kW to a level of 150 kW for the 1000 mm diameter duct line (Variant 3) and from 118 kW to 50 kW for the 1400 mm diameter (variant 4).

If the original installation (variant 1) is enlarged by a second identical installation (variant 5), then two fans with a ventilation power of 61 kW each will be required. In the case of an installation with a duct line diameter of 1400 mm (variant 2), two fans with (variant 6) a ventilation power of 15 kW each will be required.

Tables 2 and 3 show the approximate costs of the maintenance of the installation for 2021 and 2022. The calculations assume a tunnelling time of 2,000 hours and average energy costs of 0.10 euro/kWh for 2021 and 0.40 euro/kWh. For fan and duct line costs, 2021 prices were assumed and for 2022 they were increased by an inflation factor of 15%

Table 2. Summary of costs for 2021

Calculation variant	Duct purchase cost	Fan purchase cost	Energy cost	Total costs
	Euro	Euro	Euro	Euro
1	30,000	300,000	163,000	493,000
2	40,000	76,000	39,500	155,500
3	2x30,000	98,000	50,100	218,100
4	2x40,000	36,000	16,700	132,700
5	2x30,000	2x43,000	40,800	186,800
6	2x40,000	2x12,000	9,900	113,900

Source: own elaboration

Table 3. Summary of costs for 2022

Calculation variant	Duct purchase cost	Fan purchase cost	Energy cost	Total costs
	Euro	Euro	Euro	Euro
1	34,500	345,000	652,000	1,031,500
2	46,000	87,400	158,000	291,400
3	2x34,500	112,700	200,400	382,100
4	2x46,000	41,400	66,800	200,200
5	2x34,500	2x49,500	163,200	331,200
6	2x46,000	2x13,800	39,600	159,200

Source: own elaboration

In the first variant (one fan with a 1000 mm diameter duct installation), the cost of the installation, including electricity costs for 2021, was €493,000. Electricity costs accounted for approximately 30% of the total cost. After the price change with electricity in 2022, the total cost increased to €1,031,500. The share of electricity costs increased to more than 60% of total costs. Changing the diameter of the duct line from 1,000 to 1,400 mm reduces costs by 30 to 60 per cent.
The most favourable variant is the one that will use two installations with two fans and with duct lines with a diameter of 1400 mm.

ADDITIONAL INFORMATION

This research was funded by Silesian University of Technology, BK-06/050/BK_22/0133 - Multi-variant analysis of the ventilation of a tunnel during its tunnelling in terms of compliance with the new legislation on maximum allowable gas concentrations - in situ studies.

REFERENCES

1. Regulation of the Minister of the Family, Labour and Social Policy of 12 June 2018 on the maximum permissible concentrations and intensities of factors harmful to health in the working environment [Rozporządzenie Ministra Rodziny, Pracy i Polityki Społecznej z dnia 12 czerwca 2018 r. w sprawie najwyższych dopuszczalnych stężeń i natężeń czynników szkodliwych dla zdrowia w środowisku pracy]. Journal of Laws 2018, item 1286, dated 03.07.2018.
2. Regulation of the Minister of the Family, Labour and Social Policy of 12 June 2018 on the maximum permissible concentrations and intensities of factors harmful to health in the working environment [Rozporządzenie Ministra Energii z dnia 23 listopada 2016 r. w sprawie szczegółowych wymagań dotyczących prowadzenia ruchu podziemnych zakładów górniczych]. Journal of Laws 2018, item 1286, dated 03.07.2018.
3. Obracaj, D, Korzec, M and Deszcz, P 2021. Study on Methane Distribution in the Face Zone of the Fully Mechanized Roadway with Overlap Auxiliary Ventilation System. *Energies* **14**, 6379. https://doi.org/10.3390/en14196379
4. Fang, Y, Yao, Z and Lei, S 2019. Air flow and gas dispersion in the forced ventilation of a road tunnel during construction. *Undergr. Space* **4**, 168–179.
5. Hua, Y et al. 2018. Research on multi-radial swirling flow for optimal control of dust dispersion and pollution at a fully mechanized tunnelling face. *Tunn. Undergr. Space Technol.* **79**, 293–303.

6. Hua, Y et al. 2020. The development and application of a novel multi-radial-vortex-based ventilation system for dust removal in a fully mechanized tunnelling face. *Tunn. Undergr. Space Technol.* **98**, 103253.
7. Ren, T, Wang, Z and Coope, G 2014. CFD modelling of ventilation and dust flow behaviour above an underground bin and the design of an innovative dust mitigation system. *Tunn. Undergr. Space Technol.* **41**, 241–254.
8. Shi, G et al. 2017. Unsteady simulation for optimal arrangement of dedusting airduct in coal mine heading face. *J. Loss Prev. Process Ind.* **46**, 45–53.
9. Juszczyk, J et al. 2021. Impact of changing ventilation regulations during tunnelling by mining techniques with respect to Euro 4, 5 and 6 emission standards - a case study [Wpływ zmiany przepisów dotyczących przewietrzania podczas drążenia tuneli technikami górniczymi z uwzględnieniem norm emisji spalin Euro 4, 5 i 6 - studium przypadku]. In: Makówka, J (ed) *Natural hazards in underground mines*. GIG, 151-155.
10. Pawiński, J et al. 1995. The ventilation of mines [Przewietrzanie kopalń]. Wydawnictwo Śląsk.
11. Słota, K 2021. Ventilation of tunnels during their tunnelling in the aspect of safety improvement and changes in the regulations on maximum allowable gas concentrations - a case study [Przewietrzanie tuneli podczas ich drążenia w aspekcie poprawy bezpieczeństwa i zmiany przepisów dotyczących najwyższych dopuszczalnych stężeń gazów - studium przypadku]. In: Puchała, M (ed) *Safety culture - good health and safety practices.* University of Occupational Safety and Health, 129-140.
12. Szlązak, N, Obracaj, D and Borowski, M, 2003. Ventilation systems for blind workings in hard coal mines [Systemy przewietrzania ślepych wyrobisk ślepych w kopalniach węgla kamiennego]. *Przegląd Górniczy* **59**, 13-19.
13. Obracaj, D 2017. Auxiliary ventilation design during driven of headings by roadheader in copper ore mines [Projektowanie wentylacji lutniowej przy drążeniu chodników kombajnem w kopalniach rud miedzi]. *Cuprum* **3**, 13-30.
14. Bystroń, H 1990. Methods of calculating unbranched mine ventilation ducts [Metody obliczania nierozgałęzionych lutniociągów kopalnianych]. Archives of Mining Sciences **34**, 3.

Editor received the manuscript: 27.09.2022