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Abstract

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Keywords

tunnel ventilation, tunnel safety, energy cost of ventilation, forcing ventilation system

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TECHNICAL NOTE

Ventilation of tunnels during drilling using a forcing ventilation system — A case study

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Abstract

In Poland, more and more tunnels are being built using mining methods. Mostly ventilation systems are described for tunnels already commissioned. There are few examples of ventilation calculations for tunnels under construction. The paper shows a case study where calculations were made of the minimum air volume flow required to ventilate a tunnel during its tunnelling using four duct ventilation systems. The first system used two separate fans with a 1200 mm diameter duct line, the second system changed the diameter of the duct line to 1400 mm, the third system used one fan with two 1200 mm diameter duct lines connected in parallel, and the fourth system increased the diameter of the duct line to 1400 mm. Fan power requirements were determined for these layouts. The cost statement shows that it is advantageous to change the diameter of the duct line to a larger one — reducing the total cost by about 10%. With the assumed electricity prices, the more favourable variants are the systems for which two fans with separate duct lines are provided — a cost difference of about 5%.

Keywords: tunnel ventilation, tunnel safety, energy cost of ventilation, forcing ventilation system

1. Introduction

Between 2003 and 2022, twenty-two road tunnels have been built in Poland, eight tunnels are under construction, and six more tunnels are planned in the next three years [1,2]. Most of the longer tunnels in Poland are made using mining methods. Mining regulations should be used when designing ventilation for tunnelling works [3,4]. The works [5—8] present the general principles for the design of ventilation in tunnels in Poland, where the main elements for the calculation of the minimum air flow rate in a tunnel are indicated. The calculation methods were based on the regulations in force in the Polish mining industry [3,4,9]. The works [10—17] discuss ventilation design methods using modern software and CFD (computational fluid dynamics), among others. These works mainly present the results of measurements and analyses carried out, but lack a typical case study and step-by-step calculations presented. The case study allows the calculation of the minimum air flow rate for most cases in the world, where the main determining factor for the air volume is to ensure that the permissible concentrations of gases and dust are not exceeded.

According to Polish regulations [3,4], the volume of minimum airflow depends mainly on ensuring a minimum air velocity in the tunnel, not exceeding the permissible concentrations of gases and dust and ensuring a minimum of one air exchange per hour. For short tunnels and tunnels with a small cross-section, the biggest influence on the minimum air volumetric flow rate is a factor related to ensuring the right composition of the atmosphere. In contrast, for long tunnels and those with a large cross-section, the factor related to ensuring a 1-h air exchange rate will have the greatest impact. As of August 2023 [9], the regulations for permissible gas concentrations are changing, according to which the permissible concentration of nitrogen oxides will be reduced by a factor of five, and this will then be the determining factor for the minimum air volumetric flow rate required to ventilate the tunnel during their excavation. Ensuring the minimum air volumetric flow rate can be achieved by crystallising different duct ventilation systems.

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2. Materials and methods

When ventilating tunnels excavated by mining methods, the provisions of the Regulation of the Minister of Energy of 23 November 2016 on the detailed requirements for the operation of underground mining plants [4] mainly apply, in particular the legal regulations from Chapter 1 and 3 of Chapter III on ventilation and related general requirements and ventilation by duct lines, auxiliary ventilation equipment or by diffusion.

When designing separate ventilation for tunnelling [4], the required volume flow of air supplied to the face of the tunnelling shall be calculated. If the tunnelling requires the use of auxiliary ventilation, a pressurised ventilation system (less frequently suction or combined suction) is very often used forced ventilation based on duct fans, brazes and other exhaust or overlap ventilation systems components of such ventilation (e.g. duct brazes, dust collectors) [18–26]. Proper ventilation of a tunnel during their excavation affects not only the safety of the work but also the progress of the work and its costs.

The required air flow rate at minimum air velocity depends on ensuring a minimum air velocity in the tunnel (excavation), ensuring a minimum air exchange rate in the tunnel, dilution of harmful gases (carbon oxides, carbon dioxides, nitrogen oxides, nitrogen dioxides) and dust originating mainly from blasting, machinery, equipment used in the construction of the tunnel and from the rock being excavated, ensuring proper climatic conditions, as well as the number of people working in the tunnel [18–26].

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

- L – length of the tunnel, duct line – 600 m,
- S_t – cross-sectional area of the tunnel – 120 m^2,
- D – diameter of the duct line – 1.2 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 (Table 1) will be used.

Table 1. Results of the survey questions.

Emission standard	CO g/KM	HC g/KM	HC + NO_x g/KM	NO_x g/KM
EURO 4	0.50	_	0.30	0.25
EURO 5	0.50	_	0.23	0.18
EURO 6	0.50	_	0.17	0.08

Source: own compilation.

The calculations were carried out for four options:

- two duct fans with a diameter of 1200 mm of the duct,
- one fan with two 1200 mm ducts connected in parallel,
- two fans with a diameter of 1400 mm of the duct,
- one fan with two 1400 mm ducts connected in parallel.

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

3. Results and discussion

For the assumptions given in section 2, the necessary calculations [2–14] were made for the determination of the minimum air amounts (volumetric flow rates) 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:

$$\dot{V}_v = S_t \cdot v_{\min}, \mathrm{m}^3/\mathrm{s}, \quad (1)$$

where:

S_t – cross-sectional area of the tunnel = 120 m^2,
$v_{\min}$ – minimum air velocity determined for hazard control or required by legislation = 0.15 m/s.

$$\dot{V}_v = 120 \cdot 0.15 = 18.00\ \mathrm{m}^3/\mathrm{s}.$$

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

$$\dot{V}_{os} = n \cdot q_n, \mathrm{m}^3/\mathrm{s}, \quad (2)$$

where:

n – highest number of workers in the tunnel at the same time = 20 persons,
q_n – required airflow per worker = 0.067 m^3/s,

$$\dot{V}_{os} = 20 \cdot 0.067 = 1.34\ \mathrm{m}^3/\mathrm{s}.$$

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

$$\dot{V}_{wp} = \frac{S_t \cdot L}{3600}, \mathrm{m}^3\Big/\mathrm{s}, \quad (3)$$

where:

L – tunnel length = 600 m.

$$\dot{V}_{wp} = \frac{120 \cdot 600}{3600} = 20.00\ \mathrm{m}^3\Big/\mathrm{s}.$$

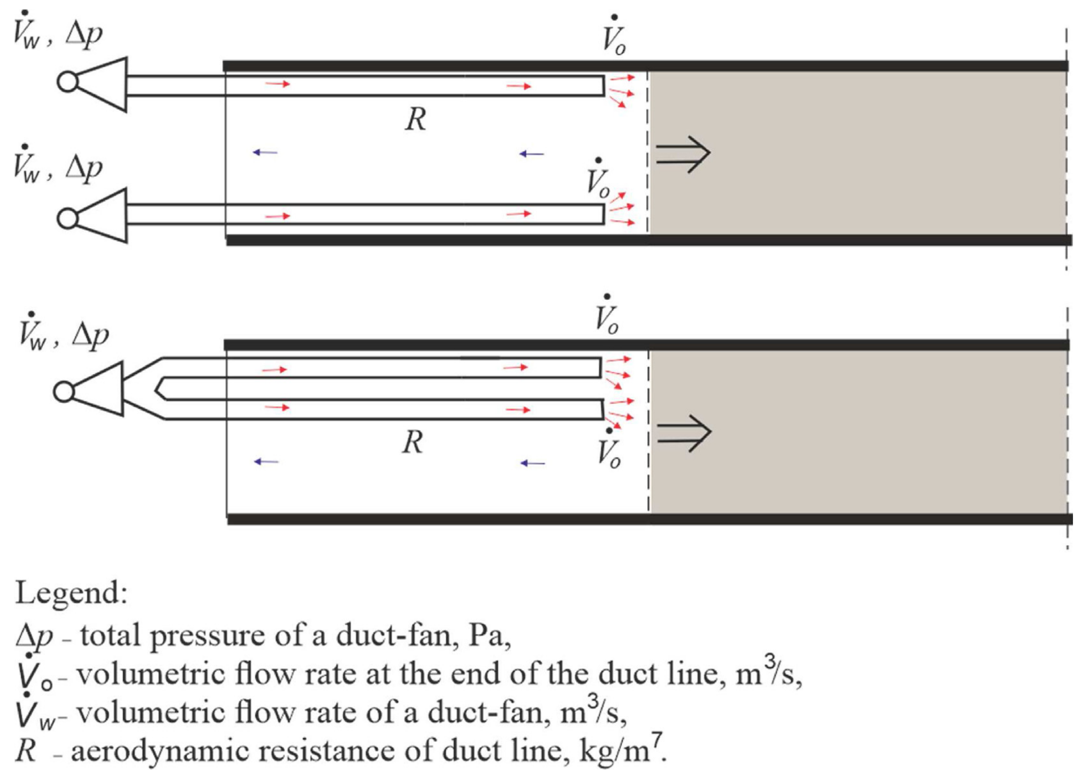


Fig. 1. Schematic diagram of the calculation variants [source: own elaboration].

Minimum airflow rate $\dot{V}_m$ in the tunnel due to machinery in operation [8]:

$$\dot{V}_m = \dot{V}_{\max}(CO; NO_x; DPM), m^3/s, \tag{4}$$

$$\dot{V}_{CO} = \frac{\dot{m}_{CO}}{NDS_{CO}}, m^3/s \tag{5}$$

$$\dot{V}_{NO_x} = \frac{\dot{m}_{NO_x}}{NDS_{NO_x}}, m^3/s \tag{6}$$

$$\dot{V}_{DPM} = \frac{\dot{m}_{DPM}}{NDS_{DPM}}, m^3/s \tag{7}$$

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 NO_x 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_{NO_x} – the maximum permissible concentration of NO_x in the air = 3.5 mg/m^3.

$$\dot{V}_{CO} = \frac{132.7}{23} = 5.77\, m^3/s,$$

$$\dot{V}_{NO_x} = \frac{57.86}{3.5} = 16.53\, m^3/s,$$

$$\dot{V}_{DPM} = \frac{2.76}{10} = 0.28\, m^3/s,$$

$$\dot{V}_m = 16.53\, m^3/s$$

The calculation for a 1200 mm diameter duct [18].

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

$$r = r_o \cdot (1 + 0.01 \cdot \lambda), kg/m^8 \tag{8}$$

where:

r_o – specific aerodynamic resistance of new duct = 0.018 kg/m^8,

λ – damage intensity function of the duct based on the assumed smoothness quality = 15.38%.

$$r = 0.018 \cdot (1 + 0,01 \cdot 15.38),$$

$r = 0.021\,\mathrm{kg/m^8}$.

Auxiliary size:

$$Q = \sqrt{\left(0.25\cdot r\cdot\theta^2\cdot 10^{-12}\right)^2 + \left(\frac{16\cdot\epsilon\cdot\rho\cdot\theta^2\cdot 10^{-12}}{3\cdot\pi^2\cdot D^4}\right)^3},\ \mathrm{m^{-3}} \quad (9)$$

where:

D – diameter of the duct = 1.2 m,

r – unit aerodynamic resistance of used duct = 0.021 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,

$$Q = \sqrt{\left(0.25\cdot 0.021\cdot 2^2\cdot 10^{-12}\right)^2 + \left(\frac{16\cdot(-1)\cdot 1.2\cdot 2^2\cdot 10^{-12}}{3\cdot\pi^2\cdot 1.2^4}\right)^3},$$

$Q = 2.077\cdot 10^{-14}\cdot\mathrm{m^{-3}}$.

Organic growth parameter:

$$a = \sqrt[3]{0.25\cdot r\cdot\theta^2\cdot 10^{-12} + Q} + \sqrt[3]{0.25\cdot r\cdot\theta^2\cdot 10^{-12} - Q},\ \mathrm{m^{-1}} \quad (10)$$

where:

Q – auxiliary size = $2.077\cdot 10^{-14}\cdot\mathrm{m^{-3}}$,

$$a = \sqrt[3]{0.25\cdot 0.021\cdot 2^2\cdot 10^{-12} + 2.077\cdot 10^{-14}} + \sqrt[3]{0.25\cdot 0.021\cdot 2^2\cdot 10^{-12} - 2.077\cdot 10^{-14}},$$

$a = 3.46\cdot 10^{-5}\ \mathrm{m^{-1}}$.

Fan capacity for a single duct line:

$$\dot{V}_w = \dot{V}_o\cdot e^{a\cdot L},\ \mathrm{m^3/s} \quad (11)$$

where:

$\dot{V}_o$ – volumetric flow rate at the end of the duct line = 10.0 m^3/s,

a – organic growth parameter = $3.46\cdot 10^{-5}$ m^{-1},

$$\dot{V}_w = 10.0\cdot e^{3.46\cdot 10^{-5}\cdot 600},$$

$\dot{V}_w = 10.21\,\mathrm{m^3/s}$.

Fan capacity for duct lines connected in parallel:

$$\dot{V}_w = 20.0\cdot e^{3.46\cdot 10^{-5}\cdot 600}$$

$\dot{V}_w = 20.42\,\mathrm{m^3/s}$

Aerodynamic resistance of a single duct line:

$$R = \frac{r}{2\cdot a} + \frac{8\cdot\rho}{\pi^2\cdot D^4}\cdot(\zeta_w + \epsilon) + \left[\frac{8\cdot\rho}{\pi^2\cdot D^4}\cdot(\zeta_o - \epsilon) - \frac{r}{2\cdot a}\right]\cdot e^{-2aL},\ kg/m^7 \quad (12)$$

where:

ζ_w – dimensionless resistance factor of the duct line inlet – forcing ventilation = 0.6,

ζ_o – dimensionless resistance factor of the end of the duct line – push ventilation = 1,

$$R = \frac{0.021}{2\cdot 3.46\cdot 10^{-5}} + \frac{8\cdot 1.2}{\pi^2\cdot 1.2^4}\cdot(0.6 - 1) + \left[\frac{8\cdot 1.2}{\pi^2\cdot 1.2^4}\cdot(1+1) - \frac{0.021}{2\cdot 3.46\cdot 10^{-5}}\right]\cdot e^{-2\cdot 3.46\cdot 10^{-5}\cdot 600},$$

$R = 13.857\,\mathrm{kg/m^7}$.

Aerodynamic resistance of two duct lines connected in parallel:

$$R_p = \frac{R_1\cdot R_2}{R_1 + 2\cdot\sqrt{R_1\cdot R_2} + R_2} + R_r,\ \mathrm{kg/m^7} \quad (14)$$

where:

R, R_1, R_2 – aerodynamic resistance of individual duct lines = 13.857 kg/m^7,

R_r – duct line branching resistance = 2.102 kg/m^7,

$$R_p = \frac{13.857\cdot 13.857}{13.857 + 2\cdot\sqrt{13.857\cdot 13.857} + 13.857} + 2.102,\ \mathrm{kg/m^7},$$

$R_p = 5.556\,\mathrm{kg/m^7}$.

Total fun pressure:

$$\Delta p = R\cdot V_w^2 \text{ or } \Delta p = R_p\cdot V_w^2,\ \mathrm{Pa}, \quad (15)$$

where:

R_p – aerodynamic resistance of duct lines connected in parallel = 5.556 kg/m^7,

$$\Delta p = 13.857 \cdot 10.21^2 = 1445 \text{ Pa},$$

$$\Delta p = 5.556 \cdot 20.42^2 = 2317 \text{ Pa}.$$

Ventilation power of the fan:

$$N_w = R \cdot V_w^3 \text{ or } N_w = R_p \cdot V_w^3, \text{W} \quad (16)$$

$$N_w = 13.857 \cdot 10.21^3 = 14754 \text{ W}$$

$$N_w = 5.556 \cdot 20.42^3 = 47313 \text{ W}$$

Calculation for 1400 mm diameter duct [18]. Actual unit resistance of the duct (per 1 m length of the duct):

r_o – specific aerodynamic resistance of duct (for 1400 mm diameter) = 0.010 kg/m^8,

$$r = 0.010 \cdot (1 + 0.01 \cdot 15.38),$$

$$r = 0.01154 \text{ kg/m}^8.$$

Auxiliary size:

$$Q = \sqrt{\left(0.25 \cdot 0.01154 \cdot 2^2 \cdot 10^{-12}\right)^2 + \left(\frac{16 \cdot (-1) \cdot 1.2 \cdot 2^2 \cdot 10^{-12}}{3 \cdot \pi^2 \cdot 1.4^4}\right)^3}$$

$$Q = 1.1538 \cdot 10^{-14} \cdot \text{m}^{-3}.$$

Organic growth parameter:

$$a = \sqrt[3]{0.25 \cdot 0.021 \cdot 2^2 \cdot 10^{-12} + 1.1538 \cdot 10^{-14}} + \sqrt[3]{0.25 \cdot 0.021 \cdot 2^2 \cdot 10^{-12} - 1.1538 \cdot 10^{-14}}$$

$$a = 2.84 \cdot 10^{-5} \text{ m}^{-1}.$$

Fan capacity for a single duct line:

$\dot{V}_o$ – volumetric flow rate at the end of the duct line = 10.0 m^3/s,

a – organic growth parameter = $2.84 \cdot 10^{-5}$ m^{-1},

$$\dot{V}_w = 10.0 \cdot e^{2.84 \cdot 10^{-5} \cdot 600},$$

$$\dot{V}_w = 10.18 \text{m}^3/\text{s}.$$

Fan capacity for duct lines connected in parallel:

$$\dot{V}_w = 20.0 \cdot e^{2.48 \cdot 10^{-5} \cdot 600},$$

$$\dot{V}_w = 20.35 \text{ m}^3/\text{s}.$$

Aerodynamic resistance of a single duct line:

$$R = \frac{0.01154}{2 \cdot 2.84 \cdot 10^{-5}} + \frac{8 \cdot 1.2}{\pi^2 \cdot 1.4^4} \cdot (0.6 - 1) + \left[\frac{8 \cdot 1.2}{\pi^2 \cdot 1.4^4} \cdot (1 + 1) - \frac{0.01154}{2 \cdot 2.84 \cdot 10^{-5}}\right] \cdot e^{-2 \cdot 2.84 \cdot 10^{-5} \cdot 600}$$

$$R = 7.700 \text{ kg/m}^7.$$

Aerodynamic resistance of two duct lines connected in parallel:

R, R_1, R_2 – aerodynamic resistance of individual duct lines = 7.700 kg/m^7,

R_r – duct line branching resistance = 1.920 kg/m^7,

$$R_p = \frac{7.700 \cdot 7.700}{7.700 + 2 \cdot \sqrt{7.700 \cdot 7.700} + 7.700} + 1.920, \text{kg}\Big/\text{m}^7,$$

$$R_p = 3.845 \text{ kg/m}^7.$$

Total fun pressure:

R_p – aerodynamic resistance of duct lines connected in parallel = 3.845 kg/m^7.

$$\Delta p = 7.700 \cdot 10.18^2 = 798 \text{ Pa},$$

$$\Delta p = 3.845 \cdot 20.35^2 = 1593 \text{ Pa}.$$

Ventilation power of the fan:

$$N_w = 7.700 \cdot 10.18^3 = 8124 \text{ W},$$

$$N_w = 3.845 \cdot 20.35^3 = 32418 \text{ W}.$$

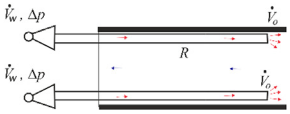
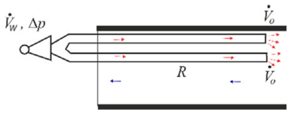
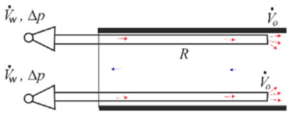
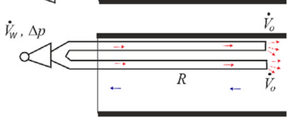
4. Conclusions

For the tunnelling of a tunnel with a cross-section of 120 m^2 and a length of 600 m, the minimum airflow rate at the face of the tunnel will be 20.0 m^3/s. For such a size, calculations of the duct line parameters and fan operation parameters were performed. The results are summarised in Table 2.

The application of a given ventilation method (calculation variant) requires corresponding costs (see Table 3). The costs will be related to the investment in equipment – the purchase of fans and duct lines - as well as related to the energy consumed by the fans [27–29].

In the first calculation variant, the installation of two 1200 mm diameter duct lines equipped with

Table 2. Summary of calculation results.

Calculation variant	Duct diameter ϕ mm	Fan volume flow rate $\dot{V}_w$ m³/s	Total fun pressure Δp Pa	Fan ventilation power N_w W
	1200	10.21	2317	14,754
	1200	20.42	1445	47,313
	1400	10.18	798	8124
	1400	20.35	1593	32,418

Source: own compilation.

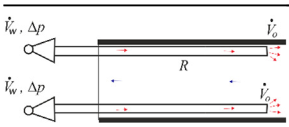
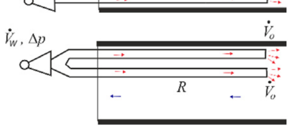
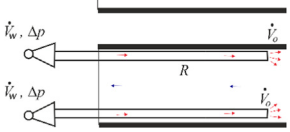
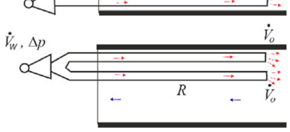
fans with a ventilation power of 14.754 kW each, giving a total of 29.508 kW, is required to ventilate the tunnel. The investment costs for the first option were for the purchase of two 15 kW fans (2 × €15000) and two 1200 mm diameter duct lines (€30000). The tunnelling speed was 0.5 m/h. The total tunnelling time for a 600 m long tunnel was 1200 h. The average fan efficiency was 60%. Due to the minimum air velocity in the tunnel, it was assumed that the volume flow rate of air flowing through the tunnel would be constant, ranging from 20.35 to 20.42 m^3/s. The energy purchase cost for the tunnelling company was €0.20/kWh (data as of 31.07.2022). The total energy cost of the running fans would be approximately €11800.

In the case of abandoning one fan and making a parallel connection of the duct lines without changing their diameter, the fan power should increase to 47.313 kW. For this solution, the energy cost would be approximately €18900.

The third calculation variant used two fans connected to 1400 mm diameter duct lines. Changing the diameter of the duct line reduced the aerodynamic resistance and, consequently, the fan power to a value of 8.124 kW. The energy cost for this solution would have been €6500.

The last variant used one fan and two 1400 mm diameter duct lines connected in parallel. The fan power, in this case, was 32.418 kW, and the energy cost was €13000.

Table 3. Summary of costs.

Calculation variant	Cost of purchasing a duct €	Cost of purchasing a fan €	Energy costs €	Total costs €
	30,000	2 × 15,000	11,800	71,800
	30,000	25,000	18,900	73,900
	33,000	2 × 12,000	6500	63,500
	33,000	21,000	13,000	67,000

Source: own compilation.

The cost statement shows that it is advantageous to change the diameter of the duct line to a larger one – a reduction in total costs of about 10%. At the assumed electricity prices, the more favourable options are systems for which two fans with separate duct lines are provided – a cost difference of about 5%. If there is a further increase in the price of electricity in the near future (as indicated by analysts' forecasts), this difference will increase further.

Ethical statement

The authors state that the research was conducted according to ethical standards.

Funding body

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Conflicts of interest

None declared.

Acknowledgments

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