

## SYSTEM FOR IMPROVING ENVIRONMENTAL CONDITIONS IN DEEP QUARRIES

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### Abstract:

**Goal.** To reduce the level of adverse factors in the air at quarry working benches by using localized ventilation systems powered by alternative energy sources.

**Research methods.** Theoretical substantiation of the system configuration and approximate parameters of the components of a localized ventilation system for quarries.

**Scientific novelty.** For the first time, a system is proposed that extracts polluted air from the quarry recirculation zone, partially cleans it, and subsequently disperses it outside the quarry, using solar energy to generate airflow in a ventilation duct.

**Practical significance.** The results can be applied in the design and modernization of localized ventilation systems in deep quarries to reduce gas and dust concentrations in working areas, which will lower energy costs, reduce greenhouse-gas emissions, improve occupational safety, and decrease anthropogenic impacts on the environment.

**The results.** A mobile localized ventilation system for deep quarries based on solar-induced buoyancy-driven draft is developed and theoretically substantiated. Analytical relationships are obtained to estimate airflow velocity and pressure depression in the ventilation duct, and the effectiveness of reducing gas and dust concentrations in working areas is demonstrated. The proposed solution shows potential to improve environmental and occupational safety while reducing energy consumption.

**Keywords:** deep quarry ventilation, solar energy, mobile localized ventilation system

### 1. Introduction

Safe and healthy working conditions in mining are largely determined by the quality of ventilation in working areas. This is particularly relevant for open-pit quarries that produce metallic ores. Workplaces occupy large areas and are ventilated mainly by natural ventilation, primarily wind-driven flows. Hazardous atmospheric factors are associated with the accumulation of exhaust gases from mining equipment and vehicles, blasting products, and large amounts of dust generated during rock crushing, loading, and haulage [1]. In addition, variable wind direction and speed resuspend deposited dust, forming a secondary component of dust loading [2, 3]. In summer, the thermal environment at workplaces deteriorates due to direct and reflected solar radiation from surfaces and convective transport of heated air [4].

### 2. Current state

The effectiveness of quarry ventilation depends on quarry depth. As depth increases, the velocity of airflows at working benches decreases, which in turn leads to poorer air exchange within the quarry. Ventilation intensity is determined by the ratio of quarry depth  $H$  to its length in the wind direction  $L$ . All

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else being equal, as the ratio  $H/L$  decreases, the quarry becomes “flatter” and is characterized by better natural ventilation conditions.

A quarry is considered shallow if  $0.1 < H/L < 0.2$ , medium-depth if  $0.2 < H/L < 0.3$ , and deep when  $H/L > 0.3$ . As the ratio  $H/L$  increases, an increasingly large portion of the quarry is not actively ventilated; a recirculation zone forms in which harmful substances accumulate. At  $H/L = 0.3$ , all lower quarry levels fall within this zone (Fig. 1).

A recirculation-through-flow ventilation pattern in quarries occurs when the slope angle of the leeward quarry wall is  $15^\circ$  or more, and when the ratio of the quarry size at ground surface in the wind direction to its depth is  $L/H = 8-10$  or higher. In this case, the quarry volumes adjacent to the leeward wall fall within the recirculation zone, whereas the volumes located outside it are ventilated by through-flow streams. Sources of exhaust, blast, and other gases, as well as locations where dust clouds form, are typically within the recirculation zone.

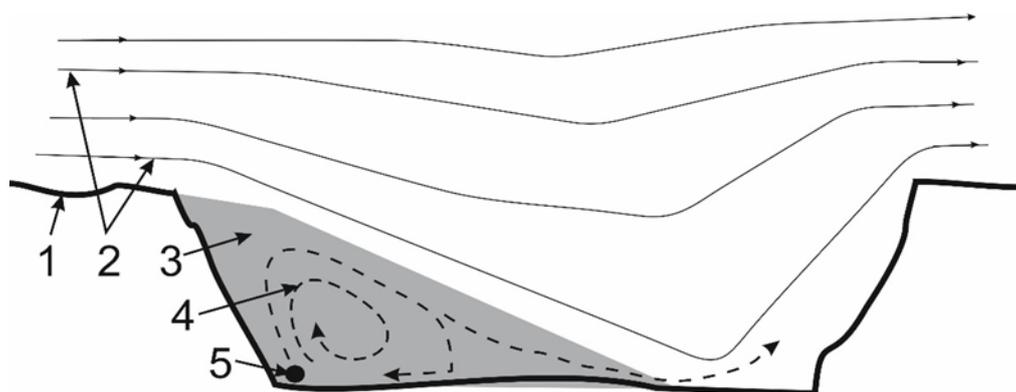


Fig. 1. Air flow distribution scheme in the quarry: 1-quarry rock contour; 2-direct-flow flows; 3-recirculation zone with increased pollution content; 4-vortices of harmful substances; 5-pollution sources

To ventilate gas-contaminated working benches, a forcing (supply) method is used with additional ventilation pipelines or dedicated mine workings. Mobile ducts are laid along the bench floor or along its wall. Fan units are installed where clean air enters. However, such a localized ventilation scheme is not sufficiently flexible and does not provide a significant reduction in dust transport. In addition, these low-mobility systems can interfere with blasting operations at the benches.

Removing harmful gaseous and dust impurities from the quarry to the near-surface atmospheric layer is of great importance. When the air jet exits a bench, its velocity must significantly exceed the minimum required to remove harmful gases and dust from the quarry ( $0,25 \text{ m/s}$  for gases,  $0,6 \text{ m/s}$  for dust). This imposes substantial constraints on the aerodynamic and energy performance of localized ventilation systems.

Modern localized (spot) ventilation and air-conditioning equipment for workplaces in quarries has been developed mainly based on aircraft engines that have reached the end of their service life [5]. Such systems are additional sources of exhaust gases and excessive noise and pose a fire hazard. The high cost of aviation fuel makes their routine use economically unjustified for normal plant operations.

In summary, the problem of providing safe and comfortable workplace conditions for miners in deep quarries remains unresolved from an engineering standpoint and is therefore relevant. The high rates of stripping and extraction require powerful mining machinery, which, while consuming large amounts of energy, is a source of intensive gaseous and dust emissions into the environment.

With increasing mining depth, quarries transition to a recirculation-through-flow ventilation pattern, which leads to the formation of recirculation zones where hazardous substances concentrate. The operation of modern technical means of localized ventilation for working spaces requires significant energy inputs and is accompanied by additional thermal and gas pollution. Rising fuel and electricity costs make their use economically inefficient. Therefore, the development of energy-efficient means of localized ventilation for quarry working spaces that simultaneously reduce the release of harmful and hazardous substances into the air environment is particularly important.

*The concept* of this study is to develop a system that extracts polluted air from the recirculation zone, partially cleans it, and subsequently disperses it outside the quarry.

*The goal* of the study is to reduce the level of adverse factors in the air at quarry working benches by using localized ventilation systems powered by alternative energy sources.

*The research method* is a theoretical substantiation of the system configuration and approximate parameters of the components of a localized ventilation system for quarries.

### 3. Research results

At present, in view of decarbonization policies, mining companies are increasingly seeking to introduce alternative energy sources into technological processes [6, 7]. This is especially relevant for mining operations located in remote regions, where it can help address energy-supply challenges for operating mines and quarries. As of the end of 2019, nearly 5 GW of alternative-energy projects had been implemented or were planned worldwide in the mining industry [8].

Projects using solar, wind, or geothermal energy have been implemented in both underground and surface mining. For example, at a mine in South Korea, combined small hydropower and solar power systems provide continuous power supply to aeration equipment used to treat acid mine drainage [9]. Wind energy contained in exhaust ventilation air from an underground mine has also been used to ventilate mine workings [10].

As a promising direction for the sustainable development of mining regions, the use of renewable energy sources on waste dumps of open-pit quarries is being considered, because it enables both rational use of disturbed land and a reduction in environmental pressure. The most justified options are wind and solar installations, whose performance has improved due to advances in photovoltaic modules and wind turbines, including vertical-axis designs. Studies confirm that integrating wind turbines on waste dumps offers environmental and economic benefits, including lower production costs, improved environmental efficiency of production infrastructure, and increased enterprise autonomy by reducing dependence on external energy suppliers [11].

The use of renewable energy sources such as solar and wind energy can provide steady power for specific processes at mining enterprises. For instance, wind energy has been considered for quarry lighting in mountainous terrain, including under unfavourable meteorological conditions [12]. Another promising direction is the use of wind energy for ventilating surface mining operations. At the same time, the practical deployment of wind turbines is limited by technical requirements for their placement: such units should be located on the surface in areas with high wind potential, typically at a considerable distance from the active mining area, which complicates the delivery of generated electricity to electric fans.

A preliminary analysis indicates that, among alternative energy types suitable for quarry conditions, solar energy is the most appropriate. It is sufficiently effective mainly during daylight hours; however, for safety reasons, most key quarry operations are also performed during the daytime.

As a driving force for airflow, it is proposed to use the so-called thermal draft (buoyancy-driven pressure depression) that forms due to a decrease in the density of heated gas in a ventilation duct. Air heating is achieved by concentrating solar radiation on a heating element of a heat exchanger. The mobile localized ventilation system is proposed as an assembly consisting of several interconnected structural elements (Fig. 2).

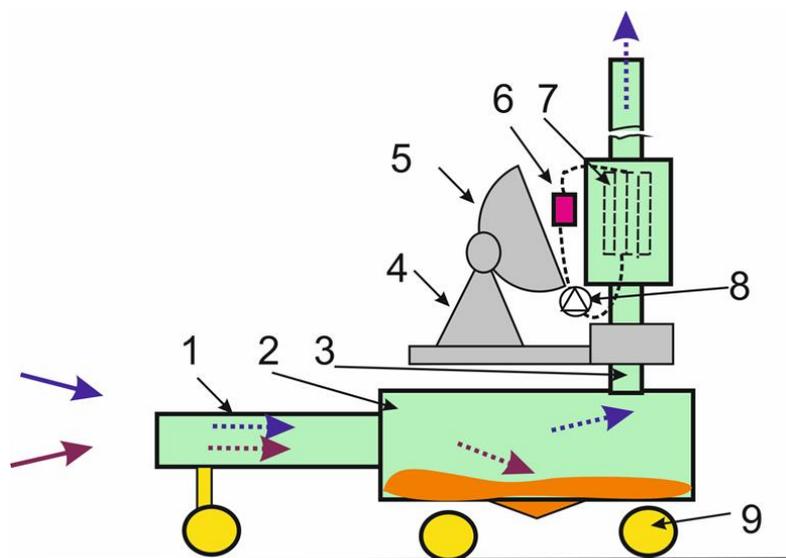


Fig. 2. Scheme of a mobile local ventilation system: 1-air intake pipe; 2- dust chamber; 3-ventilation pipe; 4-movable bracket and hinge; 5- beam concentrator; 6- heater; 7- heat exchanger; 8-pump; 9-chassis; arrows-directions of dust (red) and gas (blue) movement

To extract polluted air, a cylindrical mobile intake duct (1) made of a rigid sheet material (e.g., fiberglass) is used; it can bend in the horizontal and vertical planes. A dust chamber (2) with a dust collector is connected to it. A vertically installed metal ventilation duct (3) is connected to the chamber and has a height greater than the size of the recirculation zone. A movable L-shaped bracket (4) is mounted on the ventilation duct: its horizontal part can rotate about the duct axis, and its vertical part ends in a hinge that provides horizontal and vertical rotation of the solar concentrator (5) mounted on the bracket. The concentrator is made as a parabolic mirror, at the focus of which there is a hollow heater (6) made of a heat-resistant material and filled with a liquid heat-transfer fluid. The heater is connected to a tubular heat exchanger (7) located inside the ventilation duct. Circulation of the heat-transfer fluid is provided by an integrated pump (8). Above the heat-exchanger zone, the ventilation duct is equipped with heat-resistant thermal insulation. All components are mounted on a chassis (9), enabling movement of the system within the quarry.

The mobile localized ventilation system operates during daylight hours. Using the bracket and hinge, the parabolic concentrator is oriented so that the heater is located at the parabola focus. Concentrated solar radiation heats the heater surface and the heat-transfer fluid inside it. The heated fluid in the heater casing is pumped to the heat exchanger located in the ventilation duct. Fluid circulation heats the air passing through the ventilation duct, which causes a sharp decrease in the density of the air surrounding the heat exchanger. For example, at a standard pressure of 760 mmHg and a temperature of 20°C (293 K), the density of ambient air is  $\rho_{20} = 1.205 \text{ kg/m}^3$ ; however, after heating in the duct to 100°C (373 K), it decreases to  $\rho_{100} = 0.906 \text{ kg/m}^3$ , and at 300°C (573 K) to  $\rho_{300} = 0.574 \text{ kg/m}^3$ . Such changes in air density lead to the occurrence of the so-called thermal draft (buoyancy-driven pressure depression) in the ventilation duct. The draft is generated by a pressure difference ( $\Delta P$ ) and, in accordance with standards [13], can be calculated using the following expression:

$$\Delta P = C \cdot a \cdot h \left( \frac{1}{T_n} - \frac{1}{T_k} \right), Pa \quad (1)$$

where  $\Delta P$  – the pressure difference, Pa;  $C = 0.0342 \text{ K/m}$  – thermodynamic coefficient;  $a$  – atmospheric pressure, Pa;  $h$  – duct height, m;  $T_p$  and  $T_k$  – absolute temperatures relative to the duct (external and internal), K.

The evaluation showed that, for standard atmospheric pressure conditions ( $P_0 = 101,325 \text{ Pa}$ ),  $h = 10 \text{ m}$ , and  $C = 0,0342 \text{ K/m}$ , the calculated pressure depression  $\Delta P$  increases several-fold when the air in the duct is heated from 323 K to 373 K and the external air temperature in the quarry varies from  $-30^\circ\text{C}$  (243 K) to  $+50^\circ\text{C}$  (523 K). The calculation result is shown in Fig. 3.

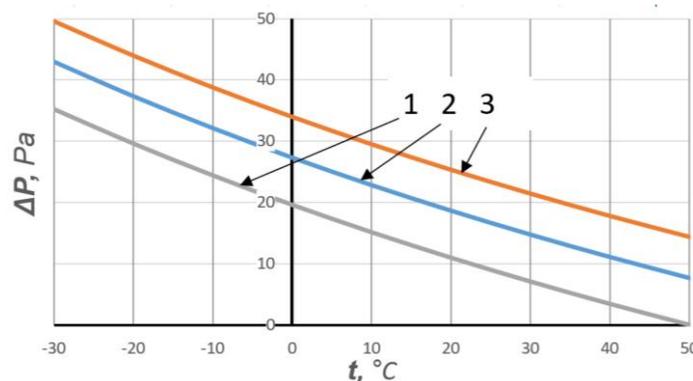


Fig. 3. Dependence of depression ( $\Delta P, \text{ Pa}$ ) in a ventilation pipe 10 m high on the temperature ( $t_n, ^\circ\text{C}$ ) of the external air in the quarry, under conditions of heating of the internal air to, K: 1-323; 2-348; 3-373

The calculations indicate that, over a wide range of quarry air temperatures  $t_p$ , a pressure depression much greater than  $\Delta P = 10 \text{ Pa}$  is achievable. The dominant factor affecting the depression magnitude is the temperature difference between the ambient environment and the air heated in the duct. As the ambient temperature increases, the depression decreases substantially. This means that, in summer, maintaining the draft requires intensive heating to a temperature several tens of degrees higher than the ambient. This requirement is not difficult to meet because solar radiation is highest in summer. A parabolic solar concentrator can heat the heater surface at the focus to several hundred degrees. For example, heliothermal installations are known where the temperature reaches about  $2000^\circ\text{C}$ , which are used in high-temperature processing of solid materials [14], as well as in metallurgy for melting metal scrap [15].

The presence of draft promotes the formation of an airflow ( $Q, m^3/s$ ) in the ventilation duct:

$$Q = C_T \cdot A \sqrt{2gh \frac{T_K - T_n}{T_n}}, m^3/s \quad (2)$$

where  $A$  – duct cross-sectional area,  $m^2$ ;  $C_T = 0.65-0.7$  – air-to-wall friction coefficient;  $g = 9.807 m/s^2$  – acceleration due to gravity;  $h$  – duct height,  $m$ ;  $T_n$  and  $T_K$  – absolute temperatures, external and average internal,  $K$ .

The results of the calculations show that the system can provide an airflow of more than  $Q = 3 m^3/s$  over a wide range of ambient temperatures when the gases in the duct are heated to  $320 K$  (about  $50^\circ C$ ) and the duct cross-sectional area is  $1 m^2$  with a height of  $10 m$  (Fig. 4). Increasing the duct cross-sectional area provides a proportional increase in airflow rate. Increasing the internal-air temperature also raises the ventilation flow rate up to  $15 m^3/s$  and, if required, to even higher values.

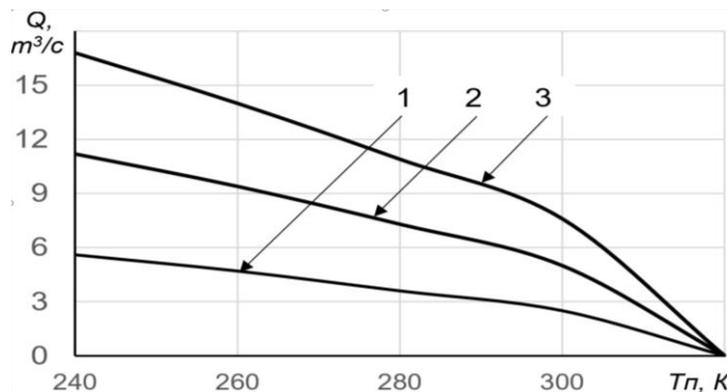


Fig. 4. Dependence of air supply ( $Q, m^3/s$ ) by the ventilation unit on the air temperature in the quarry ( $T_n, K$ ) when heating the internal air to  $T_K = 320 K$  in pipes with cross-sectional areas, respectively  $A=1, 2$  and  $3, m^2$

A substantial increase in the system airflow rate can be achieved by increasing the duct diameter or by installing two smaller-diameter ducts with heat exchangers in parallel.

Reducing gas contamination of air in working areas is achieved by avoiding engines that produce exhaust gases when consuming fossil fuels and replacing them with a solar thermal installation. An additional function of the localized ventilation system is to improve dust conditions in the quarry ecosystem. Incorporating a dust chamber into the system reduces the dust load at the quarry working levels.

Dust chambers operate on the principle of particle settling during slow movement of a dust–gas stream through a large cross-sectional working volume; therefore, the main chamber parameters are its height and length. The geometric dimensions determine the residence time of the dust–gas stream in the chamber and, accordingly, the cleaning efficiency. The dust chamber is used to capture rock particles generated during movement and excavation of blasted rock, loading onto vehicles, etc. Materials for manufacturing the chamber may include steel and wood [16].

The overall dimensions of the chamber required for settling solid particles from a gas stream are determined by the following formula:

$$L = H v_r / w_b \quad (3)$$

where  $L$  – is the chamber length,  $m$ ;  $H$  – is the chamber height,  $m$ ;  $v_r$  – is the gas velocity in the chamber (typically  $0.2...1.0 m/s$ );  $w_b$  – is the settling (terminal) velocity of particles of the specified size,  $m/s$ .

The settling (terminal) velocity of a solid particle in a gaseous medium is governed by gravitational settling, flow turbulence, drag, and several other forces. Depending on the particle diameter ( $d$ ) and the ratio of the rock density ( $\rho_t$ ) to the gas density ( $\rho_p$ ), taking into account the drag coefficient ( $\xi$ ), the settling velocity is determined by the following expression [17].

$$w_b = \sqrt{4gd(\rho_t - \rho_p) / (3\rho_p \xi)} \quad (4)$$

The calculation results (Fig. 5) show that, as dust particle size decreases, the settling velocity decreases linearly down to  $w_b \leq 4 m/s$ , which is characteristic of rock particles with  $d$  greater than  $0,0005 m$ .

For example, under conditions of  $v_r = 1.0 m/s$  and  $w_b = 4 m/s$ , the chamber length should be at least  $L = H \cdot v_r / w_b = H \cdot 1.0 / 4.0 = 0.25H$ . To settle particles smaller than  $d = 0.0005 m$ , the chamber length must be increased.

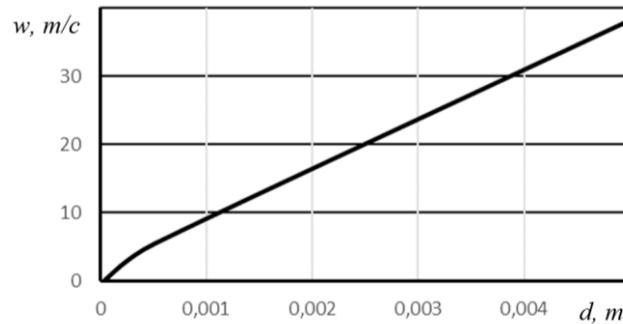


Fig. 5. Influence of the size ( $d, m$ ) of a dust particle on its settling velocity ( $w, m/s$ ) in a turbulent air flow

The chamber width is determined based on the airflow velocity adopted for the calculations, the chamber height, and the flow rate of dusty air.

$$B = Q/Hv_r \tag{5}$$

where  $Q$  – airflow rate,  $m^3/s$ .

To assess the dust-removal capability of the chamber, it is advisable to determine what particle sizes will be retained in it. Let us express  $v_r$  in terms of the gas flow rate  $Q$  by dividing  $Q$  by the duct cross-sectional area ( $H \cdot B$ ). Substituting the value of  $w_b$  from the formula, we obtain the minimum particle size  $d_q$  ( $m$ ) that will be completely settled in the chamber:

$$d_q = \sqrt{\frac{18\mu Q}{LBg\rho_p}} \tag{6}$$

where  $Q$  – gas flow rate,  $m^3/s$ ;  $L$  – chamber length,  $m$ ;  $B$  – chamber width,  $m$ ;  $\mu$  – dynamic viscosity,  $Pa \cdot s$ ;  $g$  – acceleration due to gravity,  $m/s^2$ ;  $\rho_p$  – particle density,  $kg/m^3$ .

Practical experience shows that in dust-settling chambers, dust particles larger than  $40\text{--}50 \mu m$  settle satisfactorily, while the gas-cleaning efficiency usually does not exceed  $40\text{--}50\%$ . The remaining smaller particles capable of remaining suspended are removed by the ventilation flow and dispersed in the upper air layers above the quarry (Fig. 6).

*Discussion of results.* The localized ventilation system operates in suction mode. It should be emphasized that its main purpose is to reduce the volume of the recirculation zone and remove the gases and dust contained in it. Using the system does not eliminate the need to apply dedicated dust-suppression measures at locations where pollutants are generated and accumulate.

When deciding whether to use a localized ventilation system, it is advisable to conduct a preliminary assessment of its capabilities. This can be done using approximate calculations with electronic ventilation calculators. For example, consider the proposed system type designed to provide a gas flow rate of  $Q = 5\text{--}12 m^3/s$  at a quarry air temperature of about  $20^\circ C$  ( $293 K$ ). As an initial estimate, select a duct height of  $10 m$ , a dust-settling chamber length of  $15 m$ , and an air-intake duct length of  $30 m$ . Thus, the total length of the air path is  $55 m$ . It has a cylindrical shape, an average diameter of  $2 m$ , and is made of galvanized sheet metal. Using the electronic calculator [5], we obtain the following indicators (Table 1).

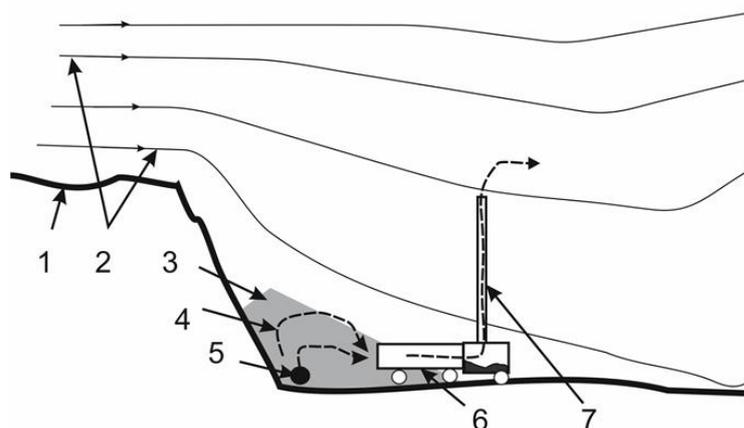


Fig. 6. Scheme of reducing air pollution zones in a quarry using a local ventilation system: 1-5 – as in Figure 1; 6 – movable air intake pipe; 7 – ventilation pipe

Table 1. Main aerodynamic parameters of the system

No	Airflow rate $Q, m^3/s$	Pressure loss $\Delta P, Pa$	Aerodynamic resistance, $R, Pa/m$	Flow velocity $v_r, m/s$
1	15	4.3	0.08	4.77
2	13.8	3.7	0.07	4.42
3	11.1	2.5	0.05	3.54
4	8.3	1.5	0.03	2.65
5	5.5	0.7	0.01	1.77
6	2.8	0.2	0.00..	0.88
7	1.4	0.1	0.00..	0.44

Based on the results, it can be preliminarily concluded that, under the specified conditions ( $T_n = 293 K$ ), the system can provide an airflow of about  $Q = 6-7 m^3/s$  (see rows 4 and 5 of Table 1 and curve 2 in Fig. 4). In this case, the flow velocity is  $v_r = 1.77-2.65 m/s$ , which exceeds the recommended level of up to  $1.0 m/s$ ; therefore, the height and width of the dust-settling chamber should be increased.

Design of localized ventilation systems requires, based on regulatory documents [18, 19], detailed calculations of the main technical characteristics of the duct sections comprising the system: the required gas flow rate, technological duct length and diameter, surface properties of the duct material, gas dynamic properties, local resistances, etc. The aerodynamic resistance and draft loss are evaluated for each duct section, along with the draft-source performance and the feasibility of achieving the required flow-rate targets.

#### 4. Conclusions

The study addresses the important problem of improving air conditions in deep quarries. A system is proposed that extracts gas- and dust-laden air from the working space, partially cleans it, and then disperses it outside the quarry.

For economic reasons, a localized ventilation system design is proposed that uses solar energy as the draft source. The system configuration and approximate parameters of its components (pressure depression, airflow rate, and flow velocity) are theoretically substantiated. An example of a preliminary system calculation is provided.

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