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Method for limiting the heating of air supplied to deep workings of coal mines

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Viktor Kostenko[1]; Iaroslav Liashok[2]; Olha Bohomaz[3]; Maryna Tavrel[4]; Tetiana Kostenko[5]*

[1] *Donetsk National Technical University, 9, Shevchenka Street, Drohobych, Lviv region, 82100, Ukraine; Technical University "Metinvest Polytechnic" LLC, 80, Pivdenne shose, Zaporizhzhya, Zaporizhzhia region, 69008, Ukraine. https://orcid.org/0000-0001-8439-6564*

[2] *Donetsk National Technical University, 9, Shevchenka Street, Drohobych, Lviv region, 82100, Ukraine. https://orcid.org/0000-0002-4302-6935*

[3] *Technical University "Metinvest Polytechnic" LLC, 80, Pivdenne shose, Zaporizhzhya, Zaporizhzhia region, 69008, Ukraine. https://orcid.org/0000-0002-8521-0394*

[4] *Technical University "Metinvest Polytechnic" LLC, 80, Pivdenne shose, Zaporizhzhya, Zaporizhzhia region, 69008, Ukraine. https://orcid.org/0000-0002-7666-4554*

[5] *National University of Civil Defence of Ukraine, 8, Onoprienka Street, Cherkasy, 18034, Ukraine. https://orcid.org/0000-0001-9426-8320*

Abstract

The purpose of this paper is to substantiate the arrangement of workings that supply cooled air to the faces based on an assessment of changes in the energy state of the rock mass under the influence of mining operations. The theoretical studies were carried out based on a systematic analysis of the fundamental equations of the classical theory of thermodynamics, taking into account experimental data on rock physics and geomechanical processes occurring during mining operations. This purpose was achieved by comparing the energy state (enthalpy) of rocks in the mass intact by mining operations and the mass formed in these rocks after coal seam extraction. The authors proposed the idea of transporting refrigerant in the form of cooled air through the workings arranged in the displaced rocks behind the longwall, which are relieved of rock pressure, degassed and cooled. This makes it possible to significantly reduce cold losses on the way to the miners' workplaces. The results of theoretical preliminary calculations confirm that the enthalpy of displaced rocks in the mined-out longwall space remains virtually unchanged regardless of the depth of mining. This confirms the validity of the idea of choosing the arrangement of the workings to save cold. The linear nature of the increase in the ratio of rock enthalpy in intact and cooled rock masses during the deepening of mining operations has been established, which proves the efficiency and prospects of the proposed method for large depths. A variant of coal seam preparation and mining is proposed to ensure the saving of the cold resource by arranging workings in displaced and cooled rocks.

Keywords:
mine workings; ventilation; energy state of rocks; thermodynamic factors

1. Introduction

The extraction of coal seams is associated with an inevitable increase in the depth of the workings. At the beginning of the XXI century, mine workings in Ukrainian coal deposits reached depths of 1,200 to 1,500 metres. In such conditions, the temperature of the rock mass reaches 40 to 50°C. In the future, the development of strata over 2,000 m where the temperature exceeds 70°C is planned.

The length of the ventilation routes from the surface to the workings is often several kilometres, and when fresh air moves through them, it warms up to a temperature close to that of the rock mass. This significantly complicates the work of the Ukrainian miners at the workplaces where the permitted air temperature should not exceed 26°C. The installation and use of various types of cooling equipment involves multimillion expenditures, and the money spent on air conditioning increases the cost of coal production and reduces the competitiveness of coal mining companies. The challenges of ensuring safe and comfortable working conditions at the miners' workplaces remain acute in the development of deep strata.

With mining operations moving to depths of more than 1,000 metres, the underground environment has become more extreme, as the temperature and humidity levels have increased due to high heat generation from the rock mass and from the mine electrical and diesel equipment. Furthermore, the increased depth resulted in additional heat being transferred to the ventilation air by air autocompression, coal self-heating and other heating sources (**Greth et al., 2017; Kuyuk et al., 2020**).

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* Corresponding author: Tetiana Kostenko
e-mail address: tatiana.kostenko@gmail.com

Abnormal microclimatic conditions not only directly affect the health of the miners underground, but also cause a decrease in perception, concentration, attention, and performance (**Nehrii et al., 2022; Cheberiachko et al., 2018**). This negative impact of temperature and humidity on the human body is called climatic hazard (**Szlązak et al., 2018**).

Studies have shown that the temperature of underground air has become the main factor affecting the safety of the miners, with humidity and air velocity being added to it. The recommended air velocity is 2 m/s, and the maximum wet-bulb temperature is 28°C for a 6-hour work shift and 26°C for an 8-hour work shift. It is difficult to ensure such conditions; a survey conducted in six Polish coal mines showed that, despite the introduction of group and central air conditioning systems, the permissible air temperature of 28°C was exceeded (**Qiaoyun et al., 2023**). Similar data were obtained in Chinese mines (**Han et al., 2023**).

In practice, many different systems and schemes are used to provide the miners' workplaces with cooled air. Each ventilation system has its own important elements, such as different branches of the system, ventilation regulators and fans. There is a study (**Zeqiri et al., 2022**), in which, based on a professional approach to the analysis of aeration systems, a comparison of reliable results was made, which indicates the real state of the microclimate in underground mines, which affects the increase in the prospects for the development of the mining industry.

Other studies focus on the possibility of using air conditioning and ensuring the safety and health of the miners. The result of the work suggests that portable air conditioners should be used during preparatory work. The study is aimed at ensuring the highest possible safety and health during the miners' operations, especially the proper dilution of mine gases, achieving optimal temperature and dust content (**Vrtalova et al., 2023**). When cooling premises of limited volume, it is recommended to use cryogenic systems (**Yan et al., 2020**) or to limit the number of personnel (**Jin et al., 2024**).

In general, there are two common underground cooling strategies. The first is the use of mine ventilation and the cooling effect of airflow, and the second is the use of refrigeration to provide workplaces with a low-temperature environment (**Kamyar et al., 2016**).

The known surface air-cooling systems, underground air-cooling systems with a surface refrigeration unit, and underground air-cooling systems with an underground refrigeration unit are widely used mine air-cooling systems.

The concepts of underground air-cooling systems with chilled water transported through insulated pipework to the boreholes, the use of ice slurry instead of chilled water to reduce pumping consumption and cost, vortex tubes that use compressed air to cool sensitive machine components, and mobile spot coolers are all considered. The role of air monitoring and control systems for the efficient operation of the miners is discussed (**Sridharan et al., 2019**). European mines often use central air conditioning in mines with cooling stations on the surface and transportation of cooling energy to underground heat exchangers (**Szlązak et al., 2009**). Cooling of mine air by horizontal volumetric air conditioners with direct spray cooling systems is considered to be quite effective due to their high performance. This type of installation can be converted into a natural cooling/heating process by re-emerging warm sprayed water from the underground air cooler to the heaters to heat the mine air on the surface and re-immersing the cooled water into underground mass air coolers (**Szlązak et al., 2018**).

Underground air cooling is used by spraying chilled water on the shearer and other sources of high temperature. Mobile medium-sized air coolers, spot coolers, underground air cooling and the use of chilled water are widely used to increase the positional efficiency of the cooling plant. The introduction of 'group' and 'central' air conditioning systems is economically feasible when significant cooling capacities are required in different areas of the mine, and it is not possible to transfer condensation heat to local return air flows. The main reasons for the low cooling parameters are the impossibility of installing air coolers in places where the air temperature is the highest and the unsatisfactory properties of the supplied water (low flow rate and excessive temperature) (**Belle and Biffi, 2018**).

Water is usually used as a refrigerant in mine air conditioners, as it has a significant heat capacity. Water is used in horizontal volumetric air conditioners with direct spray cooling systems due to their high performance. In a 1,118-metre-deep gold mine, low-temperature water stored at a depth of 640 m was used as a cooling source. The effective air flow rate in the workings was 3.0 m^3/s, the temperature at the workplaces was reduced by 5 to 6°C and amounted to 27.6°C, and the relative humidity was reduced to 76% (**Guo et al., 2013**). It was advisable to use the return air of the deep mine as a refrigerant for the cooling system (**Nie et al., 2018**).

The capacity of mine air conditioning units is considerable, which leads to high financial costs. When designing a central method of air conditioning in mines with cooling stations on the ground surface and transporting cooling energy to underground heat exchangers, the heat load is more than 4 MW (**Szlązak et al., 2009**).

Cooling by medium-sized mobile air coolers, spot coolers, underground air cooling, and the use of chilled water to increase the positional efficiency of the cooling plant assumes an integrated capacity of these systems in the range of 6 to 10 MW of cooling capacity (**Belle and Biffi, 2018**).

The surge in electricity prices is forcing companies to look for energy management strategies to correct the inefficiencies of current cooling systems or reduce excessive electricity consumption.

The situation can be improved by introducing new monitoring systems. Implementing management strategies to generate cooling by recovering thermal energy from available resources and improving the performance of current cooling are the main ways to achieve savings (**Guo et al., 2013**). There is a well-known example when, by monitoring the amount of water, water temperature in the cooling system, and air temperature, thermodynamic equilibrium parameters were achieved in the analysis of cooling energy production and cold distribution, which resulted in a reduction in the temperature and humidity at the workplaces by 8 to 12˚C and 8 to 15%, respectively (**Nie et al., 2018**).

The generalisation of information on the thermal situation in deep workings at different types of deposits has confirmed the increase in climatic hazard in all mining regions. The main way to overcome thermal hazards at the workplaces is to use various types of local air conditioning systems. Promising ways to improve the efficiency of air conditioning are to increase the efficiency of the units and improve ventilation networks. The use of all technical solutions for mine air conditioning is associated with the complexity of mining operations and the high cost of the process of artificial cooling of the refrigerant. Supplying refrigerants over long distances causes significant cold losses, which leads to a huge increase in air conditioning costs. The above causes the need to find a qualitatively different way to ensure the standard air temperature at the miners' workplaces.

The authors put forward a working hypothesis about the need to justify the possibility of reducing the cost of air conditioning of the mine atmosphere by limiting its heating on the way to the workings by arranging workings with fresh air in previously cooled parts of the mine rock space.

The purpose of the paper is to substantiate the arrangement of workings that supply cooled air to the faces based on an assessment of changes in the energy state of the rock mass under the influence of mining operations.

2. Methods

The theoretical studies were carried out based on a systematic analysis of the fundamental equations of the classical theory of thermodynamics, taking into account experimental data on rock physics and geomechanical processes occurring during mining operations. This purpose was achieved by comparing the energy state (enthalpy) of rocks in the intact mass by mining operations and the mass formed in these rocks after coal seam extraction.

Objective.

- To estimate the energy state of rocks in the intact mass;
- To present the changes in the main thermodynamic factors of rocks in the process of coal seam extraction;
- To evaluate the energy state of the rock mass as a result of extraction;
- To justify the rational arrangement of mine workings for fresh air supply.

3. Results and discussion

This study was motivated by the results of research on the stability of mine workings behind the face in the collapsed rocks of the coal seam roof, known since the mid-twentieth century (**Zborshchyk, 1978**). The researchers focused on reducing the stress-strain state of such rocks in terms of conducting and maintaining development workings. Thermal assessments of such working arrangements were not an issue at that time because the mining depths in Donbas were only approaching the 1,000 m mark.

This method of protecting preparatory workings from mining pressure is considered by modern researchers as promising for various conditions of the development of layered rocks (**Nehrii et al., 2018; Wang et al., 2020; Nehrii et al., 2020**).

As a typical example, we should cite the ventilation drift of the 15th western panel at the Abakumov mine in the city of Donetsk, Ukraine, which was carried out at the level of the immediate sole of the formation by blasting at a depth of 720 m (**Nazimko, 2024**). The thickness of such removed layer was 1.6 m, the method of managing the roof was complete collapse. The stretch had a cross-sectional area of 11 m^2 and was secured by steel arches with an installation step of 0.8 m. The distance between the ventilation drift and the boundary of the created space was from 7 to 34 m (see **Figure 1**).

In this paper, we consider the energy states of an arbitrary virtual fragment (V_m) of a rock mass as an open thermodynamic system, which was initially in its primary (intact) state, and then in the situation after the seam was extracted.

3.1. Initial energy state of rocks

A rock mass found at a certain depth is considered as a set of solid porous substance compressed by the all-round pressure, which contains fluids, primarily methane and water. No movement occurs in such a mass, so there is no kinetic energy in such an environment. Instead, the rock pressure is a manifestation of potential energy, and the temperature is a manifestation of internal energy.

At a depth of H, (m), such a system, due to the action of rock pressure, is in a compressed state and occupies a volume of V_m (m^3). Compression is determined by gravitational forces, its value is:

$$P_m=\rho_m \cdot g \cdot H, (Pa) \tag{1}$$

where ρ_m is the density of the mass, kg/m^3; g is the acceleration of free fall, m/s^2.

The temperature of rocks in the entire volume V_m is equal to that inherent in this depth T_m, (K). Methane plays the main role among the fluids contained in the sedimentary rock mass. Sedimentary rocks contain various fluids in a liquid or gaseous state. Their presence or

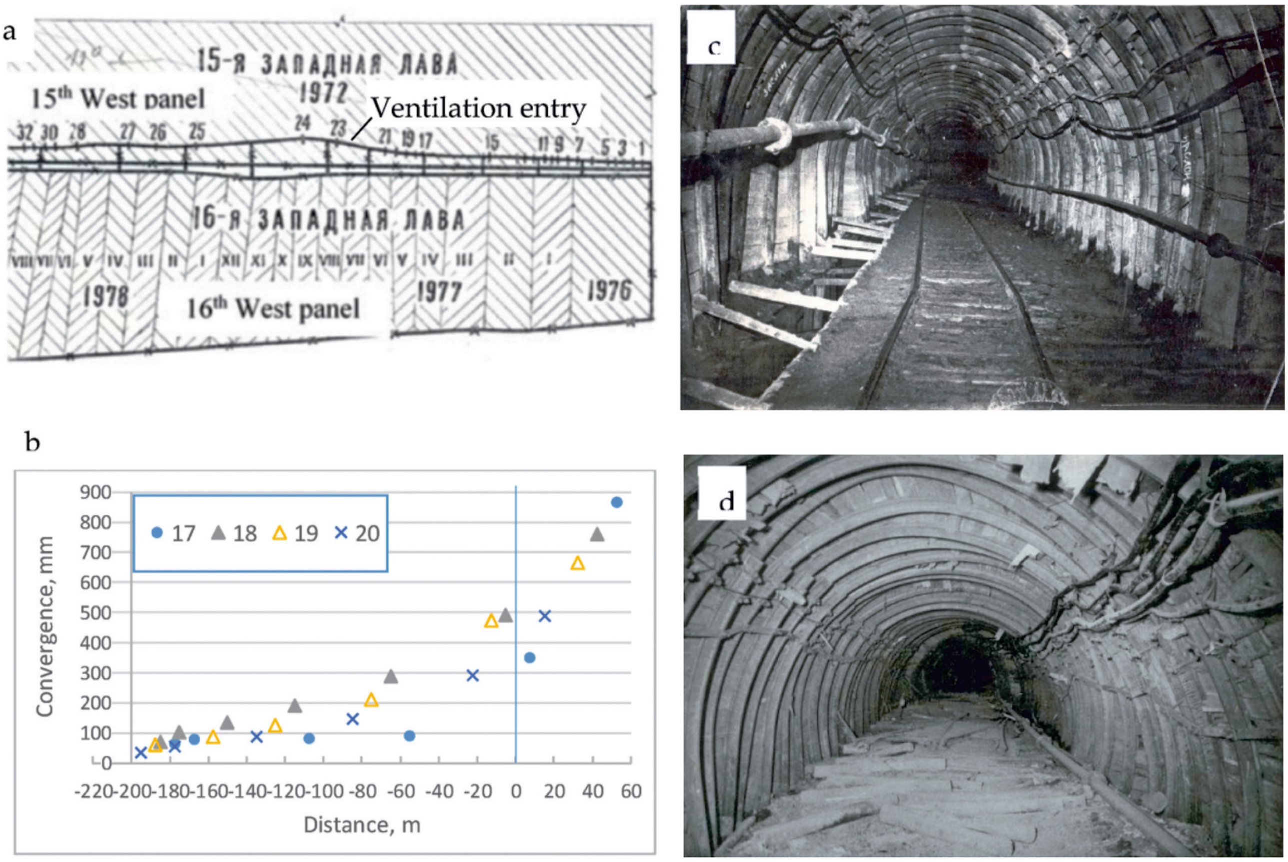

Figure 1: Monitoring the stability of the ventilation shaft in the Abakumov mine in the city of Donetsk, Ukraine (**Nazimko, 2024**): a – mine map fragment; b – convergence of roof and sole; c – before the development of the 16th western panel; d – after the development.

absence has a significant impact on the mechanical and thermodynamic properties of the rock. For example, the striking difference in fragility, thermal conductivity, density and other indicators of dry and wet clay. Changes in the properties of sedimentary rocks are influenced not only by the size of fluid molecules, but also by sorption, electrical, and other parameters. For each type of rock, an individual evaluation of the interaction with fluids is necessary.

The most common type of fluids in the Donetsk coal basin is methane, therefore, this article considers its influence on the main types of rocks that make up the mountain range. The gas is found in a compressed state in voids, in a sorbed form on the walls of solid particles and cavities, and as a component of organic macromolecules of coal and rocks. The layers of gas sorbed on the surfaces of the solid medium act as a lubricant, reducing friction between sedimentary rock particles and contributing to their all-round compression. This confirms the validity of the hypothesis about the close-to-hydrostatic nature of mining pressure in gas-bearing masses (**Antoshchenko et al., 2013**).

It is difficult to estimate the amount of gas sorbed on the surface of solid rock particles due to the lack of data on the indicators that characterise sorption processes in compressed rocks. There is also no way to reliably estimate the amount of methane dissolved or chemically bound to the organic components of the rock mass. We can rely on the indicators of total gas emission from coal and rocks obtained during geological analyses during field exploration q_g, (m^3/m^3). For sedimentary rocks such as shales and sandstones for coal deposits, this figure is q_g=0…15, m^3/m^3, sometimes more. The temperature of methane is equal to the temperature of rocks at a given depth T_m, (K).

The potential energy concentrated in the solid component of the fragment is due to gravitational forces acting in the volume:

$$E_{mp}=V_m \cdot \rho_m \cdot g \cdot H, \ (J) \tag{2}$$

The internal energy of the system in the intact mass E_{mk} consists of the internal energy of the solid part E_{mm} together with the gas chemically bound to organic matter and sorbed on the pore surfaces, as well as the energy of the gas compressed in the voids E_{ms}. The relative internal energy of the solid part of the system can be calculated based on its temperature:

$$E_{mm}=\rho_m \cdot V_m \cdot c_m \cdot T_m, \ (J) \tag{3}$$

where: c_m is the heat capacity of the mass rocks, $J/(kg \cdot K)$; T_m is the temperature of the rocks, K.

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Let's assume that the pressure of methane compressed in pores does not exceed the mechanical component of the rock pressure $P_{ms}=P_m$. The volume of compressed gas is equal to the volume of pores $V_{mr}=\kappa_{pm}\cdot V_{m,}$ where: κ_{pm} is the porosity coefficient.

Based on thermodynamics, for multi-atomic gases, namely CH_4, the value of the internal energy of the compressed gas in the system will be

$$E_{ms}=3\cdot P_{ms}V_{mr}=3\cdot V_m\cdot \kappa_{pm}\cdot g\cdot H\cdot \rho_{m,}\ (J) \qquad (4)$$

Thus, the enthalpy of a fragment of the intact mass can be estimated:

$$\begin{aligned} E_{mk} &= E_{mp} + E_{mm} + E_{ms} = \\ &= V_m\cdot \rho_m\cdot g\cdot H + \rho_m\cdot V_m\cdot c_m\cdot T_m + 3\cdot V_m\cdot \kappa_{pm}\cdot g\cdot H\cdot \rho_m = \\ &= \rho_m V_m\,[(g\cdot H + c_m\cdot T_m) + 3\cdot \kappa_{pm}\cdot g\cdot H] \qquad (5)\end{aligned}$$

The enthalpy component related to potential energy (E_{mp}) characterises the stability of mine workings carried out in such a mass, and the thermodynamic component ($E_{mm}+E_{ms}$) characterises the heat exchange between the mass and the air moving in these workings.

3.2. Change in the main thermodynamic parameters of rocks after coal seam extraction

As it is known from the modern concepts of geomechanical processes that occur during coal seam extraction, a part of the rocks of the immediate and main roof of the seam is separated from the rest of the mass and forms the so-called vault of completely displaced rocks (see **Figure 2**). The vault of completely displaced rocks is composed of collapsed layers of the immediate roof of the coal seam, as well as settled rocks of the main roof. The main driving force forming the vault is gravity, which is counteracted by the stiffness of the rock layers.

The size of the collapse step of the immediate roof is determined not only by the physical and mechanical properties and strength of its layer, but also by the magnitude and mode of loading and unloading and the magnitude of the fastening resistance in the extractive mine. This affects the structural characteristics of the crushed layer that is formed on the immediate sole after the excavation of the formation.

In the conditions of mining gently sloping formations of Donbas, the shape of the vault is similar to a trapezoid, its height *h, (m)* is approximately equal to the length of the working face *l, (m)* and is much less than the depth *H* (**Zborshchyk, 1978**). The depth of extraction *H* and the height of the vault *h* are in the ratio $h/H=\kappa_r$, hence $h=H\kappa_r$. The base of the trapezoid is a fractured rock environment with a thickness of 6 to 12 times the thickness of the spent seam. These rocks are almost completely degassed and cooled to a temperature close to the temperature of the ventilation air (**Antoshchenko et al., 2013**). A small part of the rocks at the bottom of the seam is also degassed and cooled.

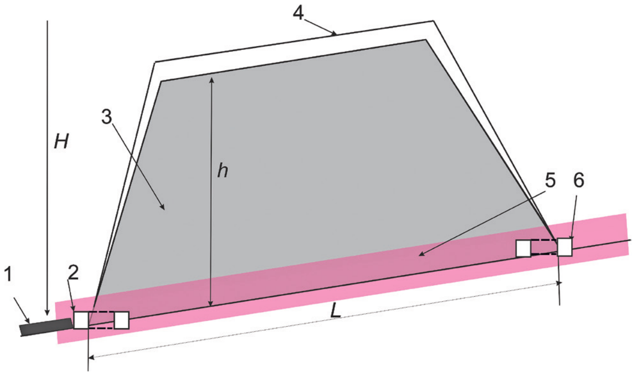

Figure 2: Scheme of the formation of a vault of completely displaced rocks (from **Zborshchyk, 1978**) and areas of degassed and cooled rocks: 1 – coal seam; 2, 6 – coal headings; 3 – vault of displaced rocks; 4 – rock mass; 5 – area of cooled and degassed rocks; *H* – depth to the surface; *h* – height of the vault; *l* – length of the working face.

Deformation mainly occurs through the mutual movement of particles that form sedimentary rocks, an increase in the size of natural fractures and pores, the emergence of fresh fractures caused by mining pressure, and increased stratification of rock layers. Among the types of deformation that have occurred, quasi-elastic and brittle (fracture) deformations prevail, while others are of a much smaller scale and can be neglected at the first stage of analysis. As a result of fracture formation, the conditions for diffuse and filtration fluid movements are improved many times over. This releases the gas trapped in the pores, desorbs methane from surfaces that change the shape and size, and breaks chemical bonds in organic macromolecules with the release of methane, hydrogen and other gases. In the areas of rock close to the faces and development workings, there is close to complete degassing ($q_g\approx 0$) and gradual replacement of compressed methane with air at atmospheric pressure in open voids. A significant proportion of methane enters mine workings where it is diluted with air to a safe level and released to the surface with the outgoing ventilation stream, and part of the methane is removed using degassing systems.

The extraction of a coal seam consumes electrical energy, mainly due to the supply to the mining site and further conversion into mechanical energy, and the miners' muscular energy. Furthermore, the thermal energy of the ventilation air flow is supplied to the faces, and the air flow heated from the rocks with the addition of methane is removed. These types of energy are used to break coal and rocks, move solid, liquid and gaseous components in the system under consideration and beyond. Thus, the ventilation stream heats up when it interacts with hot rocks and a significant proportion of thermal energy is carried outside the system in the form of a heated mixture of air and methane, while a part of the rock mass cools down to a level close to the air temperature in the face T_v *(K)*. It is important to note that the cooled part of the rock environment (see **Figure 1**) can be considered suitable for the arrangement of workings intended for air supply to the working faces. In this case, the heat exchange of fresh air supplied to the drifting and mining faces with the walls of the workings will be negligible, and, accordingly, the loss of cold potential will be significantly lower.

The removal of fluids from the rocks and depressurisation lead to certain irreversible changes in the physical parameters that characterise the resulting rock environment. The value of the established indicators is determined in laboratory conditions when testing depressurised, degassed and cooled rock samples. The following physical and mechanical indicators are assessed in laboratories: elastic modulus (E_o, *Pa*), transverse strain coefficient (μ_o), density (ρ_o, kg/m^3), porosity coefficient (κ_{po}), as well as thermal indicators: linear thermal increase coefficient (α_o, *1/K*), heat capacity (c_o, $J/(kg{\cdot}K)$), associated thermal conductivity (λ_o, m^2/s), etc.

Thanks to the knowledge accumulated in modern rock physics, it is possible to estimate similar indicators for the intact mass in an indirect way. This is difficult for the subsoil in which fluids are concentrated, but it is possible to determine a qualitative trend and sometimes an approximate numerical estimate of changes relative to laboratory data.

The density of degassed rocks is determined mainly by the loss of methane, so depressurised rocks or samples of them with pores filled with air (ρ_o) are tested in laboratories. Based on this, the initial density of the mass rocks can be determined:

$$\rho_m = \rho_o + \rho_{сн4} \cdot q_{g,}\ (kg/m^3) \qquad (6)$$

where:

ρ_o = 2,500 is the density of sedimentary rocks established in laboratory conditions, kg/m^3;

$\rho_{сн4}$ = 0.714 is the methane density under normal conditions, kg/m^3;

q_g = (0…15), m^3/m^3 is the gas emission from sedimentary rocks, established during the field exploration, m^3/m^3.

This research examines the process of the degassing of sedimentary rocks that make up the coal-bearing stratum. The methane content in the rocks is an order of magnitude lower than in the coal seam, which is due to the significantly lower content of the organic component in the mudstones, siltstones, and sandstones that make up the coal-bearing layer in the Donetsk coal basin. During the degassing of sedimentary rocks, their shrinkage was not registered.

Calculations have shown that degassing leads to a decrease in rock density of no more than 1 to 1.5% and can be neglected, hereinafter we denote the density as ρ.

In the process of depressurising rocks under the influence of loosening mechanical stresses, the internal bonds between rock particles decrease. Friction, grain adhesion, and rock strength are significantly reduced, elasticity and brittleness parameters are reduced, and rock crushability is increased. In the study of solid samples, the porosity of depressurised and degassed rocks is measured, e.g. for sandstones, this indicator, according to literature reports, is κ_{po} = 0.67…6.7%.

Compaction occurs under the influence of hydrostatic pressure, resulting in deformations in rocks, which lead to a decrease in porosity; depending on the nature of the rock compaction pressure, it is the closure of pores and an increase in the contact area of grains. With compaction, the cross-sectional areas through which pressure and energy are transferred increase, and therefore the strength, elastic properties, thermal conductivity, etc. also increase. The decrease in porosity in the mass depends on the pressure, so it is approximately:

$$\kappa_{pm} = \kappa_{po} \cdot h/H = \kappa_{po} \cdot \kappa_r \qquad (7)$$

Due to the decrease in the level of rock pressure in the vault from $P_m = H \cdot g \cdot \rho_o$ to $P_a = h \cdot g \cdot \rho_o = H \cdot \kappa_r \cdot g \cdot \rho_o$, the rocks are depressurised, which leads to an increase in volume from V_m to V_o. In the case of the volumetric stress state of the rock, the relationship between the depressurising of P_m-P_o and the relative change in volume DV is expressed through the modulus of all-round compression K_m, which can be calculated by the formula (**Zhdanova et al., 2012**).

$$K_m = E_m/[3(1-2\mu_m)] \qquad (8)$$

where E_m, μ_m are the elastic modulus and transverse strain coefficient of the rock in the intact mass, respectively.

The relative increase in volume after complete (close to zero) depressurising can be estimated by taking into account the volumetric modulus of elasticity of rocks K_m:

$$DV = P_m/K_m = 3 \cdot H \cdot g \cdot \rho\ (1-2 \cdot \mu_m)/E_m \qquad (9)$$

Thus, for an extreme depth of H=3,000 *m*, and the sandstone elastic modulus E_m=10^{10} *Pa* and μ_m=0.45, the volume increase is only DV=0.002205. Based on this, assuming as a first approximation that the volume of the intact medium is close to a perfectly elastic body, it is possible to calculate the ratio of volumes before V_m and after V_o depressurising:

$$V_o = V_m + V_m \cdot DV = V_m(1+DV) \qquad (10)$$

It is customary to accept based on the results of the calculation: $V_m \approx V_o$, further – V.

Depressurising and degassing contribute to an increase in the cavity component of the rock volume. The value of V_{ro} can be determined by taking into account the porosity of the rock in the κ_{po} sample studied in the laboratory (**Suyarka, 2019**). It should be noted that the porosity measured in the laboratory for depressurised and degassed rock samples is significantly higher than that established in the subsurface. Linear deformations of sedimentary rock-forming minerals are relatively small, and a significant part of the increase in volume is due to the increase in fractures between pieces of fractured rock rather than empty space. It should be noted that a significant proportion of fractures appear under the influence of mining operations, so they are automatically excluded in laboratory tests of solid samples, which allows us to assume:

$$V_{rm} \approx V_{ro} \cdot \kappa_{pm} \quad (11)$$

The removal of the main fluids present in the mass (methane and water) leads to an increase in the cavity and changes in the physical and mechanical properties of rocks, such as the linear (E) and volumetric (K) elastic moduli and the transverse strain coefficient (μ) (**Yalanskyi et al., 2014**). The degassing and drying of rocks is the reverse process of their saturation with fluids, which allows us to analyse the nature of the transformations of rocks that were under the influence of mining.

It is known that when sandstones are saturated with water, the compressive strength decreases almost twice, the elastic modulus decreases four times, and the transverse strain coefficient increases 2.3 times (**Liashok et al., 2020**); when the rock is dried, the reverse process is observed. In the future, we choose an increase in the transverse strain coefficient in the middle of the specified interval:

$$\mu_m = 1.5\ \mu_{o.} \quad (12)$$

Since the closure of pores and the accompanying increase in the number and area of grain contacts during compression are mainly completed at a pressure of 50 to 100 *MPa*, the most significant increase (up to three times) in the elastic modulus of most rocks is observed up to these pressure levels, i.e.:

$$E_m = (1.5\ldots3)\ E_o \quad (13)$$

In the vault of complete displacement, the processes inverse to the saturation of the rock with fluids occur, and a number of related thermodynamic parameters change along with physical and mechanical ones: heat capacity (c), thermal conductivity (λ), thermal conductivity (a), etc. It is known that the moistening of porous rocks leads to an increase in their thermal conductivity. Thus, the thermal conductivity of clay saturated with water is 6 to 8 times higher than that of dry clay (**Mala hirnycha entsyklopediya, 2013**). The specific heat capacity increases with decreasing rock density and increases with increasing temperature and humidity within 0.4 to 2, *kJ/(kg·K)*, thus we **accept:**

$$c_o = c_m / \kappa_r \quad (14)$$

The rocks are cooled by the ventilation flow, and the rock temperature approaches the air temperature in the face T_v.

3.3. Energy state of rocks after the coal seam extraction

Let's consider the energy processes that occur in the rock mass under the influence of mining operations. They are influenced by many factors that cannot be reliably taken into account, so the assessment of energy changes is carried out tentatively to establish the main patterns or trends in order to use them to achieve the purpose.

In the mass underworked by mining operations at the depth of the bottom of the vault of complete displacements *h, (m)*, the value of geostatic compression is:

$$P_o = \rho \cdot g \cdot h,\ (Pa) \quad (15)$$

where: ρ is the density of the substance in the degassed underworked mass, kg/m^3; g is the acceleration of free fall, m/s^2.

The system under consideration is in the depressurised state and occupies a volume of $V,\ (m^3)$.

The potential energy concentrated in the depressurised and degassed solid is due to the gravitational forces acting in the volume:

$$E_{po} = \rho \cdot V \cdot g \cdot h,\ (J) \quad (16)$$

The relative internal energy of the degassed and cooled solid component of the system can be calculated based on its temperature:

$$E_{to} = \rho \cdot V \cdot c_o \cdot T_v \quad (17)$$

where: c_o is the heat capacity of the degassed and cooled mass, *J/(kg·K)*, T_v is the temperature of rocks in such a mass, close to the temperature of the air supplied to the face, *K*.

The enthalpy (total internal energy) of the depressurised and degassed mass is:

$$E_{mo} = E_{po\,+}\, E_{to} = \rho \cdot V \cdot g \cdot h + \rho \cdot V \cdot c_o \cdot T_v =$$
$$\rho \cdot V (g \cdot H \cdot \kappa_r + c_o \cdot T_v) \quad (18)$$

Guided by the above data on the ratio of physical characteristics of rocks in the mass and in samples, we transform the terms of the equation of the total enthalpy of the system in the intact mass into derivatives from the results of laboratory tests of rock samples:

$$E_m = \rho \cdot V\,[(g \cdot H + c_m \cdot T_m) + 3 \cdot \kappa_{pm} \cdot g \cdot H] =$$
$$= \rho \cdot V[(g \cdot H + c_m \cdot T_m) + 3 \cdot \kappa_{pm} \cdot g \cdot H] =$$
$$= \rho \cdot V\,[(g \cdot H + T_m \cdot c_o / \kappa_r) + 3\ g \cdot H \cdot \kappa_r \cdot \kappa_{po}] \quad (19)$$

Considering the geological and technological conditions inherent in the Donetsk coal basin, the ratio of enthalpies (E_m/E_{mo}) of the rock in intact and underworked rock masses was estimated. The calculations were performed for a depth range of 1,000 to 3,000 *m*, the height of the vault of total displacements is h=200 *m*; the rock elastic modulus $E_o = 10 \cdot 10^9$ *Pa*; transverse strain coefficient $\mu_o = 0.3$; porosity coefficient $\kappa_{po} = 2.0\%$; heat capacity $c_o = 0.8.103$ *J/(kg-K)*; fresh air temperature $T_v = 295$ *K*, and the temperature of the rock mass is proportional to the depth, from 310 to 365 *K*. The results of the comparison are shown in **Table 1** and **Figure 3**.

Table 1: Effect of depth on the change in the relative enthalpy of the intact and depressurised and cooled rock mass

Depth *H, m*	$E_m/(\rho\ V)$, *J/kg*	$E_{mo}/(\rho\ V)$, *J/kg*
1,000	1,250.976	237.960
1,500	1,954.308	237.911
2,000	2,740.776	237.960
2,500	4,268.100	237.960
3,000	4,424.242	237.940

As can be seen from **Table 1**, an increase in the depth of deposit development leads to an increase in the enthalpy of the rock mass in which mining operations are carried out. With the deepening of the workings from 1 to 3 *km*, the $E_m/\rho V$, *J/kg* increases by more than 3.5 times both under the influence of mining pressure and with an increase in the temperature of the rock mass.

On the contrary, due to depressurising, degassing and cooling of rocks in the vault, the level of relative enthalpy $E_{mo}/\rho\ V$, *J/kg* remains practically unchanged over the entire depth range from 1 to 3 *km*.

The plot of the enthalpy ratio E_m/E_{mo} with increasing depth *H* has a linear form (see **Figure 2**). This illustrates the possibility of a significant reduction in the consumption of resources for cooling the air transported through the workings to the faces.

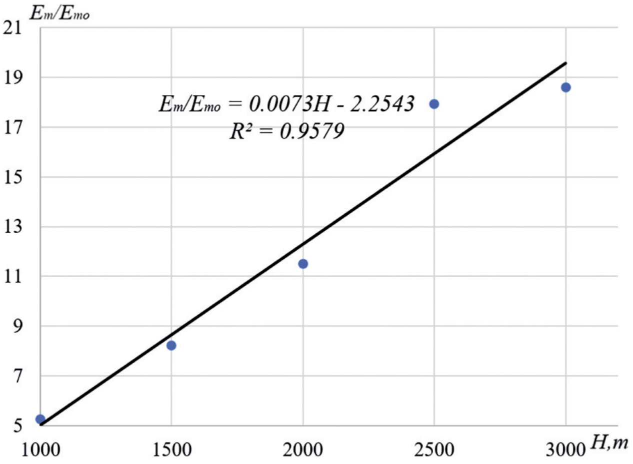

Figure 3: Dependence of the ratio of rock enthalpy in intact (E_m) and depressurised, degassed and cooled (E_{mo}) rock masses on the depth (*H, m*) of coal seam development.

The obtained theoretical results are of great practical importance. They substantiate the possibility of increasing the efficiency of air conditioning in deep mines due to a qualitatively new approach, namely, the arrangement of such air supply workings behind the longwall in the cooled and degassed displaced rocks of the immediate roof and the bottom of the seam. The refrigerant, in the form of cooled air, can be transported through such lines with minimal cold losses. These conclusions are valid for other types of refrigerants, such as liquid and solid (e.g. ice).

A weakness in the studies is the insufficiently substantiated and inaccurate data on changes in rock properties at deep strata. The trend is predicted correctly, and the theoretical calculations are qualitatively correct, but the numerical values require further study and refinement. Furthermore, it is advisable to consider the peculiarities of geomechanical processes occurring in the underworked rock mass during the development of extraction operations within the mine seam in the future (**Nazimko et al., 2021**).

The conducted research made it possible to scientifically substantiate the parameters of the location of the mine workings for supplying fresh cooled air to the mining face. It has been established theoretically and partly practically that degassed rocks at the level of the spent coal seam have low heat capacity and thermal conductivity. In addition, as a result of the preliminary excavation of the formation, these rocks are cooled to the state of the temperature of the ventilation flow. **Figure 3** shows a version of the improved scheme of preparation and system of reservoir development at great depths. It differs in that the preparatory mine workings, which are intended for supplying air to the mining face, are located within the cooled rocks in the vault of the completely shifted roof massif. This makes it possible to reduce the heat exchange between the cooled mountain massif and the ventilation flow and bring air with a reduced temperature to the mining faces. A promising variant of the system for the preparation and development of reservoir mineral deposits is shown in **Figure 4**. The seam was

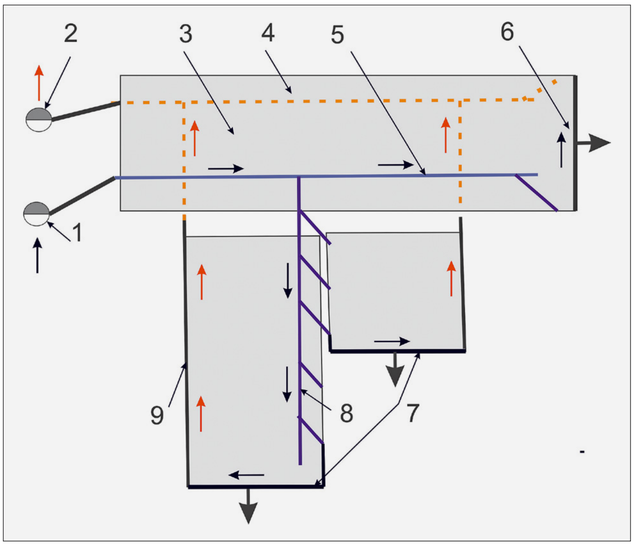

Figure 4: Scheme of preparation and seam development system at great depths: 1, 2 – air supply and ventilation shafts, respectively; 3 – mined-out space of the bedrock; 4, 5 – ventilation and main drifts, respectively; 6, 7 – bedrock and sectional working faces, respectively; 8, 9 – air supply and ventilation passages, respectively; arrows: blue – cold, red – warm air; workings: solid – at the seam level, dashed – field.

opened by means of shafts 1 and 2 with cross-drifts. The first of them is designed to supply fresh air, the other is a ventilation shaft. The shaft supplying air is equipped with an air-cooling unit, which is not shown in Figure 3 for clarity. In the initial period, coal is extracted in the so-called 'bedrock' using air cooling equipment. Given the small size of the mine workings, the capacity of the cooling unit is relatively moderate. As the face of the bedrock moves away from the face entry, working space 3 is formed, in which a degassed, depressurised and cooled area is formed (see **Figure 2**). It is suitable for the arrangement of main ventilation drift 4 and air supply drift 5. They supply air to the faces of bedrock 6 and, subsequently, to sectional longwalls 7. It is also advisable to arrange sectional air supply 8 and ventilation 9 workings in the cooled area in the mined-out space, which provides additional conditioning effect.

In this way, the purpose of the work is achieved, namely: based on theoretical studies, an estimate of the decrease in the energy state of the rock space in the mine heading affected by the mining was obtained. This made it possible to justify the arrangement of rational, from the point of view of conditioning, flushing of workings that supply refrigerants to the faces.

4. Conclusions

Further deepening of underground operations is associated with an increase in the temperature of the rock mass and the threat of a climatic catastrophe for the miners.

The known modern developments in the field of mine air conditioning are mainly aimed at improving the means of cooling air at the workplaces and rational distribution of cold resources through the workings. Such an approach implies a huge increase in air conditioning costs in the future due to significant cold losses during the transportation of refrigerants to deep workings.

The idea of transporting refrigerant in the form of cooled air through the workings arranged in the displaced rocks behind the longwall, which are relieved of rock pressure, degassed and cooled, is proposed. This makes it possible to significantly reduce cold losses on the way to the miners' workplaces.

The results of theoretical preliminary calculations confirm that the enthalpy of displaced rocks in the mined-out longwall space remains virtually unchanged regardless of the depth of mining. This confirms the validity of the idea of choosing the arrangement of the workings to save cold resources.

Theoretically, a linear nature of the increase in the ratio of rock enthalpy in intact and cooled rock masses with deepening of mining operations has been established, which illustrates the efficiency and prospects of the proposed method for large depths.

A promising variant of coal seam preparation and mining is proposed to ensure the saving of the cold resource by arranging workings in displaced and cooled rocks. It is distinguished by the fact that the preparatory workings, which supply air to the mining face, are located within the cooled rocks in the vault of the completely displaced massif of the roof.

6. References

Antoshchenko, M.I., Filimonov, P.Ye., Bokyy, B.V., Kostenko, V.K. Koptikov, V.P., Zavialova, O.L. and Okalelov, V.M. (2013): Geomekhanicheskiye i tekhnologicheskiye usloviya gazodinamicheskikh protsessov v ugol'nykh shakhtakh *(Geomechanical and technological conditions of gas--dynamic processes in coal mines)*. Alchevs'k, DonHTU, 219p. (in Russian)

Belle, D.B. and Biffi, M. (2018): Cooling pathways for deep Australian longwall coal mines of the future. International Journal of Mining Science and Technology, 28(6), 865-875. https://doi.org/10.1016/j.ijmst.2018.02.001.

Cheberiachko, S., Cheberiachko, Yu., Sotskov, V. and Tytov, O. (2018): Analysis of the factors influencing the level of professional health and the biological age of miners during underground mining of coal seams. Mining of Mineral Deposits, 12(3), 87-96. https://doi.org/10.15407/mining12.03.087

Greth, A., Roghanchi, P. and Kocsis, K. (2017): A review of cooling system practices and their applicability to deep ad hot underground US mines. 16th North American Mine Ventilation Symposium, Golden, CO, 11, 1-9.

Guo, P. and Chen, C. (2013): Field experimental study on the cooling effect of mine cooling system acquiring cold source from return air. International Journal of Mining Science and Technology, 23 (3), 453-456. https://doi.org/10.1016/j.ijmst.2013.05.008

Han, Q., Debo, L., Xiaojie, Y., Kongqing, L. and Wei, Y. (2023): Thermal environment control at deep intelligent coal mines in China based on human factors, Sustainability, 15 (4), 3193. https://doi.org/10.3390/su15043193

Jin, T., Zhang, Z., Ge, L., Liang, X., Wu, H.,Zhou, J. and Mao, R. (2024): Investigation on temperature control performance of an underground confined space under ventilation. Thermal Science and Engineering Progress, 50, 102591. https://doi.org/10.1016/j.tsep.2024.102591

Kamyar, A., Aminossadati, M. S., Leonardi, C. and Sasmito, A. (2016): Current developments and challenges of underground mine ventilation and cooling methods. Proceedings of the 2016 Coal Operators' Conference, Mining Engineering, University of Wollongong, 18-20.

Kuyuk, A. F., Ghoreishi-Madiseh, S. A. and Hassani, F. P. (2020): Closed-loop bulk air conditioning: A renewable energy-based system for deep mines in arctic regions. International Journal of Mining Science and Technology, 30(4), 511-516. https://doi.org/10.1016/j.ijmst.2020.05.011.

Liashok, Ya.O., Serhienko, O.I., Kutserubov, V.M., Kohtieva, O.P. and Serhienko, L.V. (2020): The influence of the moisture on the physical and mechanical properties of the sandstone (Separate Unit "Kapitalna" coal mine", Donbas). Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, 2, 11-16. https://doi.org/10.33271/nvngu/2020-2/011

Mala hirnycha entsyklopediya u tr′okh tomakh *(A small mining encyclopedia in three volumes)*. Donets′k, Skhidnyy vydavnychyy dim, 2013, 644 p. (in Ukrainian)

Nazimko, V. (2024): Dissipative structures as a cause of the asynchronous development of the damaged zone surrounding underground roadways. International Journal of Rock Mechanics and Mining Sciences, 175, 105660. https://doi.org/10.1016/j.ijrmms.2024.105660

Nazimko, V., Zakliarova, L., Kusen, A. and Penh, S. (2021): Rock pressure relief is the basic alternative for sustainable underground mining. E3S Web of Conferences 284, 08020 ICSF 2021. https://doi.org/10.1051/e3scon ff/ 202 l280O8020/

Nehrii, S., Nehrii, T., Kultaev, S. and Zolotarova, O. (2020): Providing resistance of protection means on the soft adjoining rocks. E3S Web of Conferences 168, 00033. https: //doi.org/10.1051/e3sconf/202016800033

Nehrii, S., Nehrii, T, Volkov, S., Zbykovskyy, Y. and Shvets, I. (2022): Operation complexity as one of the injury factors of coal miners. Mining of Mineral Deposits, 16 (2), 95-102. https://doi.org/10.33271/mining16.02.095

Nehrii, S., Sakhno, S., Sakhno, I. and Nehrii, T. (2018): Analyzing kinetics of deformation of boundary rocks of mine workings. Mining of Mineral Deposits, 12 (4), 115-123. https://doi.org/10.15407/mining12.04.115

Nie, X., Wei, X., Li, X. and Lu, C. (2018): Heat treatment and ventilation optimization in a deep mine. Advances in civil engineering, Volume 2018, Article ID 1529490. https://doi.org/10.1155/2018/1529490

Qiaoyun, H., Lin, D., Yang, X., Li, K. and Yin, W. (2023): Thermal environment control at deep intelligent coal mines in China based on human factors. Sustainability, 15(4), 3193. https://doi.org/10.3390/su15043193

Szlązak, N., Obracaj, D. and Borowski, M. (2009): Free-cooling in free-cooling in central air-conditioning systems of underground mines. Górnictwo i Geologia. Kwartalnik Wydziału Górnictwa i Geologii. Politechnika Śląska, 4, 122-131.

Szlązak, N., Obracaj, D. and Swolkień, J. (2018): An evaluation of the functioning of cooling systems in the Polish coal mine industry. Energies, 11, 2267. https://doi.org/10.3390/en1109 2267 https://www.mdpi.com/1996-1073/11/9/2267.

Sridharan, J.S. and Pandey, A. (2019): Current developments in mine air cooling systems: Case study of an Indian coal mine using different cooling strategies. Conference: Recent Advances in Mining Technology (RAMT), 2019.

Suyarka, V.H. (2019): nzhenerna heolohiya (z osnovamy heotekhniky) : pidruchnyk dlya studentiv vyshchykh navchal′nykh zakladiv *(Engineering geology (with the basics of geotechnics): a textbook for students of higher educational institutions)*. Kharkiv, Kharkivs′kyy natsional′nyy universytet imeni V. N. Karazina, 278p. (in Ukrainian)

Yalanskyi, A.A., Sapunova, I.O., Slashchov, A.I. and Novikov, L.A. (2014): Substantiation of initial parameters for modeling geomechanical processes in problems on estimation of safety of maintenance of mine workings. Heotekhnichna mekhanika, 119, 282-295.

Yan, L., Yantek, D., Lutz, T., Yonkey, J. and Srednicki, J. (2020): Underground mine refuge alternatives heat mitigation. Journal of thermal science and engineering applications, 12(2), 021019. https://doi.org/10.1115/1.4044345

Wang, X., Wang, J., Chen, X. and Chang, Z. (2021): A roadway in close distance to coal seam in deep mine: location selection and supporting practice based on creep characteristics of surrounding rocks. Archives of Mining Sciences, 66 (3), 407-419. DOI:10.24425/ams.2021.138597

Vrtalova, P., Palicka, D., Hrinko, M. and Bubnik, J. (2023). Ventilation of the Ostrava-Karvina coal mine order to ensure the operation and extraction during mining in the Chech Republic. Conference: 23rd SGEM International Multidisciplinary Scientific GeoConference. DOI: 10.5593/sgem2023/1.1/s03.60

Zborshchyk, M.P. (1978): Okhrana vyrabotok glubokikh shakht v vyrabotannom prostranstve *(Protection of workings of deep mines in mined-out space)*. Kyyiv, Tekhnika, 176p. (in Russian)

Zeqiri, I., Gashi, J., Brahimaj, F. and Zeqiri, R. (2022): Effectiveness of ventilation regulation in a simple diagonal system of underground mines. Mining of Mineral Deposits, 16(2), 81-86. https://doi.org/10.33271/mining16.02.081

Zhdanova, O.O. and Samedov, A.M. (2012): Pruzhni kharakterystyky slantsevykh hirs′kykh porid *(Elastic characteristics of shale rocks)*. Visnyk ZHDTU, 1 (60), 109-115. (in Ukrainian)

SADRŽAJ

Metoda za ograničavanje zagrijavanja zraka koji se dovodi na duboka radilišta rudnika ugljena

Članak obrazlaže raspored radova koji omogućava najbolje dovođenje ohlađenoga zraka na čelo radilišta na temelju procjene promjene energijskoga stanja stijenske mase tijekom rudarskih radova. Teorijska istraživanja provedena su na temelju sustavne analize osnovnih jednadžbi klasične teorije termodinamike te uzimajući u obzir eksperimentalne podatke o fizici stijena i geomehaničkim procesima koji se odvijaju tijekom rudarskih radova. To je postignuto usporedbom energijskoga stanja (entalpije) u intaktnoj stijenskoj masi i stijenske mase nastale nakon vađenja ugljenoga sloja. Autori predlažu ideju transporta rashladnoga sredstva (ohlađenoga zraka) kroz radove postavljene u stijenama iza širokoga čela, koji su oslobođeni stijenskoga pritiska te su otplinjeni i ohlađeni. Time se može znatno smanjiti gubitak hladnoće na putu do radilišta. Rezultati teoretskih preliminarnih proračuna potvrđuju da entalpija stijena u otkopanome dugom prostoru ostaje gotovo nepromijenjena bez obzira na dubinu rudarenja. Tako je provedena provjera valjanosti ideje odabira rasporeda radova za uštedu na hlađenju. Utvrđena je linearna priroda porasta omjera entalpije stijena u netaknutim i ohlađenim stijenskim masama tijekom produbljivanja rudarskih radova, što dokazuje učinkovitost i perspektivnost predložene metode za velike dubine. Predlaže se ovakva varijanta pripreme ugljenoga sloja i otkopavanja kako bi se osigurala ušteda hladnoga resursa postavljanjem radova u ohlađenim stijenama sa sekundarnim stanjem naprezanja.

Ključne riječi:
rudarski radovi, ventilacija, energijsko stanje stijena, termodinamički čimbenici

Author’s contribution

Viktor Kostenko (1) (doctor of technical sciences, professor) initialized the idea, developed a methodological approach, managed the whole process and supervised it from the beginning to the end. **Iaroslav Liashok (2)** (doctor of economic sciences, professor) participated in the completion of the literature review, creating graphs and figures. **Olha Bohomaz** (3) (PhD, associate professor) reviewed literary sources, processed and analysed the results. **Maryna Tavrel (4)** (master of engineering) processed and analysed the results. **Tetiana Kostenko (5)** (doctor of technical sciences, professor) submission and review of the paper and the completion of the literature review, analysis of the results.