Modeling and Simulation of the Methane Risk in the Mining Production Process

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INTRODUCTION

The process in the economy is defined as a cycle of related activities integrated by: time and costs consisting in the production of goods and provision of services and the achievement of the company's goals. The first and most important phase of this process is production, understood as a purposeful and organized human activity consisting in the production of material goods or the provision of services in order to satisfy the consumer's needs and bring profits to producers (Biały, 2011). This means that in economic processes a new economic value is created, the measure of which is the so-called added value (Kubiak and Nakonieczna-Kisiel, 1999). If an economic process is carried out on a large quantitative scale and in repeated cycles, it is referred to as an "industrial economic process". The processes implemented in Polish hard coal mines and mining enterprises extracting hard coal are of such nature (Korski J. and Korski W., 2015).

The production of hard coal with appropriate quality parameters is a multi-element process with a complex structure. This structure consists of successive stages divided into activities and technological operations. These stages are carried out in a specific time and space, by human teams using specific technical means (Brodny et al., 2017a, Brodny et al., 2017b).

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Table 1 List of fundamental mining technologies

<table>
<tr><th colspan="6">Technologies that make the deposit available</th></tr>
<tr><th colspan="3">I. Excavation</th><th colspan="3">III. Model of the deposit cut</th></tr>
<tr><td colspan="3">Access to the deposit: shafts, tunnels, crossroads and ditches</td><td colspan="3">1. Stone model
2. Carbon model
3. Coal-stone model</td></tr>
<tr><th colspan="3">III. Mining</th><th colspan="3">IV. Support</th></tr>
<tr><td colspan="3">1. Shooting (explosives)
2. Mechanical mining (shearer, plow)</td><td colspan="3">Susceptible arched, wooden, anchored, mixed, shell, masonry</td></tr>
<tr><th colspan="6">Preparatory technology</th></tr>
<tr><th colspan="2">I. Excavation</th><th colspan="2">II. Mining</th><th colspan="2">III. Suppot</th></tr>
<tr><td colspan="2">1. Corridor, longwall, fall, ramps
2. Ventilation, transport
3. Glades</td><td colspan="2">1. Shooting (explosives)
2. Mechanical mining</td><td colspan="2">Susceptible arched, wooden, anchored, mixed, shell, masonry</td></tr>
<tr><th colspan="6">Exploatation technology</th></tr>
<tr><th colspan="3">I. Landing systems</th><th colspan="3">II. Longwall systems</th></tr>
<tr><td colspan="3">1. Short takes
2. Long takes
3. Ventricular
4. Sidewalk
5. Chamber-pillar</td><td colspan="3">1. Oblong, with a collapse of the ceiling
2. Oblong with hydraulic support
3. Oblong with a dry backing
4. Transverse collapsed roof
5. Transverse with hydraulic proppant
6. Transverse with dry filling</td></tr>
<tr><th colspan="2">III. Special systems</th><th colspan="2">IV. Mining</th><th colspan="2">V. Support</th></tr>
<tr><td colspan="2">1. The landing sidewalk
2. Landing deck
3. Underground gasification
4. Dressing and traveling
5. The "jankowicki" system
6. The "miechowicki" system
7. Multilayer system</td><td colspan="2">1. Shooting (explosives)
2. Mechanical mining: longwall shearers, plows, continuous miner</td><td colspan="2">steel
mechanized
anchor</td></tr>
<tr><th colspan="6">Coal mechanical processing technologies</th></tr>
<tr><td colspan="4">1. Enrichment of coal with a grain size greater than: (10) 20mm and above (0.1) 0.5mm
2. Coal enrichment in the full grain size range</td><td colspan="2">Coal enrichment to the full extent graining</td></tr>
</table>

Source: Own study based on (Trenczek, 2007)

In the hard coal production process, in underground mining plants, there are successive – access and preparation processes. The most important of the basic processes is mining, while the final process is the mechanical processing of coal (Biały, 2020). The primary processes preceding coal production are infrastructure processes, i.e. auxiliary technologies: ventilation, transport and dewatering. A summary of these processes is presented in Table 2.

Table 2 List of general mining auxiliary technologies

<table>
<tr><th colspan="3">Transport</th></tr>
<tr><th>Vertical</th><th>Horizontal</th><th>Slanted</th></tr>
<tr><td>rope</td><td>belt, rail, scraper</td><td>rope, rail, belt, scraper</td></tr>
<tr><th colspan="3">Ventilation</th></tr>
<tr><th colspan="3">Streamlined (ascending / descending)</th></tr>
<tr><td colspan="3">1. Ventilation of the functional chambers
2. Ventilation of corridor excavations
3. Ventilation of mining excavations</td></tr>
<tr><th colspan="3">Separate</th></tr>
<tr><td colspan="3">1. Ventilation by diffusion
2. Ventilation using auxiliary ventilation devices
3. Ventilation with fans
3.1. airborne 3.2. electric
3a. pressure ventilation 3b. suction ventilation 3c. combined ventilation</td></tr>
<tr><th colspan="3">Dehydrated</th></tr>
<tr><th>Main</th><th colspan="2">Local</th></tr>
<tr><td>1. Direct
2. Indirect
3. Mixed</td><td colspan="2">1. Gravity (sewage, drilling)
2. Forced by pumps (air, electric)
3. Water excavations</td></tr>
</table>

Source: Own study based on (Trenczek, 2007)

On the basis of the work (Korski J., Korski W., 2015), a simplified diagram has been prepared presenting the mining production process (Fig. 1) as a list of chronological activities, starting from the moment the deposit is made available until it is delivered to the customer. Both the activities performed in the underground part of the mine and those performed on the surface were included.

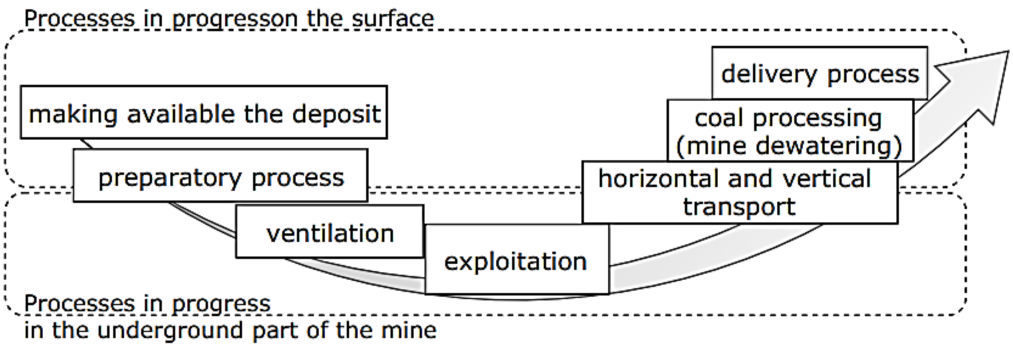

Fig. 1 Underground process of hard coal production

Source: Own elaboration based on (Korski J., Korski W., 2015)

Underground hard coal mining is characterized by very difficult and complicated mining and geological conditions, which is why the mining industry is one of the most dangerous and accident-causing work environments (Palka; 2017, Palka et al.; 2017). Dangerous events are usually determined by many factors, among which, depending on the adopted criteria, the following groups can be distinguished:

- natural conditions (e.g. deposits, faults, water basins),
- technical and technological level of works (e.g. selection of machines and devices, excavation support, exploitation system),

- determination of the potential level of occurring threats and making forecasts of the risk shaping during operation,
- lowering the level of threats by recognizing, monitoring and forecasting threats, as well as appropriate design of operation and taking preventive measures,
- predictability of hazardous events and coincidence of natural hazards (e.g. coal spontaneous combustion, gas and rock explosion, rock tremors, rock bursts, coal dust explosions)
- active threat identification; control and monitoring of the operating area and the parameters of machines and devices as hazardous technical factors,
- trained and aware staff (high level of risk awareness, knowledge of skills in the field of technical operation of mining machinery and equipment)
- appropriate procedures (the degree of their dissemination among the staff, the possibility of quick information and alerting) and the ability of decision-makers to maintain the rigors contained in the procedures (Trenczek, 2007).

The existing mining hazards have a negative impact not only on the safety of the crew, but also on the mining machines used in underground excavations. Their effectiveness determines the continuity of work, and thus the efficiency of the entire coal mining process (Brodny et al., 2017). The mining environment and related natural hazards may also adversely affect the ventilation processes in the mine, thus disrupting the continuity of the coal production process (Tutak 2018, Tutak 2019, Brodny and Tutak 2018).

One of the most dangerous threats accompanying the exploitation of hard coal is the methane hazard. Methane in the mine atmosphere rises under the roof of the excavation, is itself an inert gas for the respiration process, but at higher concentrations it can displace oxygen. In the rock mass, this methane appears in three forms: gas dissolved in water, carbon-bound sorbed gas, and free methane found in fissures, macropores and mesopores. Free methane flows into excavations, creating an explosion and fire hazard and an oxygen-free atmosphere. It is this type of gas that poses a deadly threat to the mining crew, and can also cause the continuity of coal mining to be interrupted and huge material losses (Łukaszczyk, 2019, Łukaszczyk, 2020).

Methane is released into the excavations as a result of disturbing the balance of the rock mass. Drilling of corridors in the deposit as well as operational activities, such as mining, depressurization or degassing of the seams, disturb the sorption equilibrium as a result of lowering the pressure of the gas contained in the deposit. Lowering the methane pressure in the fissures and pores causes the phenomenon of desorption, i.e. the transition of methane from sorbed to free state. As a result, there is a slow release of methane, which forces gas to migrate towards the mine excavationss. However, specific methane-carbon-rock mass systems can cause sudden outflows of methane or outbursts of gases and rocks (Łukaszczyk, 2019, Łukaszczyk, 2020).

The present concentration of methane in the excavation determines the preventive measures taken to combat the methane hazard. If the concentration of methane in the mining excavation exceeds 2%, the electric power supply, including all machines and devices, is switched off. In addition, the appropriate person from the traffic supervision is notified, additional measurements are made and appropriate measures are taken to limit the accumulated gas. However, if the concentration of methane in the mining excavation exceeds 3%, the crew withdraws and secures the exits to the endangered area (Matuszewski, 2011).

It can therefore be assumed that ensuring the appropriate quality of the environment in which mining is carried out has a multi-threaded nature and is a very complex process. The overriding goal in production management is to undertake activities aimed at developing and implementing modern solutions ensuring progress in the field of safety of the mining staff as well as machinery and equipment used in mining excavations. One of the tools that can be used in the methane hazard assessment process is modeling and numerical simulations. These methods make it possible to determine the expected amount of methane that may be released into the analyzed mining area. The obtained data allow for the appropriate selection of preventive measures, the task of which is to reduce the concentration of this gas in the mining excavation, and thus – reduce the level of methane hazard (Brodny and Tutak, 2019).

METHODOLOGY

Modeling and computer simulation, based on mathematical models, are an extension of theoretical sciences, making it possible to obtain new cognitive results. Models describe physical phenomena and are the basis of scientific theories. Simulation can be used to design new experiments, test and validate new theories. Moreover, computer simulation is an alternative solution to experimental and observational techniques, when the phenomena are difficult to observe or too expensive (Burczyński, 2016). Therefore, it seems reasonable to say that with the current dynamic development of computer techniques, apart from theory and experiment, computer simulation can be mentioned as the third pillar of science, as shown in Fig. 2 (Kleiber 1990).

Computer simulation makes it possible to verify the developed model in terms of significant factors in terms of its application and the phenomena and processes taking place in it. In addition, it allows you to detect potential errors, assess the properties of models and make corrections. This approach enables the model to be repeatedly tested without generating losses and costs, contrary to the experiments. The advantage of computer simulation is also the possibility of visualizing the performed tests and visualizing the final results (Burczyński, 2010).

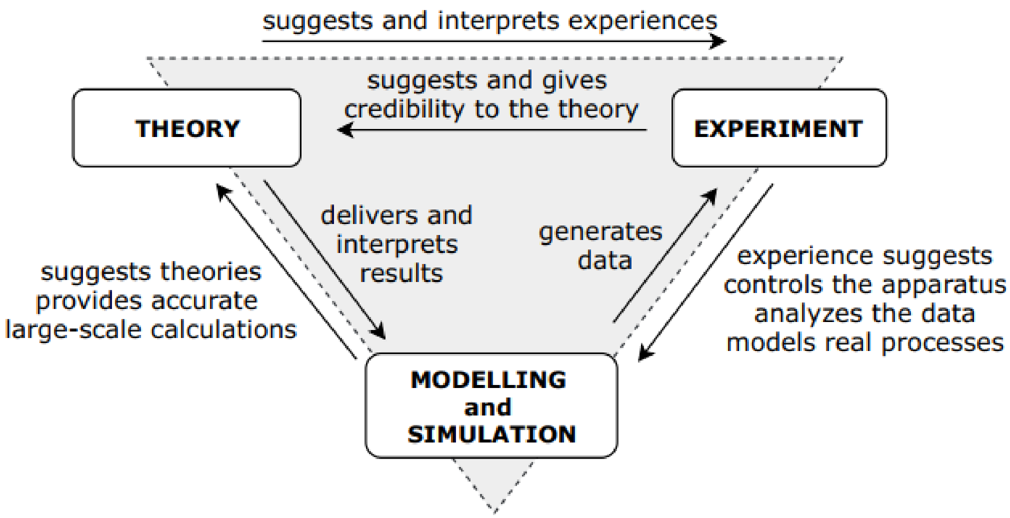

Fig. 2 Modeling and computer simulation as the third pillar of science
Source: Own study based on (Kleiber, 1990)

The process of creating a simulation can be divided into the following stages:
1. Problem formulation – recognition and interpretation of the simulated phenomenon. Errors resulting from a misunderstanding of the idea of a simulated phenomenon cause very serious and often irreversible complications.
2. Purpose of the simulation and overall plan – determining the purpose of the simulation to be performed determines the model parameters and the stages of work progress. Incorrect interpretation of the target completely distorts the simulation results.
3. **Model construction** – the real object is replaced by an abstract model defined by mathematical relationships.
4. Data collection – collecting the necessary data in the form of parameters, conditions and factors to conduct the simulation.
5. Programming the simulation – setting the boundary conditions, assigning parameters for the behavior of an object or phenomenon, determining a decent scale of the simulation and the expected results.

- **Model validation** – If you discover errors in simulation design, go back to step 3 and reanalyze the model.

6. Design, test execution and sample analysis – testing is difficult and laborious occupation. The greatest possible care should be taken to carry it out. Performing test simulations is aimed at the maximum reflection of the real world, the object and the phenomena taking place.
7. Documentation and presentation of simulation results – simulation documentation is a compilation of visualization, scale and numerical results presented most often in the form of reports.
The computer simulation process carried out in this way covers the entire research cycle, from problem identification to the interpretation of the obtained simulation results. On the other hand, the modeling process itself is a set of activities aimed at bringing the reality closer to the scientific description in the most faithful representation.

Modeling and computer simulations are ideal tools to assess methane hazard in mining. The numerical method allows for the assessment of methane emitted to the areas of hard coal production with high probability, along with the determination of its distribution, which in turn will enable the selection of methods and preventive measures that should be applied to improve the safety level in the studied area (Brodny and Tutak, 2019).

RESAULTS

Methane migration to underground mine excavationss leads to the formation of explosive mixtures of this gas. Free methane, found in crevices, macropores and mesopores, flows into the excavations, releasing from the rocks, where it is diluted successively by the ventilation air. Knowledge of the process of mixing methane with the ventilation air is of great importance for the definition of potentially explosive zones, and thus for ensuring a safe and effective coal production process (Kissell, 2006).Many works are carried out in this area, both experimental and theoretical (Szlązak, 2000). Currently, in the era of dynamic progress of computerization, computer modeling with the use of Numerical Fluid Mechanics (CFD) methods is a valuable supplement. Examples of such studies are: (Brodny and Tutak, 2019, Tutak and Brodny, 2017, Brodny et al., 2018, Branny et al., 2013, Kurnia et al., 2014; Kurnia et al., 2016), Great opportunities in this regard are offered by software that uses the finite volume method to solve equations of fluid mechanics (Tutak, 2020)

Numerical Fluid Mechanics (CFD) is the analysis of systems involving fluid flow, heat transfer, and related phenomena such as chemical reactions, using computer simulation. Modern CFD programs allow for solving flows taking into account viscosity and compressibility, multiphase flows, flows with combustion processes and flows through porous structures. Most modern CFD programs are based on the Navier-Stokes equations (mass, momentum and energy conservation equations for a fluid) and discretize them using the finite volume method, the finite element method or the finite difference method. The technique is very powerful and covers a wide range of both industrial and non-industrial applications. Examples include (Versteeg and Malalasekera, 2007):

- biomedical engineering: blood flow through arteries and veins,
- meteorology: weather forecast,
- marine engineering: loads on coastal structures,
- environmental engineering: distribution of pollutants and wastewater,
- chemical process engineering: mixing and separation,
- construction engineering: wind load, heating, ventilation,
- aerodynamics of planes and vehicles: lift and drag,
- hydrodynamics of ships,
- power plant: combustion in internal combustion and gas engines,
- hydrology and oceanography: flows in rivers, estuaries, oceans.

The CFD codes used in the simulation process that solve fluid flow problems are built from numerical algorithms. However, currently available IT tools provide advanced user interfaces for entering data, problem parameters, and analyzing the results. Hence, all codes contain three main elements: preprocessor, solver, and postprocessor.

In this work, the Ansys Fluent tool was used to carry out an example simulation. Fig. 3 shows the successive stages of the research.

The parameters of the flow area adopted for calculations were taken from an active underground mining plant. The modeled area includes a 30 m long section of a wall 2.15 m high and 8 m wide, and a walkway 50 m long, 3 m high and 3.5 m wide. Due to the nature of this study, the detailed description of the parameters was omitted.

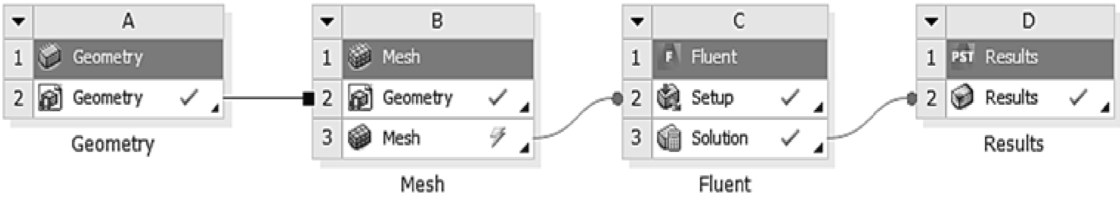

Fig. 3 Next steps in Ansys Fluent software

Source: Own study

The first stage (Fig. 3A) is creating the geometry of the tested object and generating the mesh (Fig. 3B). The geometry is drawn on the basis of the obtained data or by making a scan. The meshing can run automatically or it can be created highly crafted. The mesh affects the accuracy, convergence and speed of the solution. The geometry and the mesh are shown in Fig. 4.

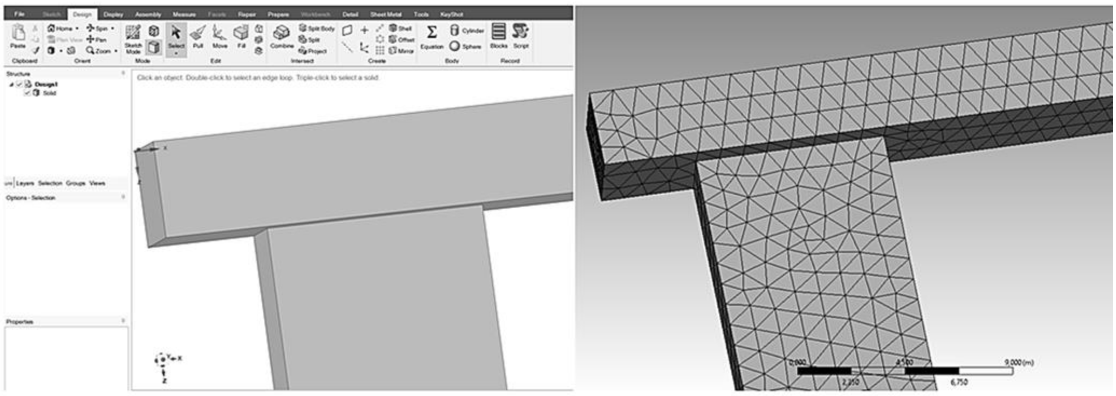

Fig. 4 Object geometry and mesh

Source: Own study

A key element of the research is to run simulations to visualize the flow behavior and obtain the results. An example of a fragment of the simulation is shown in Fig. 5.

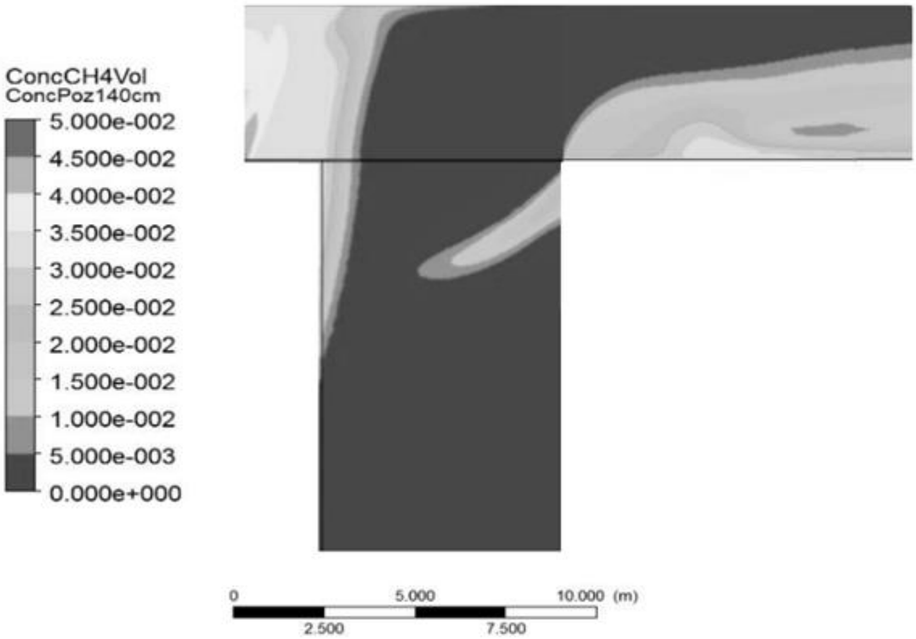

Fig. 5 An example of the distribution of methane concentrations in a mining excavation

Source: Own study

With today's growing computing power, numerical methods can be used to identify, monitor, forecast and distribute methane and other gas concentrations or overall ventilation flows. Numerical simulations have already found wide application in the literature, among others, to determine the impact of changes in the volume of methane emissions as well as changes in pressure and air flow on the distribution of methane concentrations in mine excavations and goafs (Dziurzyński, 2002; Nawrat et al., 2006; Krause et al., 2008; Brodny and Tutak, 2019; Tutak and Brodny, 2017; Brodny et al., 2018; Branny et al., 2013; Kurnia et al., 2014; Kurnia et al., 2016, Tutak, 2020). Therefore, it seems reasonable to say that this method is a tool with great implementation potential. In this article, it was decided to signal the possibilities of using numerical methods in underground coal mining to improve the safety and efficiency of the production process.

CONCLUSION

The process of hard coal production can be defined as a set of integrated downstream processes, including: planning and design of exploitation, deposit availability, preparation activities, mining of coal, horizontal and vertical transport, coal processing, spoil haulage. The process is continuous, in the following stages: planning, preparation, implementation of extraction, as well as monitoring and implementation of new solutions. These solutions in particular relate to increasing the efficiency of the production process, which is determined by work safety in mining excavations. The safety of the staff, machinery and equipment as well as excavation infrastructure determines the continuity of the hard coal mining process, and this directly translates into the effectiveness of the entire mining production process. From a business point of view, it is of great importance for the functioning of individual enterprises and the entire industry, and thus for the country's economy.

In underground hard coal mining, there are a number of phenomena that threaten the safety of work and the operation process. However, the most dangerous threats are those that cause the highest death toll. Methane hazards occupy the leading position in this group. Due to the physicochemical properties of methane, this gas causes many dangerous events, often of a catastrophic nature. These events are most often associated with huge material losses, damage to machinery and equipment, mining excavations and often fatal accidents. The presence of methane in the mining exploitation process may significantly disturb this process and have a negative impact on its efficiency.

The method of modeling and computer simulation, as one of the pillars of modern science, enables the precise determination of the distribution of methane concentration at any point in the mining excavation being tested. In this way, it is possible to designate potentially dangerous zones in which the permissible methane concentration may be exceeded. These tests performed in real conditions are practically impossible.

The article presents the procedure of simulation tests, the purpose of which was to determine the distribution of methane concentrations in the mining area. The research was carried out for the actual area of coal mining, one of the active mining enterprises. Modeling and simulation were performed using the finite volume method in ANSYS Fluent. The use of numerical methods in conjunction with the results of tests carried out in real conditions can effectively support the assessment of the methane hazard state, and further improve the safety of work in mines. Information on the structure of threats and their effects is of great importance as they enable the targeting of preventive measures to the most dangerous areas. Obtaining current and reliable information on the state of safety in the mining industry may also constitute the basis for taking effective measures to improve the level of occupational health and safety in mining and to improve the efficiency of the entire production process.

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Abstract: The mining production process is of particular importance for the area of Upper Silesia, as well as a very significant impact on the economy of the entire country. One of the most common and most dangerous threats to this process is the methane hazard. It is related to the presence of methane in coal seams, which under appropriate conditions is a flammable and explosive gas. Events related to the methane hazard constitute a huge threat to the life and health of the crew as well as the infrastructure and equipment of excavations. Therefore, they have a huge impact on the efficiency of the entire mining production process. In order to ensure the safety and continuity of the production process, it is necessary to prevent the formation of dangerous methane concentrations in the area covered by the operation. One of the tools that can be used to assess the state of methane hazard are model studies supported by numerical simulation. Based on these studies, the article analyzes the distribution of methane concentration in the mining area. This area included an actual mining excavation in one of the hard coal mines. The model tests were carried out with the use of the finite volume method in the ANSYS Fluent software. The obtained results can be used for preventive measures and constitute an important source of information for the assessment of the methane hazard state.

Keywords: numerical modeling and simulations, mining production process, process efficiency, methane hazard, hard coal mining