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Article

The Use of the Open Innovation Concept to Develop a Method to Improve Safety during the Mining Production Process: A Case Study of the Integration of University and Industry

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Abstract: Growing competition in the education economy has caused companies to look for new innovative solutions that can increase their competitiveness. These processes practically concern the whole world, and the development of new technologies that are related to the concepts of Industry 4.0 and sustainable economy has accelerated innovation even more. In order to adapt to these trends, companies are taking extensive measures to apply new technologies and implement innovative solutions. The use of an open business model that is based, for example, on the concept of open innovation (OI) could be helpful in this process. By reinforcing their own solutions with external ideas and proposals and by cooperating on joint projects, companies have the chance to maintain beneficial relationships with customers and remain competitive. This also applies to the mining industry, for which the production processes are additionally affected by the natural hazards that are associated with the environment in which these processes are carried out. This article presents a relevant example of using the OI concept to develop and implement an innovative method for reducing the fire hazard that is caused by the spontaneous combustion of coal in underground coal mines. The method was based on the model tests that were conducted by the Silesian University of Technology. Since the mining enterprise in question was looking for an external solution to the problem of the formation and development of endogenous fires, it was open to cooperation. The open exchange of knowledge and ideas resulted in the development of an innovative method that was successfully applied in this coal mine. This paper presents a model for the cooperation between a research unit and an enterprise that included the open exchange of knowledge, which significantly enriched both sides of the project. It also discusses the innovative solution that was developed, which involved the use of model tests to identify potential locations for underground fires and an installation to supply certain substances to these areas in order to limit the occurrence and development of these fires. The results of the research, which confirm the effectiveness of the developed method, are also presented. The application of the IO concept and the cooperation between scientific research and industry made it possible to solve a specific and current problem that has a significant impact on the efficiency of the production processes of mining companies. The implementation of the developed method prevented an endogenic fire, and the mining process proceeded without any major disturbance. The developed solution and the applied model of open cooperation between a research unit and industry could together create the possibility of generating innovative solutions that can be quickly commercialized and implemented. Thus, the concept of OI presents a great opportunity for the development of an innovative knowledge-based economy.

Keywords: open innovation; production process; mining hazards; underground fire; coal spontaneous combustion

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1. Introduction

One of the most important elements of the economy that has a significant impact on the level of its modernity is intersectoral cooperation, which is also undertaken between scientific and research units (e.g., universities) and enterprises. The openness of these entities to exchange their experiences, ideas and solutions is the basis of the open innovation (OI) concept [1–3]. Therefore, an important and desirable activity for the modern economy is the cooperation between research and development units and enterprises. A classic example of such cooperation is that between a university and a company or a group of companies. Currently, such cooperation is being realized to an ever greater extent and takes different forms, which are adapted to the needs and capabilities of both parties [4–7]. The factors that determine university–industry relationships include the potential benefits arising from the cooperation [8], geographical proximity, entrepreneurship ecosystems, transfer mechanisms [9], implications for public policy [10] and the availability of cooperation resources in the form of infrastructure, as well as previous experience of such cooperation [11,12].

From the point of view of a university, this cooperation also provides the possibility of obtaining relevant knowledge and experience, which could expand the scope and possibilities for conducting research [13,14] and could be used within the educational process. It should also be noted that knowledge transfer and the commercialization of research results is one of the basic tasks for academic centers, and they are also a measure of innovation and the quality of scientific and research work that is conducted in these centers [15–18]. Thus, the concept of open innovation strongly favors the process of the commercialization and implementation (whether commercial or non-commercial) of research results that are obtained by academic centers [19–22].

In turn, companies gain the opportunity to implement modern, innovative solutions that can increase their competitive advantage within the market. In addition, they can directly participate in the creation of innovative solutions through implementation projects or the implementation of applied research, which is quite common. This approach means that the innovation process can be more product- or customer-oriented, which increases the chances for faster implementation. The open innovation approach to creating innovative solutions also results in entrepreneurs gaining new knowledge and building business and research networks and connections. These activities fit in very well with the implementation of the UN's Sustainable Development Goals [23–25], which is also due to the fact that the cooperating entities complement each other and create added value for both the economy and society.

The presented advantages of the cooperation between universities and businesses are becoming increasingly important for all stakeholders within these processes [9]. However, the benefits of this cooperation may vary depending on the specific objectives and industry. Practice has shown that such cooperation usually benefits all parties, especially in high-tech and industrial sectors [26,27].

In Poland, the mining and quarrying sector is one of the industrial sectors in which the OI concept has a great chance of being more widely used. This sector mainly comprises underground hard coal mining, which in turn is closely related to the energy sector and the economy of sustainable development and environmental protection. In Poland, hard coal mining is one of the traditional sectors that constitutes the basis of the power industry, the greatest development of which took place during the period of the centrally planned economy [28]. With the ongoing political, social, economic, and climatic changes and economic development, the importance of this industry has decreased, and the development of the free market economy and renewable energy sources (RESs) has accelerated the transformation of this industry [29]. Despite these changes, the role and importance of mining within the country's economy remain significant. This mainly concerns the energy sector, which is largely based on hard coal and the production of coke, which is an important ingredient in steel production. However, the fierce competition within the market for raw energy materials makes the implementation of innovative solutions to improve the safety and efficiency of the processes increasingly important [30]. Mining companies realize that without such solutions, their production will not be able to withstand global competition.

Underground hard coal mining, due to a number of hazards, including mainly natural perils, is very dangerous [31–33]. These hazards affect the safety of mining in Poland and around the world (in China, the USA, Australia, Russia, India, Poland, the Czech Republic, and South Africa) and pose a serious problem for the work of mining crews and the continuity and effectiveness of the production process [34,35]. The importance of this problem is also confirmed by the fact that despite the decreasing output, the number of dangerous events related to natural hazards has not changed. Particularly dangerous are the consequences of these events, as they cause large material losses and a threat to the health and life of the crew [36].

Currently, one of the biggest problems reported during the exploitation of hard coal is the fire hazard associated with the possibility of self-ignition of coal (so-called underground fire, endogenic fire) [37–41]. The increasing intensity of these types of events requires actions aimed at ensuring health and safety protection for employees as well as reducing the economic losses of mining companies. So far, actions taken independently by mining companies to fight the fire hazard, despite some successes, have not been satisfactory.

The aim of the study was primarily to solve a specific problem concerning the improvement of work safety in the mine by establishing scientific cooperation and open innovation between a university and a coal mine. Its implementation involved the development of a method for reducing the risk of underground fires caused by the spontaneous combustion of coal. The method involved the identification of a zone of particular risk for the spontaneous combustion of coal in goaves with the use of the CFD technique and the injection of an ash-water mixture or an ash-water mixture with carbon dioxide into this zone by means of a specially designed installation. Therefore, the main part of the research involved the use of model tests to identify the size and location of this zone.

The method utilized the latest structural modeling solutions implemented by the university and the results of in situ research conducted jointly by mine and university personnel. The result of these activities was the development of a solution that has been successfully applied in one of Poland's underground hard coal mines.

Undoubtedly, the most valuable achievement of this open and closely cooperative process of creating an innovative solution was the development of an integrated preventive method to reduce the fire hazard. Its basis was the result of research in both real and model conditions; through its implementation, the potential of both the mining company and the university were combined. In addition to the creation of a predictive model to determine zones that are susceptible to spontaneous combustion of coal and the implementation of measures to make this zone inert in order to prevent the onset and development of fires, it also demonstrates the flow of knowledge between the stakeholders of the project. Therefore, it can be assumed that the presented example is a positive result and a practical application of the OI concept in the mining industry. Moreover, this is immensely valuable, as this industry is conservative when it comes to implementing new solutions.

When comparing this solution to examples presented in the literature, it can be stated that the subject of cooperation between universities and industry in the field of open innovation has received much attention. Available publications in this area focused on, for example, cooperation models [42–47], knowledge transfer, or benefits that this cooperation brings to both sides. However, these studies are usually of a general nature and lack specific examples of the application of solutions resulting from such cooperation.

Since this article presents a successfully implemented solution resulting from the application of the OI concept between a university and the mining industry, it can be considered a new approach to this subject. The validity of the presented solution is also confirmed by the fact that apart from the obvious economic advantages, it also improves safety in the process of underground mining. Additionally, the developed and implemented solution, which has universal features and can be widely applied in other mining companies, may indirectly improve energy security in Poland and other countries where hard coal plays an important role in energy production.

2. A Model of Cooperation between a University and a Coal Mine Based on a Fire Hazard Caused by Spontaneous Combustion of Coal

In a knowledge-based economy, there is a growing need for a deeper and more productive interaction between universities and industry. However, the full utilization of academic knowledge resources requires an appropriate strategy, motivational systems, investment incentives, and the creation of conditions for cooperation between universities and companies. Transfer of knowledge combined with the process of its commercialization gives a chance for its practical application for the benefit of all stakeholders in this process. Important factors that affect success in this area are trust, commitment, and benefits derived from such projects by all stakeholders [48].

The employees from the Silesian University of Technology that undertook this example of an effective use of the OI concept are a group with a focused interest in the processes of technology transfer and research commercialization. The University has the Center for Incubation and Technology Transfer, which is a university-wide unit responsible for the supervision and implementation of the process of commercialization of intellectual property of the University employees. Its main objective is to promote the results of research and development work in the business environment and assist in the process of their implementation.

Openness to new solutions, knowledge, willingness to cooperate, and complete trust were the basis for cooperation between the University and the mining company in developing innovations related to combating the fire hazard arising from the spontaneous combustion of coal.

This issue has been of scientific interest for many years. In academic centers and scientific institutes, research has been conducted for years on the mechanism of this process, e.g., [49–52], the identification of its causes, and factors influencing its creation, e.g., [53–60]. The initiation process for the self-heating of coal left in goaves, as indicated by accepted knowledge and mining practice, depends on many factors, which can be conventionally divided into natural (geological) and mining factors [53–60] (Table 1).

Table 1. Factors conducive to the self heating of coal (own elaboration based on [53–60]).

Natural Factors	Mining Factors
– properties of the coal substance, – activation energy of coal, – petrographic composition, – degree of metamorphism, – moisture of coal, – content of volatiles, – slope of the coal seam, – tectonic disturbances (faults) – primary temperature of the rock mass, – depth of exploitation, – mechanical properties of coal seam, – type of roof rock	– exploitation system – direction of coal seam exploitation, – mining technology, – thickness of coal seam, – longwall length, – the purity of coal getting – progress of the longwall, – longwall ventilation system, – the intensity of the longwall ventilation, – temperature of air in longwall

Many works also concern the possibility of limiting the occurrence of this phenomenon or minimizing its effects [61–67]. In this regard, research on the identification of symptoms indicating the occurrence of an endogenous fire and its development is very important. Mining companies that use these solutions are trying to reduce the possibility of this phenomenon and its consequences as much as possible. However, these actions are not always successful. Despite the preventive measures and almost continuous monitoring of chemical parameters of the mine atmosphere, such fires occur quite often. The spontaneous combustion of coal and associated fires are reported in China, the USA, India, Poland, Australia, Indonesia, South Africa, and other coal-producing countries [68–70]. The economic impact of such events is very high, which explains the willingness of these companies to cooperate with academia in order to reduce the possibility of such a fire and/or limit its effects [71,72].

This problem has been addressed by university employees dealing with the study of porous media and their modeling. It turned out that the self-heating process of coal takes place in longwall goaves, which are composed of porous media. At the same time, this process is strictly dependent on the velocity of air passing through a goaf and its oxygen content. The combination of scientific knowledge in model tests of porous media with practical knowledge and a testing ground for this type of media, such as goaves, made it possible to conduct this research and develop an innovative method for limiting this hazard.

With the use of model tests, zones in which an endogenic fire may occur or has occurred were identified. The knowledge gained in this area can be used in two ways. To be specific, as prevention, by limiting the supply of oxygen to the area of potential danger and not allowing the initiation of this phenomenon. In turn, in the case of fire, through the analysis of physical and chemical parameters of the mine atmosphere, the identification of the place of its occurrence allows mine services to take quick and effective actions and isolate this area, preventing the inflow of oxygen to the endangered zone.

In both cases, the basis for action is the identification of the location of a fire hazard zone, which is a scientific task, while the subsequent actions are taken by mine services. A detailed description of the developed method with an outline of the occurrence of an endogenous fire is presented in Section 3 of this paper.

The cooperation between the University and the coal mine in developing a method of combating the fire hazard caused by the spontaneous combustion of coal was carried out according to the diagram of the cooperation model presented in Figure 1. Its versatility means that it can be used to solve a variety of problems related to the mining production process, especially in terms of improving its safety and efficiency.

In this model, the actual activities undertaken in the process of creating this innovative solution are summarized, along with the directions of cooperation and the benefits that this cooperation brought to its stakeholders. The process of commercialization of this solution was also taken into account, which, however, from the point of view of the study itself, is somewhat less important. Therefore, the presented model is an example of a practical application of the OI concept and a two-way transfer of knowledge and experience between the cooperating entities to solve a real problem. Its characteristic features are:

- strong interaction between a university and industry, which guaranteed a two-way flow of knowledge and added value for both parties,
- interest of both parties in the problem reported in the company and the possession of adequate resources by the university for its solution,
- benefits for both parties involved in solving the problem,
- significant impact of the cooperation on both society and the environment,
- development and implementation of this innovative solution, improving the safety and efficiency of the production process.

An important factor is also the fact that the cooperation established within the implementation of this project has the potential for further continuation and thus could lead to further innovative solutions. Both parties also declare, which is the essence of the Open Innovation concept, the possibility of expanding the team, including other industry representatives and specialists from other research units. This process will obviously depend on the demand for new solutions and the capabilities of individual parties.

The presented model can be successfully utilized for cooperation in other fields and can be freely extended. The basis of its universality is an openness and willingness to cooperate and exchange knowledge between interested organizations.

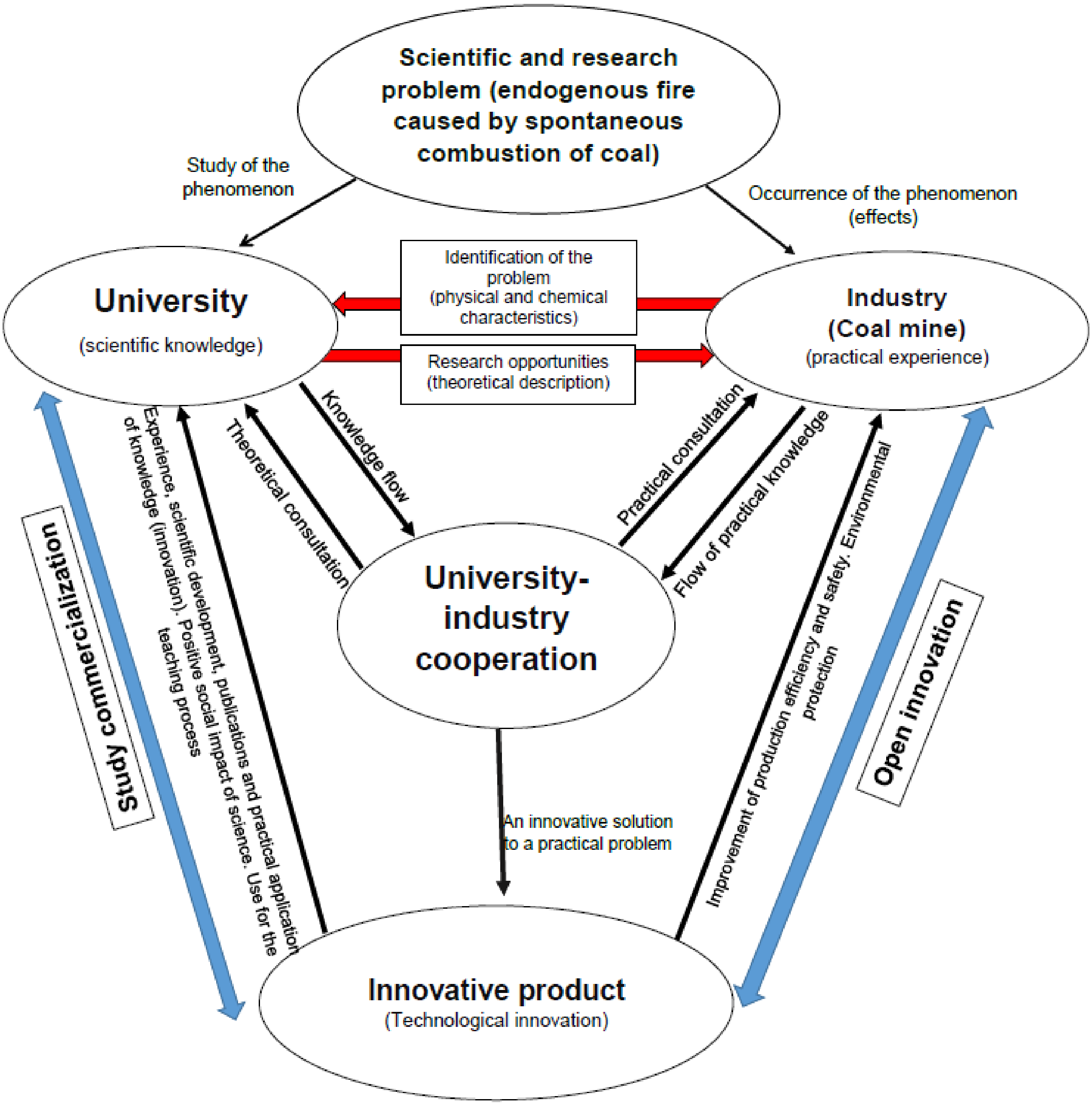


Figure 1. The model of cooperation between the University and the mining company (industry) within the framework of creating an innovative solution to combat the fire hazard.

3. Characteristics of an Innovative Method of Reducing the Fire Hazard Caused by Spontaneous Combustion of Coal Created within the Framework of Open Innovation Cooperation

The result of the presented university–industry (coal mine) cooperation was the development of a method to reduce the fire hazard caused by the spontaneous combustion of coal, namely, the occurrence of an underground fire (induced by the spontaneous combustion of coal).

The method consists of three main stages:

1. Conducting measurements of ventilation parameters in the mining area and determining the compressive and tensile strength of roof rocks in order to determine the permeability of goaves;

2. Identifying a zone of fire hazard (induced by spontaneous combustion of coal) using the CFD methods;
3. Designing an installation that enables the administration of an ash-water mixture with inert gas (carbon dioxide and/or nitrogen) and antipyrogenic foam to this zone by means of pipelines and the process of supplying these substances to the endangered zone.

The first stage involves identifying (as accurately as possible) the ventilation parameters of a region where mining exploitation is carried out. An important element of this stage is to determine the physical parameters of a collapsing zone (longwall goaves, the space left after the mining of coal). Thus, this stage consists in measuring the ventilation parameters of the air, the geometry of mine workings in the examined area, and determining the structure of rocks forming a given goaf. The determined values are the basis for the development of a numerical model of the examined region and the determination of boundary conditions. The accuracy of the acquired data is critical for ensuring the quality of the model and the results obtained.

The second stage involves determining a zone (area) in which the process of low-temperature oxidation of coal can be initiated (beginning of fire). This process can occur only in such a goaf area, where the conditions necessary for its initiation are met. The conditions include the presence of crushed coal, which is prone to spontaneous combustion, an airflow of a certain velocity, and oxygen concentration. The area in which these conditions are met can be referred to as the endogenous fire hazard zone. In this zone, the physical and chemical parameters of the air reach certain limits that are conducive to the initiation of carbon oxidation. Based on these conditions, criteria were formulated to determine this fire hazard zone. They are as follows:

- presence of crushed coal left in goaves,
- air velocity through goaves within the limits from 0.0015 m/s to 0.02 m/s,
- oxygen concentration in the air flowing through goaves equal or higher than 8%.

The determination of a fire hazard zone in real conditions is impossible because it is created in coal excavations (goaves) which are inaccessible to humans. For this reason, in order to determine this zone, model tests—based on numerical simulations—were applied, which are successfully used for variant analysis of processes connected with airflow through the mine interior and for the analysis of emergency conditions that may occur there and their potential consequences.

The commercial software, ANSYS Fluent, was used to perform this stage of analysis. The methodology of model testing involved the development of a geometric model of the studied region and its discretization, followed by the creation of a mathematical model and the adoption of boundary conditions. For the model developed in this way, calculations were performed. The Finite Volume Method was used to discretize the geometric model. The mathematical representation of airflow through the longwall and galleries was based on the Navier–Stokes (N-S) equation and the k-ε turbulence model. The momentum balance in porous medium and continuity in porous medium equations were used for estimating airflow through the porous media, and the species conservation and energy conservation equations were used for flow analysis. The permeability of the goaves was determined based on the results and equations presented in one study [73].

Determining such a zone makes it possible to locate an area in goaves (in the spatial arrangement) in which preventive measures can be taken. In the developed solution, these actions involved supplying pipelines with either an ash-water mixture and/or inert gas.

The third stage of the developed method involved designing and constructing an installation to administer a substance (or a mixture of substances) into the determined area, depending on the location and size of the determined zone [40]. In the presented case, the substance was an ash-water mixture, either with or without an inert gas (carbon dioxide), which was fed into the endangered zone. The maximum production capacity of the developed and constructed installation is about 100 tons/h of the ash-water mixture. For industrial use, it uses fly ash stored in two ash bins, each with a capacity of 225 m^3, and a flow mixer that enables the continuous production of the mixture. Fly ash is supplied to the mixer from the storage reservoir through dosing devices (celluveyor) and an auger conveyor. Dosing capacity is adjustable and ranges from 20 to about 100 t/h. The ash is mixed in the mixer with saline mine water in the proper proportion. The ash and water are fed to the mixer via devices that enable continuous control of the flow rate (via electromagnetic flow meters). At the outlet of the mixer, the density of the mixture is monitored by an isotope flow densimeter. The mixture is gravitationally fed to the intermediate reservoir and then, through technological openings and pipelines, to the identified zone of fire hazard in the longwall goaves. The dosed components (ashes, water) and the density of the mixture are continuously monitored. The mixture is fed into the goaf with inert gas. Only those fly ashes which contain additional calcium oxide (CaO) are used for the water-ash mixture. Good penetrating and binding properties of this mixture cause better sealing of goaves, which is their main task.

The individual stages of cooperation in developing a method for reducing the fire hazard caused by the spontaneous combustion of coal are shown in Figure 2.

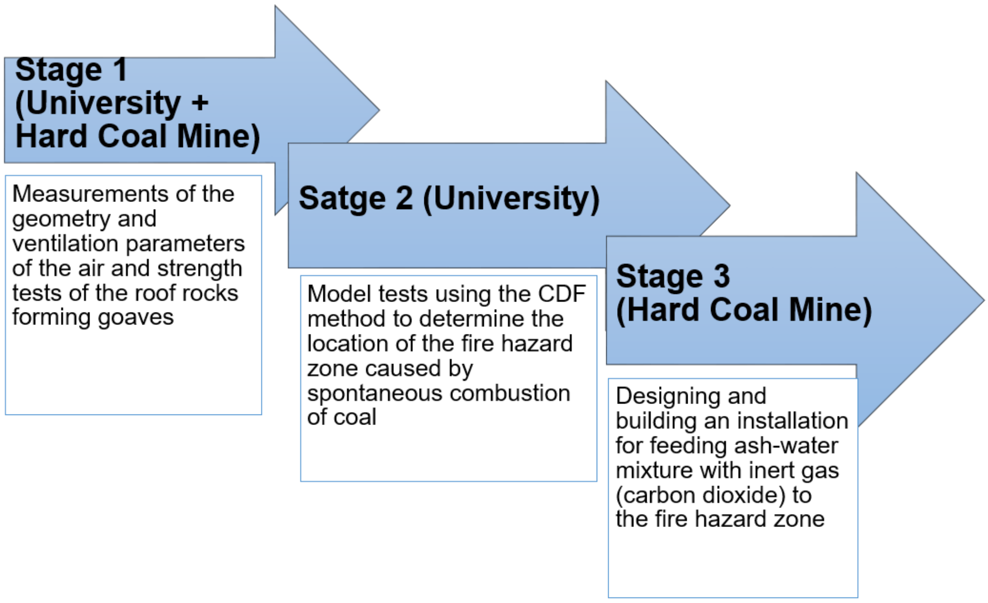


Figure 2. The stages of cooperation between the University and the mining company when developing and applying the innovative solution.

4. Results

As a result of the study carried out, the developed method was put into practice (implemented) in one of the hard coal mines.

According to the stages presented in Figure 2, the geometry of the examined area and the strength parameters of the roof rocks forming the collapsing zone were determined first, and ventilation parameters were measured. The obtained data were used to develop a model of the examined region, including the longwall, the headings, and the goaves.

The process of building this model consisted of three parts (Figure 3): the construction of a geometrical model as well as the discretization and creation of a mathematical model. The process of creating a mathematical model is preceded by defining unambiguous conditions and involves the selection of a model characterizing the fluid flow (e.g., turbulent or laminar flow), the identification of material properties of gases (and also solids), the assignment of values for initial conditions (based on roof rock strength tests), and boundary conditions (based on ventilation measurements).

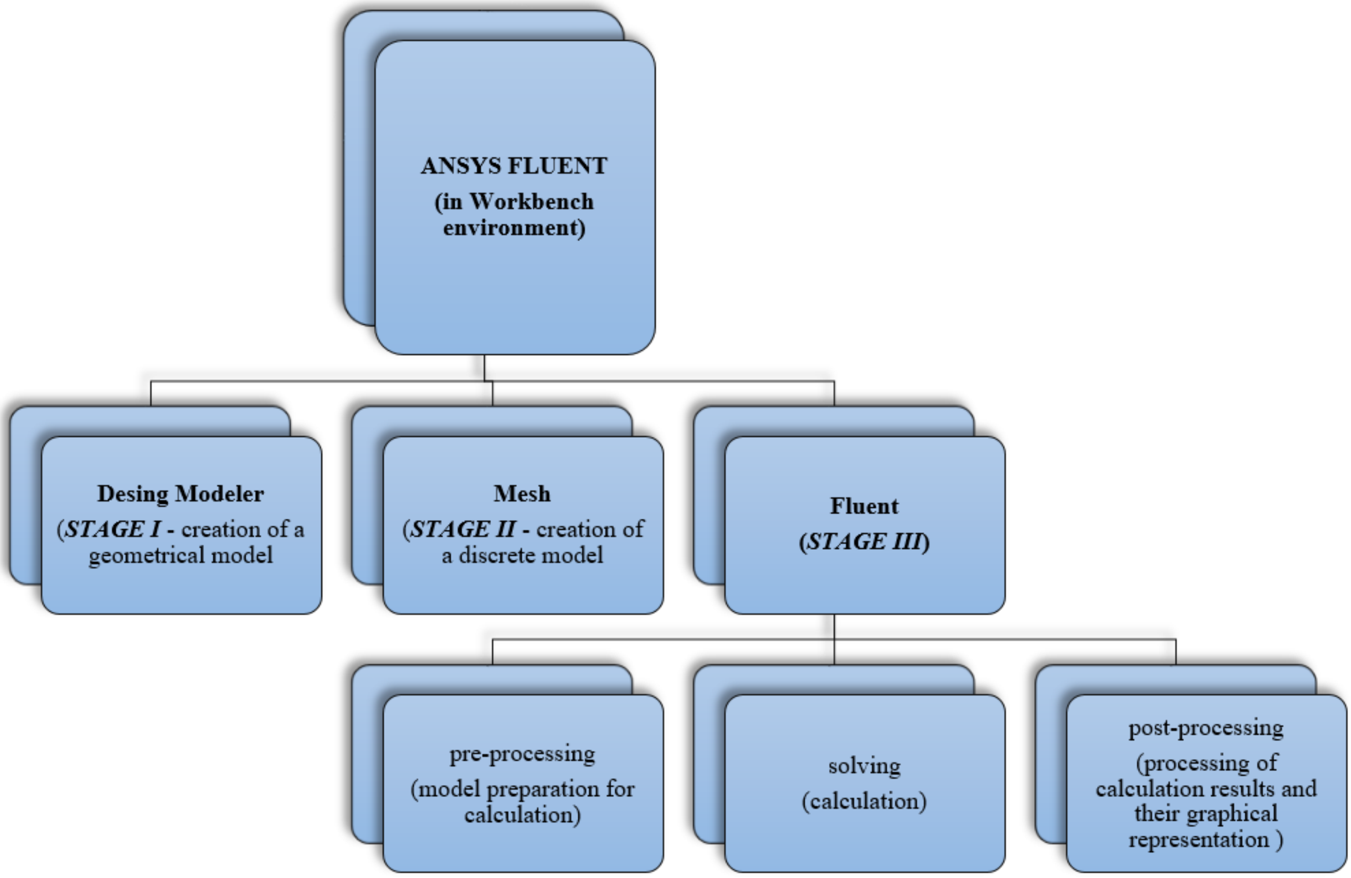


Figure 3. The scheme of conducted model tests (stage 2 of cooperation).

The model of the studied area for which the fire hazard zone was determined (developed by the University representatives) is shown in Figure 4.

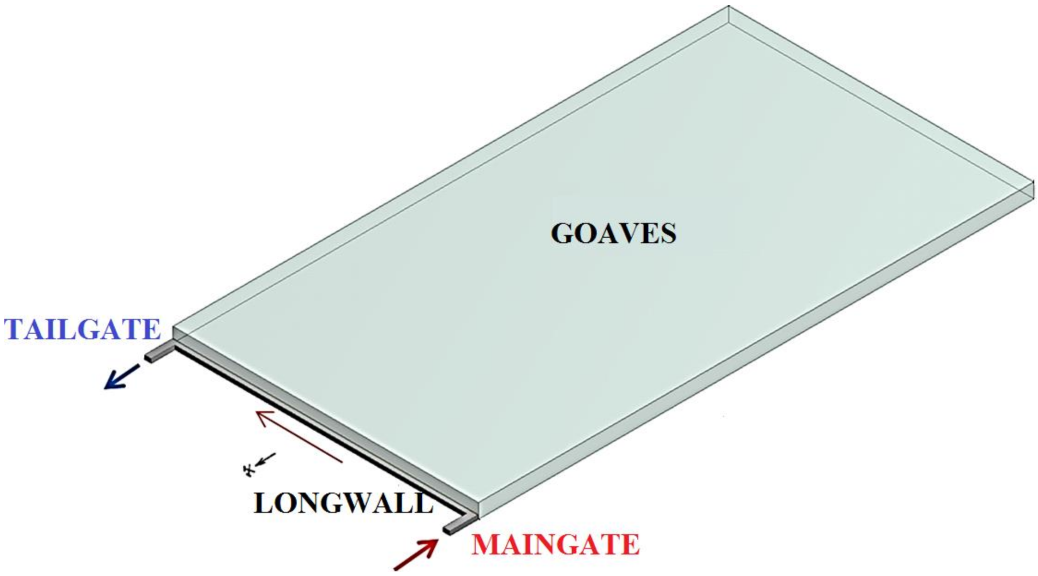
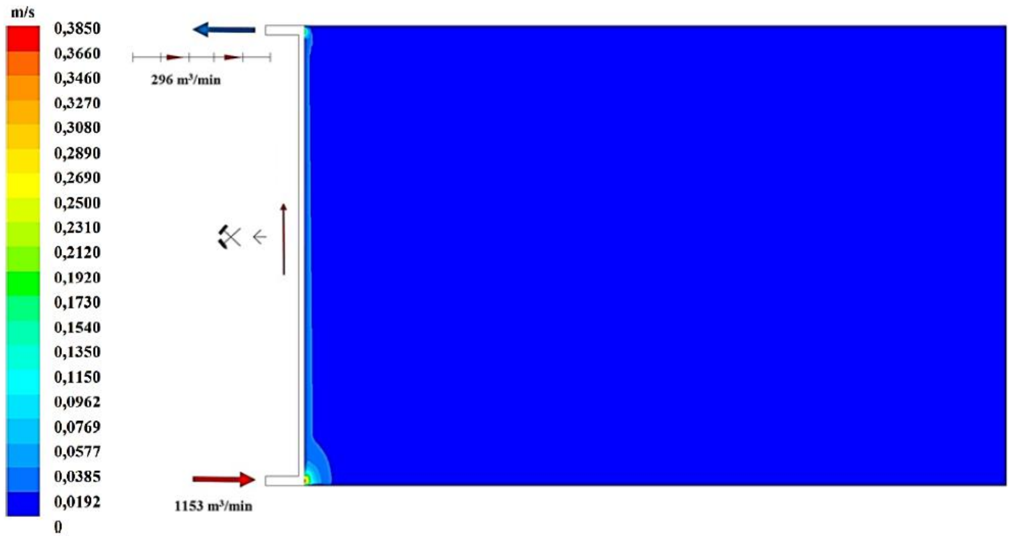


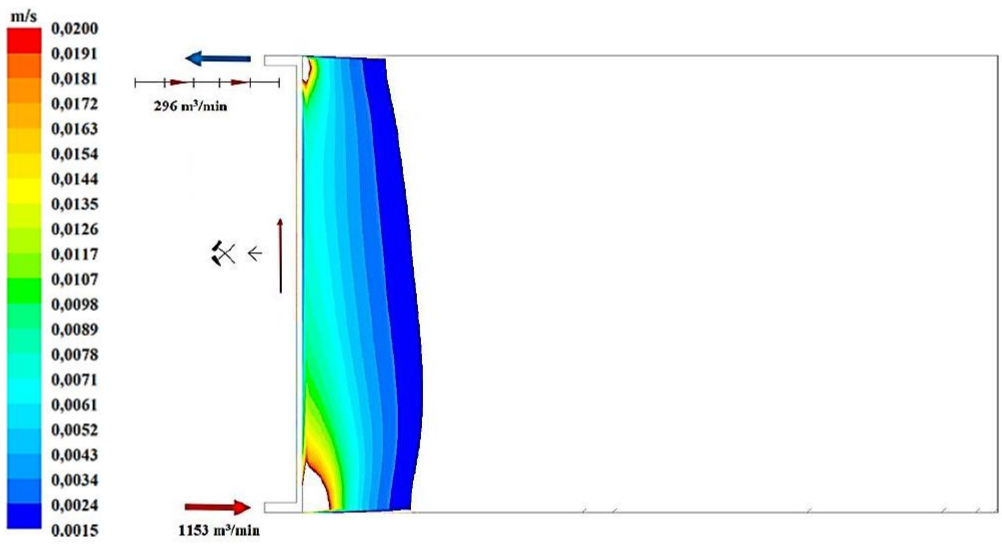
Figure 4. The model of the studied mining area.

The developed model was subjected to analysis, and as a result of this, the distributions of the physical and chemical parameters of the air stream flowing through the goaves were determined. The distribution of these parameters can be determined in any area and any point of the goaf.

Figure 5 shows the distribution of air velocity (Figure 5a) and the velocity considered dangerous due to the fire hazard caused by the spontaneous combustion of coal (Figure 5b). The distribution of oxygen concentration in the air flowing through the longwall goaves at a distance of 2.0 m from the bottom of the exploited seam is presented in Figure 6.



(**a**)



(**b**)

Figure 5. Air velocity distribution (**a**) and dangerous velocity (**b**) in the longwall goaves.

On the basis of the air velocity distribution and the oxygen concentration in the air flowing through the longwall goaves, a fire hazard zone was determined. The range of this zone is presented in Figure 7 and Table 2.

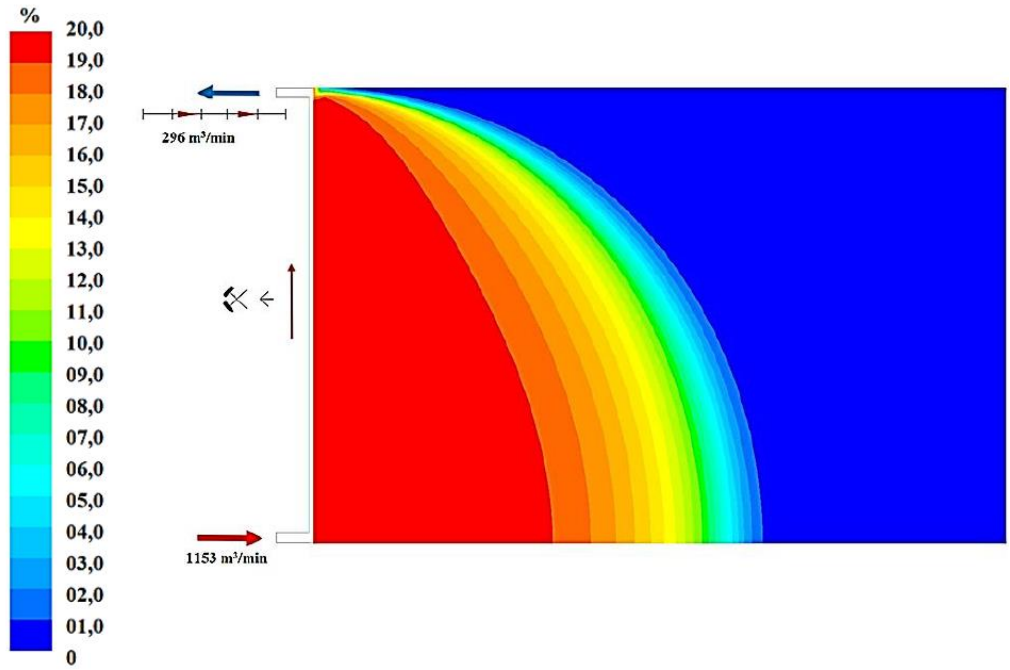


Figure 6. The distribution of oxygen concentration in the air flowing through the longwall goaves in the distance of 2.0 m from the bottom of the exploited seam.

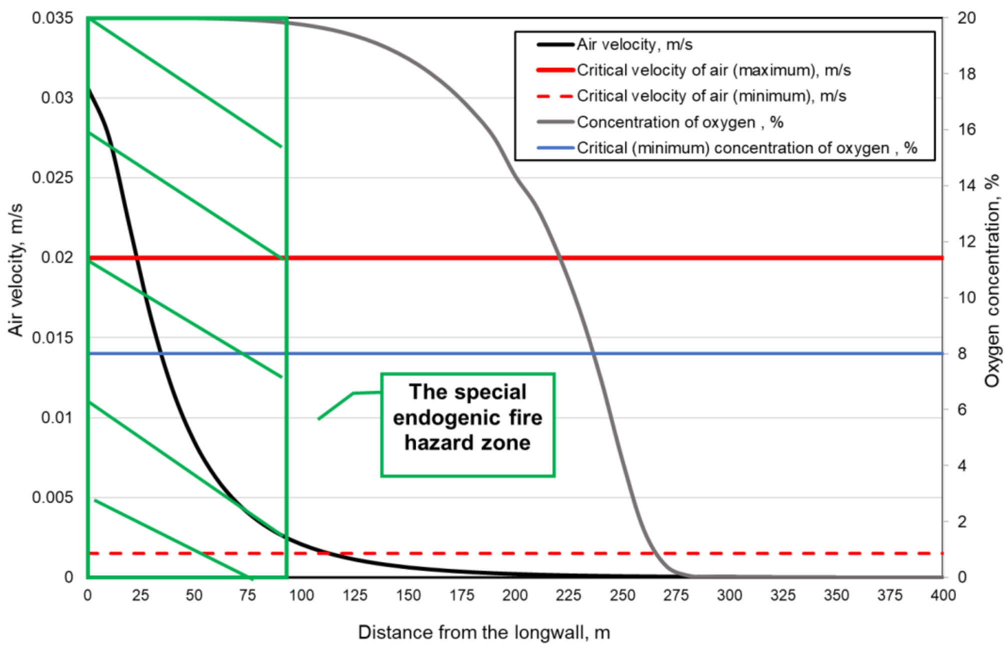


Figure 7. The location of the fire hazard zone in the longwall goaves.

Table 2. The range of the fire hazard zone caused by spontaneous combustion of coal in the longwall goaves.

Location of the Zone in Relation to the Critical Velocity of Air Flowing through the Longwall Goaves	Location of the Zone Due to the Critical Concentration of Oxygen in the Air Flowing through the Longwall Goaves	Location of the Special Endogenic Fire Hazard Zone
0–95.0 m	0–188.0 m	0–95.0 m

The endogenic fire hazard zone determined in this way unambiguously indicates areas in the goaves that are particularly exposed to the initiation of the process of low-temperature oxidation of coal. Thus, the location of this zone defines an area that must be taken into account in the process of preventive actions that are aimed at reducing or even eliminating the possibility of such a fire.

The identification of a zone in which there is a possibility of an endogenous fire led to further actions related to the reduction of this threat. These activities were undertaken by specialized mine services. They involved supplying the ash-water mixture with inert gas (carbon dioxide) through a network of underground pipelines. The mixtures were prepared on the mine surface in a specially designed and constructed installation. A general scheme of a technological line for preparing and administering appropriate mixtures to the endangered zone is shown in Figure 8.

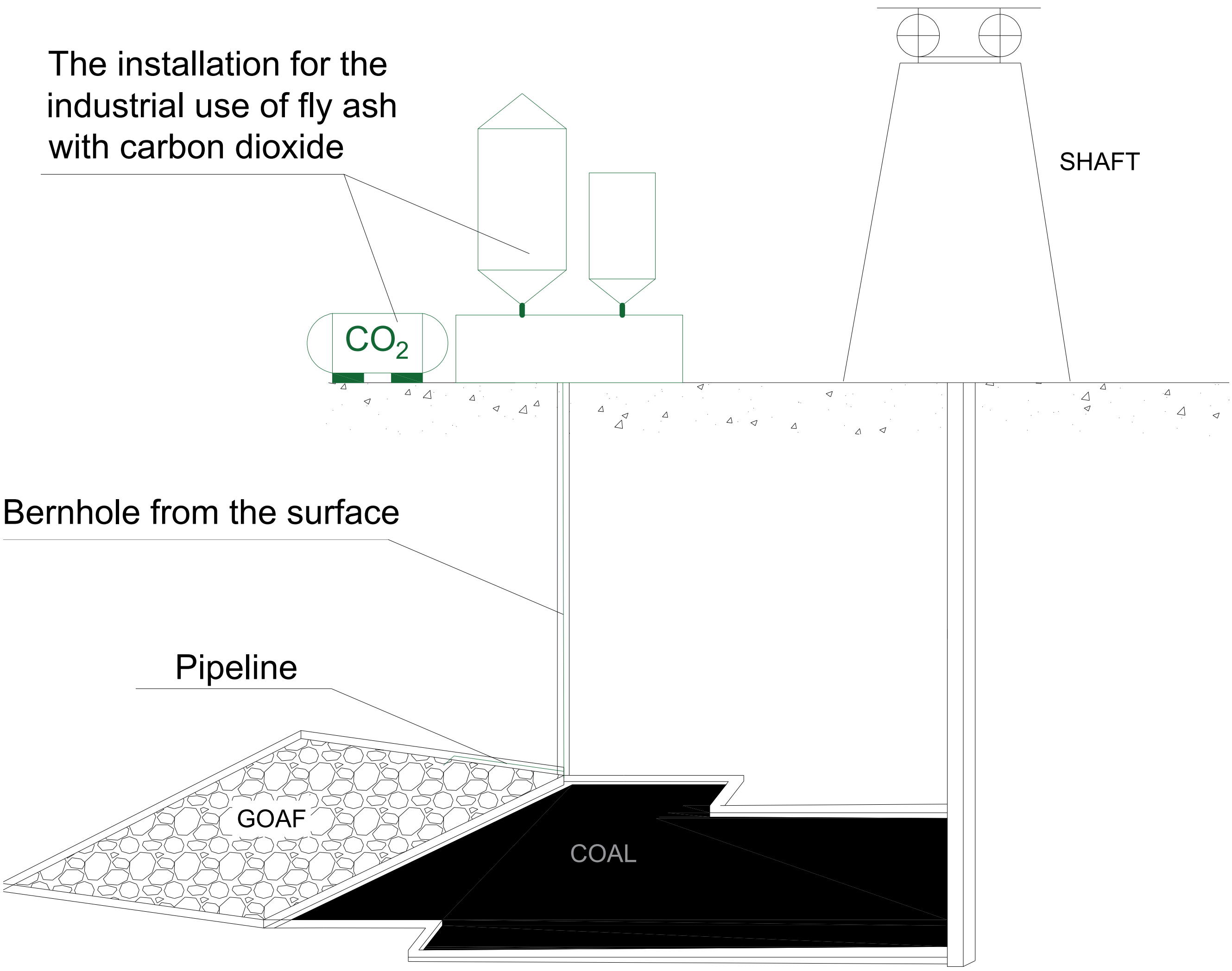


Figure 8. A technological pipeline for the production and transport of substances used for fire hazard reduction in the goaves.

A diagram of the examined region with the location of the fire hazard zone and the manner of administering the neutralizing mixtures is shown in Figure 9. In this diagram, when defining a zone of a potential threat of an endogenic fire, the initial section of the goaf (directly behind the casing) was taken into consideration, which, due to the incubation time, should be regarded as a neutral zone.

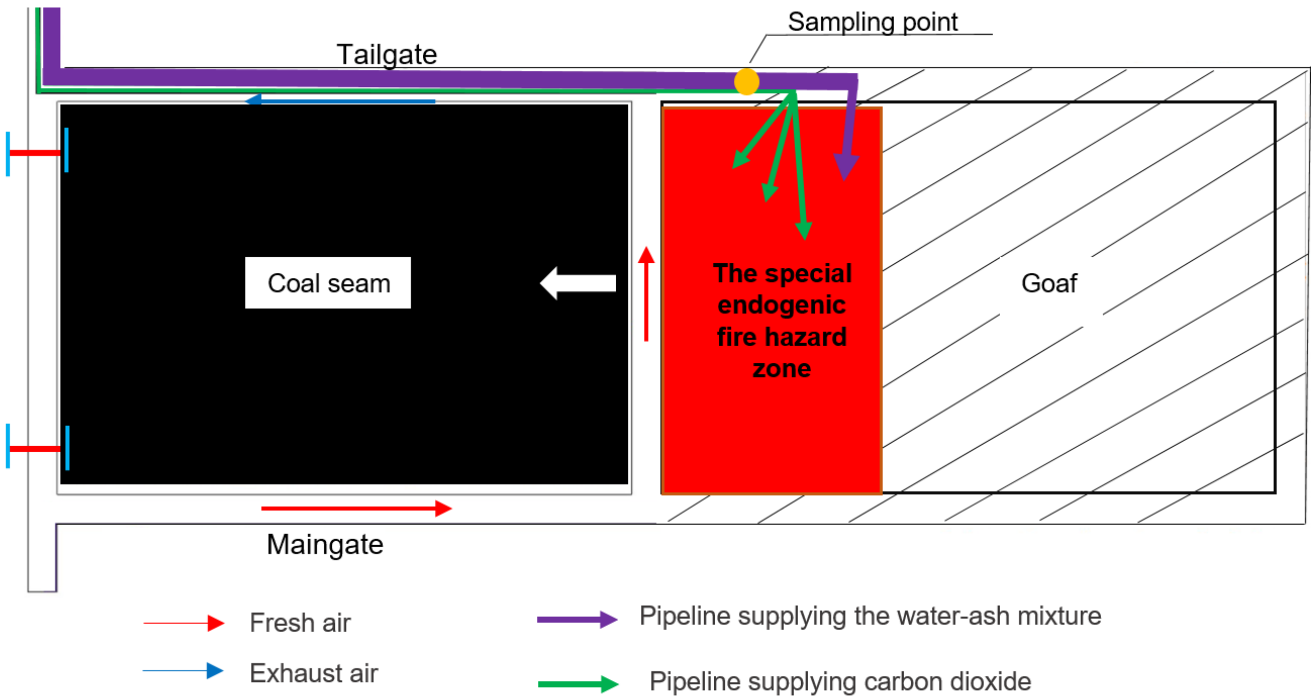


Figure 9. Diagram of the examined area with the method of administering substances limiting the occurrence of an endogenic fire to the hazard zone.

The process of limiting the fire hazard in goaves, from the moment a dangerous zone is determined, consists of the effective and timely introduction of a means to limit the oxygen flow into this zone. In the final stage of this process, these agents are delivered through pipelines installed in a tailgate (Figure 9), and then they are introduced into the dangerous zones in the goaves.

Nitrogen (inert gas) administered to goaves from the side of a tailgate, in accordance with the distribution of aerodynamic potentials, limits the migration of air from a longwall to a collapsing zone. Additionally, appropriately selected parameters of the mixture flow make it possible to lessen drops in aerodynamic potentials, which in turn hinders the maintenance of physical and chemical parameters of air which are favorable for the coal oxidation process.

Supplying inert gas (nitrogen) to goaves decreases their oxygen concentration, which in turn limits the formation and development of the self-heating process of coal. Inerting the fire hazard zone with nitrogen also reduces the possibility of creating an explosive mixture, which is connected to the presence of methane. Therefore, it can be assumed that the developed solution limits the possibility of dangerous events occurring both as a result of an endogenous fire as well as an explosion or the ignition of methane in this zone.

The developed method also enabled the supply of the ash-water mixture from the side of the tailgate. The use of these mixtures is aimed at sealing goaves as well as cracks and fissures created in the rock mass as a result of mining exploitation. In general, ash-water mixtures have properties that penetrate goaf debris and make it possible to seal them and reduce the fire hazard level. This process limits the flow and migration of oxygen-rich air from a longwall to goaves.

On the other hand, supplying the other inert gas (carbon dioxide) from the side of a maingate improves the efficiency of inerting goaves. Carbon dioxide injected into a goaf is supposed to prevent the start of the self-heating process of coal by reducing the rate of its oxidation reaction. Carbon dioxide, as an inert gas, has absorbing properties, which limits the oxygen access to crushed coal deposited in goaves.

The practical experience of coal mine workers (industry representatives) has shown that the best effects of inerting with carbon dioxide are achieved if it is injected at the initial stage of the coal-heating process. Therefore, it is very important to conduct early fire detection and air quality research (chromatographic analyses—stage 1 of the developed methodology) and to determine a hazard zone using model tests conducted by the academic community (stage 2 of the developed methodology).

As can be seen, the tests of chemical parameters of ventilation air flowing out of a longwall are immensely important in the developed methodology. The appearance of elevated concentrations of carbon monoxide, as well as hydrocarbons (ethylene, propylene, acetylene, or hydrogen) in this air unambiguously indicates the beginning of the coal self-heating process. The identification of these substances in the ventilation air at the initial stage of the coal-heating process enables the quick reaction of the appropriate mine services in order to limit the possibility of fire development. Thus, the created solution enables the integration of all preventive actions against the development of an endogenous fire. Early detection of symptoms and decisive actions aimed at specific locations (determined by model tests) make it possible to effectively limit this danger.

Monitoring the quantity of injected substances and the analysis of aerodynamic potentials are carried out based on the results of precise chromatographic studies of air composition taken from goaves mainly on the side of a maingate. On this basis, changes in the coal temperature are also determined, which also has a significant impact on the diagnosis of the threat of endogenic fires.

In cases where there are limited possibilities for sealing goaves (which often happens in practice) and with low exploitation progress, inerting goaves with carbon dioxide and nitrogen is the most effective prevention against the initiation and development of the coal self-heating process in goaves.

The discussed method of limiting the danger of endogenic fires in underground mining exploitation was applied in practice. The results of changes in the contents of carbon monoxide (CO) and unsaturated hydrocarbons of the C_2–C_4 group (during mining) obtained from the research confirmed its effectiveness (Figures 10 and 11) [40]. They also proved that open cooperation between a university and a production company operating in a very difficult environment might generate measurable effects.

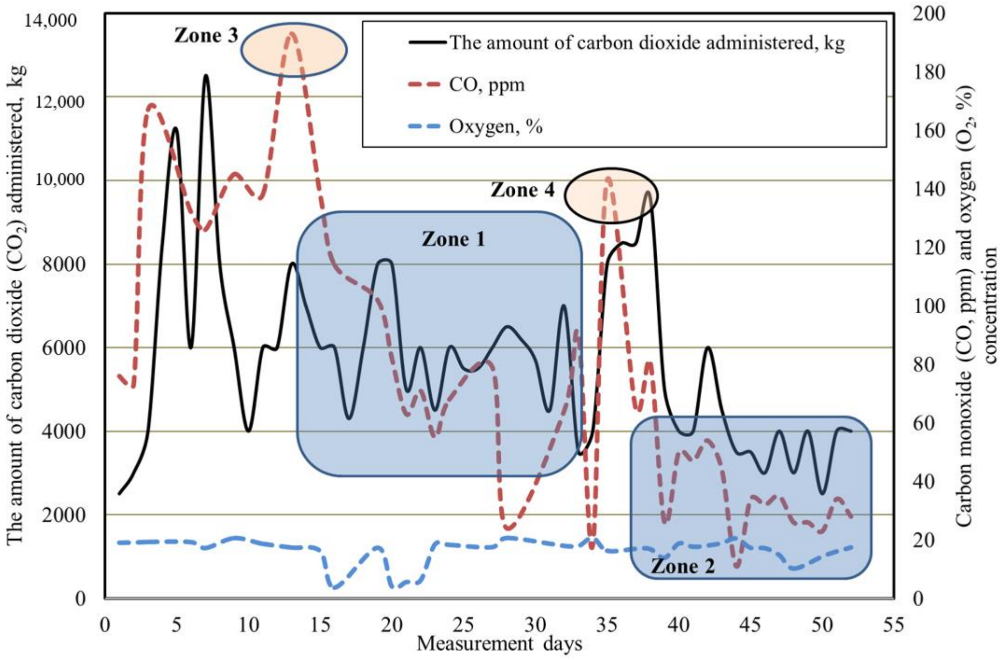


Figure 10. Temporary changes of carbon monoxide (CO) and oxygen (O_2) concentrations in the mine atmosphere while inerting the goaves with carbon dioxide (CO_2).

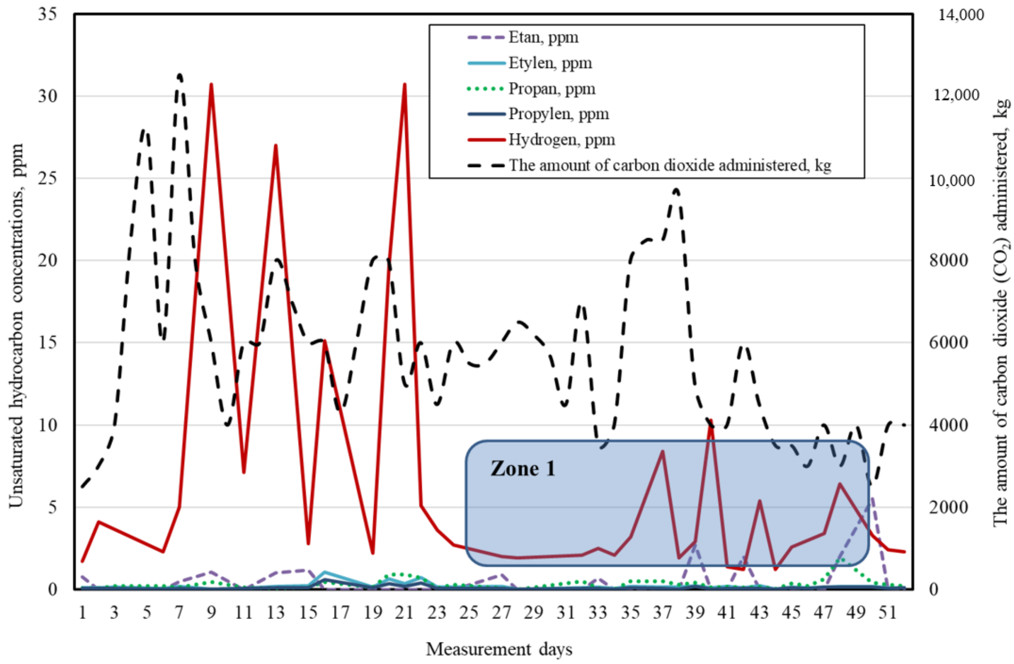


Figure 11. Temporary changes of unsaturated hydrocarbon concentrations in the mine atmosphere while inerting the goaves with carbon dioxide (CO_2).

Figure 10 presents the time changes of carbon monoxide (CO) and oxygen (O_2) contents in the mine atmosphere and the amount of carbon dioxide (CO_2) supplied at that time as inert gas to the goaves. In this diagram, zones (1 + 2) with a distinct decrease in carbon monoxide concentration due to prophylactic measures are marked. There are also zones (3 + 4) with momentary increases in concentration, which decreased with time and an increase in the amount of supplied inert gas.

Time waveforms of unsaturated hydrocarbon concentrations in the mine atmosphere were also determined for the same test time (Figure 11). The recorded changes proved that the coal heating process was reduced, which is particularly visible in zone 1.

The analysis of the obtained gas concentrations (products of the coal heating process) showed that the application of the developed method considerably decreased the threat of an endogenic fire.

The resulting measurements of fire gas concentrations in the air taken from the long-wall goaves in which the method was implemented showed that their values decreased on successive days of inert gas administration. This means that the oxidation reaction of coal, which could have led to a fire if the method had not been applied, was limited. At the same time, this confirms the effectiveness of the measures taken and the application of the developed method.

When analyzing the graphs presented, it should be stressed that in Polish hard coal mining, carbon monoxide (toxic gas) is the most important indicator gas that relates to the occurrence of reactions connected to the oxidation and self-heating of coal, consequently leading to its self-ignition. Therefore, the measurements of its concentration (Figure 10) indicate that its share in the air decreased with each day on which the ash-water mixture and carbon dioxide were injected into the goaves. On the other hand, hydrogen, ethane, propane, propylene, and ethylene (Figure 11) belong to gases that are emitted into the mine atmosphere with increasing coal temperature. Thus, an increase in their concentration indicates the development of self-heating coal. In the presented case, however, such a phenomenon did not occur, and concentrations of these gases showed a decreasing trend, which was caused by the undertaken measures.

To sum up, it can be stated that the obtained results of the measurements of fire gas concentrations in the air samples from the goaves, to which the ash-water mixture with carbon dioxide was supplied, do not indicate the occurrence of endogenic fires. Therefore, these findings prove the effectiveness of the applied method. The comprehensive approach to the problem of fires brought satisfactory results. The exploitation of this longwall was carried out without major disturbances, and its liquidation proceeded according to plan with no major disturbances either.

5. Discussion: Mining Open Innovation

The developed and presented method of fire hazard reduction is a technological innovation and defines a completely new direction and approach to combating the fire hazard caused by the spontaneous combustion of coal in underground mining. In terms of broadly understood safety and effectiveness of the mining production process, this method can be used to combat the fire hazard not only in underground goaves of hard coal mines but also, e.g., on coal or mining waste heaps. It can also be successfully applied to reduce the methane hazard. Thus, the presented approach can be considered a very modern and effective solution resulting from open cooperation between scientific and working communities.

The method of limiting the danger of the spontaneous combustion of coal (endogenous fire) presented in this paper differs from the methods used so far, mainly in the precise identification of the endangered zone (by means of model tests). This causes higher effectiveness and lowers the costs connected with the goaf inertization process. Furthermore, another original element involves the composition of the mixture fed to the goaves, which consists of water and ashes containing additional calcium oxide (CaO). Moreover, this mixture is enriched with inert gas (CO_2). So far, in order to reduce fires, mainly three-phase foam consisting of silt, nitrogen, and water [64] or a slurry consisting of sand, cement, water, and a high content of fly ash with a certain amount of aerated foam [65] has been fed into goaves. On the other hand, Zhang [66] used gel for inerting the goaves, it being a material that combines water and solid particles well. On the other hand, Liu and Weng [67] developed a technology based on N2-inhibitor-water mist (NIWM).

What is crucial in the presented methodology is the original method of determining an appropriate zone in a goaf into which the prepared mixture should be administered. This reduces the area of isolation and thus minimizes costs and increases the effectiveness of the operations. The key in this process was the determination of the critical air velocity, which promotes the carbon oxidation process. In the literature, large discrepancies on this subject can be found. For example, Cheng et al., in their study, assumed the value ranging from 0.004 to 0.0016 m/s [73]. On the other hand, Chumak et al. [74] assumed that the critical velocity value is between 0.015 and 0.0017 mm/s. Szlazak, on the other hand, reported that the value is in the range of 0.015 to 0.0015 m/s [75], while Wang et al. [76] reported that the value is between 0.001 and 0.02 m/s. The velocity ranges given are quite wide, so in the method developed, the velocity was assumed to be between 0.02 and 0.0015 m/s. The adoption of such values allowed the determination of a slightly wider danger zone, which, however, reduced the possibility of making mistakes and was positively verified in practice.

The effectiveness of the developed solution is particularly visible in the case of coal seams exploitation, where coal has a short incubation time. The progress of exploitation is then crucial, and without the application of the developed solution, it will be difficult to control this hazard, and if it is successful, the costs are much higher. In this case, determining the location of sites of potential fires plays a decisive role.

The importance of the developed innovation as a result of the cooperation between the University and industry has been noticed and appreciated not only in mining and academic circles but also in the national forum. This solution was awarded the first prize in the 47th edition of the National Competition for the Improvement of Working Conditions in Poland. This competition was organized by the Ministry of Family, Labour, and Social Policy in cooperation with the Supreme Technical Organization, the Higher Mining Authority, the Technical Supervision Authority, inspection authorities, insurance institutions, and social partners. The effectiveness and openness of cooperation between the stakeholders of this solution and its importance for the economy were appreciated above all.

The developed and implemented solution, which resulted from the implementation of the open innovation concept in the mining industry, showed that despite the conservative approach of the representatives of this sector to new solutions, cooperation with the academic environment can bring very measurable and positive effects. As indicated by one study [30,77,78], the capacity for technological innovation in a hard coal mine consists of four elements: research and development capacity, resource exploitation capacity, organizational management capacity, and financial capacity. The solution presented in this paper confirms these elements, proving that it is possible to effectively implement innovations—particularly desirable in the area of safety—also in this industry.

6. Conclusions

The concept of Open Innovation is a great opportunity for the development of an innovative knowledge-based economy. Its practical application requires openness, willingness to share knowledge, and close cooperation between stakeholders. This paper presents a valuable example of the application of this concept, which concerns an important and current problem. Improving work safety and, consequently, process efficiency, especially in the mining industry, is an extremely valuable achievement. Its basis was the openness of both the academic community and the industry representatives, who for many years have had a problem with effectively reducing endogenous fire hazards. Their openness in presenting this issue and willingness to solve it made a group of scientists—specialists in porous media model tests—interested in this joint venture. Moreover, the openness and willingness to help and apply the developed tools for modelling these complex physical phenomena resulted in cooperation in taking on the indicated problem. The result of these activities was the development of an innovative method to reduce the risk of endogenic fires in hard coal mines. The involvement and positive attitude of the mining company management towards new innovative solutions resulted in the implementation of the developed method.

The method, which uses model tests to identify fire hazard zones, enables—thanks to the developed installation, the administration of the ash-water mixture with inert gas to the designated zone to reduce the fire hazard. Directing preventive activities to a precisely defined region significantly reduces the costs of prevention and increases the speed of reaction to the emerging symptoms of danger, which significantly reduces the occurrence of hazardous events.

The originality of the developed and applied method of limiting endogenic fires caused by the spontaneous combustion of coal can be determined by several factors. First of all, its application enables the efficient use of resources for fighting these fires. This, in turn, improves occupational safety and ensures continuity of the exploitation process. Achieving these results was possible thanks to close cooperation between science and industry (coal mines), which is a positive example of the application of the OI concept. An unquestionable achievement of the paper is the precise identification of the zone threatened by an endogenic fire. The use of model tests and measurements in real conditions confirms the enormous potential for the effective modelling of complex physical phenomena and practical use of the results of such studies. Another important and new element of this method is the developed installation that makes it possible to deliver appropriate mixtures to goaves at deep depths (below 700 m). The capacity of this installation, developed by representatives of the industry (coal mines), is over 100 tons/hour. The composition of the supplied mixture and its combination with inert gas (CO_2) dosing, which reduces the possibility of coal self-heating, is also original. Adding fly ash containing calcium oxide (CaO) to the mixture results in good sealing of goaves, which limits the possibility of oxygen inflow to the danger zone.

Therefore, it can be concluded that the precise identification of the fire endangered zone and then the injection of the original water-ash mixture and inert gas into it is a new and effective approach to fighting this danger, as proven by the research results. It is worth emphasizing that this method can also be applied to other deposits threatened by endogenic fires. In such cases, however, it is necessary to conduct model tests to identify such an endangered zone, which in each case may be located differently. Nevertheless, the methodology itself remains unchanged.

A particularly important achievement of the study is the implemented model of cooperation (Section 2, Figure 1) between science and industry, which can be successfully applied to solve other problems related to the mining process and other industries.

The most important practical achievement of the developed method was the prevention of fire in the area where the mine (enterprise) was extracting hard coal (the main raw material for energy production in Poland). This allowed effective and safe operation of the longwall without interrupting the exploitation process. The costs of preventive actions carried out within the framework of the implemented solution made it possible to avoid a situation in which a fire would result in damming of the exploitation area and thus huge economic losses for the mine related to the discontinuation of exploitation and immobilization of the longwall machinery.

Therefore, the developed innovative solution met its objectives while confirming the validity of the adopted model of cooperation between an academic centre and a production company. In the presented case, the knowledge transfer was bi-directional. This means that the University provided scientific knowledge to the industrial partner, who supported the University staff with practical knowledge in the scope of the implemented production processes and access to a real research (testing) ground. Thus, the application of the IO concept made it possible to solve an important problem, and the experiences gained should be used in subsequent joint ventures. Building a knowledge-based economy must take into account open possibilities for the flow of knowledge, ideas, and also information about experienced problems, which can be an inspiration to generate new innovative solutions. At the same time, the commercialization of research results and their implementation, as well as the related transfer of knowledge to the socio-economic environment, including the non-commercial one, should be the ultimate goal of innovation policy.

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