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STANISŁAW NAWRAT*

INVASIVE FILLING OF SEALED HEADINGS AND GOAFS IN COAL MINES WITH METHANE — EXPERIMENTAL AND MODEL RESEARCH

INWAZYJNE WYPEŁNIANIE METANEM OTAMOWANYCH WYROBISK I ZROBÓW W KOPALNIACH WĘGLA KAMIENNEGO — BADANIA EKSPERYMENTALNE I MODELOWE

The control and regulation of gaseous states in sealed headings and goafs is a very important problem in coal mines, especially in view of the dangers associated with endogenic fires and explosions of methane or fire gases.

The compositions and concentrations of gases in sealed headings and goafs can be influenced by means of the following factors:

- natural factors — the inflow of methane and carbon dioxide from the rock mass,
- internal factors — the inflow and outflow of goaf gases and the inflow of the products of oxidation and coal burning in goafs,
- external factors — the inflow of air caused by ventilation and methane drainage,
- external invasive factors — the supply of inert gases or the mixtures of air and methane and the mixtures of goaf gases by means of installations.

Because of its considerable effectiveness in limiting the hazards associated with fires and explosions of fire gases, the methane filling method has been used on numerous occasions in the coal mines belonging to the Jastrzębię Coal Mining Holding in the period 1978–1998.

In order to acquire a full knowledge on the course of filling sealed headings and goafs with methane, experimental research was conducted in normal conditions in sealed areas of longwalls in the "Pniówek" and "Zofiówka" coal mines, which are characterized as containing the greatest absolute methane-bearing capacities in Poland. In the process of methane filling, in sealed headings and goafs appeared non--explosive mixtures because of the excess of methane, which is extremely important for work safety. During the experiment the oxygen content was falling proportionately to the increase in methane concentration, which had a favourable influence on reducing the hazard of an endogenic fire in goafs.

For designing a methane filling process for sealed headings and goafs. and especially for the evaluation of changes in gas concentrations and safety, a mathematical model has been developed. Such a mathematical model, supported by computer calculations, makes it possible to carry out simulations of the influence of particular parameters on the effectiveness of the process. Computer simulations generate additional information on changes taking place in the composition of gases in a given area that are not obtained by means of experimental research.

* KATEDRA GÓRNICTWA PODZIEMNEGO, AKADEMIA GÓRNICZO-HUTNICZA, AL. MICKIEWICZA 30, 30-059 KRAKÓW, POLAND.

It was shown experimentally that the application of the method of filling sealed goafs and headings with methane enabled:

- to regulate within a specific range the composition and concentration of goaf gases, especially the concentration of methane and oxygen,
- to change under control the composition and concentration of gases — the air-methane mixture with a view to reducing its explosiveness,
- to lower the concentration of oxygen, and by this, to reduce considerably the possibility or speed of the development of the process of self-heating of coal or an endogenic fire.

This paper is a contribution to the development of the scientific principles of the invasive filling of sealed headings and goafs with gases with a view to regulating the composition and concentration of goaf gases with respect to fire and explosion hazards, which consequently should improve work safety in coal mines.

Key words: methane, explosion hazard, regulating the composition of goaf gases, experimental and model research, simulation, fire and explosion preventive measures

W kopalniach węgla kamiennego bardzo ważnym problemem jest kontrola i regulacja stanów gazowych w otamowanych wyrobiskach i zrobach, szczególnie w aspekcie zagrożenia pożarami endogenicznymi i zagrożenia wybuchem metanu lub gazów pożarowych.

Składy i stężenia gazów w otamowanych wyrobiskach i zrobach mogą być kształtowane pod wpływem czynników:

- naturalnych — dopływ gazów: metanu lub dwutlenku węgla z górotworu,
- wewnętrznych — dopływ i odpływ gazów zrobowych oraz dopływ produktów procesu utleniania i palenia węgla w zrobach,
- zewnętrznych — dopływ powietrza w wyniku przewietrzania kopalni, prowadzenia
- odmetanowania,
- zewnętrznych inwazyjnych — doprowadzenie gazów inertnych lub mieszanin metanowo-powietrznych i mieszanin gazów zrobowych za pomocą instalacji.

Ze względu na dużą skuteczność w zakresie ograniczenia zagrożenia pożarowego i wybuchem gazów pożarowych metoda wypełniania metanem stosowana była wielokrotnie w kopalniach Jastrzębskiej Spółki Węglowej S.A. w latach 1978–1998.

W celu uzyskania pełnego rozeznania przebiegu procesu wypełniania metanem otamowanych wyrobisk i zrobów przeprowadzono badania eksperymentalne w warunkach normalnych, w otamowanych rejonach ścian w kopalniach „Pniówek" i Zofiówka", które charakteryzują się największymi metanowościami absolutnymi w górnictwie polskim. W czasie wypełniania metanem w otamowanych wyrobiskach i zrobach wystąpiły mieszaniny niewybuchowe ze względu na nadmiar metanu, przy czym podawanie metanu w znacznym stopniu przyspieszyło wystąpienie mieszanin niewybuchowych ze względu na nadmiar metanu, co jest niezmiernie ważne w aspekcie bezpieczeństwa pracy. W czasie eksperymentu w odpowiedniej proporcji do wzrostu stężeń metanu następował spadek zawartości tlenu, co wpływało w sposób korzystny na ograniczenie zagrożenia powstania pożaru endogenicznego w zrobach.

Dla projektowania procesu wypełniania metanem otamowanych wyrobisk i zrobów, szczególnie dla oceny przebiegu zmian stężeń gazów i bezpieczeństwa, został opracowany model matematyczny, który przy wykorzystaniu obliczeń komputerowych umożliwia przeprowadzenie symulacji wpływu parametrów na efektywność procesu. Symulacja komputerowa pozwala na uzyskanie dodatkowych informacji o zachodzących zmianach w składzie gazów rozważanego obszaru, których nie uzyskano drogą badań eksperymentalnych.

Eksperymentalnie wykazano, że zastosowanie metody wypełniania metanem otamowanych wyrobisk i zrobów pozwoliło na:

- regulowanie w określonym zakresie składu i stężenia gazów zrobowych, szczególnie stężenia metanu i tlenu,
- zmienianie w sposób kontrolowany składu i stężenia gazów — mieszaniny metanowo-powietrznej pod kątem ograniczenia jej wybuchowości,

- obniżenie stężenia tlenu, a tym samym w istotnym stopniu ograniczenie możliwości lub prędkości rozwoju procesu samozagrzewania węgla lub pożaru endogenicznego.

Praca jest przyczynkiem do rozwoju naukowych zasad inwazyjnego wypełniania gazami otamowanych wyrobisk i zrobów w celu odpowiedniego pod kątem zagrożenia wybuchowego i pożarowego regulowania składu i stężenia gazów zrobowych, co w konsekwencji pozwoli poprawić stan bezpieczeństwa pracy w kopalniach węgla kamiennego.

Słowa kluczowe: metan, zagrożenie wybuchowe, regulowanie składu gazów zrobowych, badania eksperymentalne i modelowe, symulacja, prewencja przeciwpożarowa i przeciwwybuchowa

1. Introduction

Since its very beginning Poland's coal mining industry has had to cope with various natural hazards accompanying mining operations, especially with the methane hazard. And the problems connected with such associated hazards as the methane, coal dust explosion and fire hazards have not lost their urgency in view of the conditions of high concentration of mining operations in coal mines, which is necessary for ensuring the economic profitability of production. This is also confirmed by the high absolute methane-bearing capacity of Poland's coal mines, which in 1999 equalled 1432.7 m^3 CH_4/min. (744.5 million m^3 CH_4/year), in which methane drainage comprised 252.2 m^3 CH_4/min. (130.2 million m^3 CH_4/year), which constituted just 17.6% of the absolute methane-bearing capacity.

Therefore the problems of managing the methane hazard with a view to ensuring work safety have been, and still are, the subject of research and experiments carried out by many scientists and men of practice, which can be confirmed by very rich literature on the subject.

In the past scientists concentrated in their research mostly on finding solutions to problems connected with ensuring methane concentrations in the coal mine air admissible by appropriate regulations and defining conditions for effective measures preventing methane explosions. On the other hand, issues connected with the occurrence of methane and other gases in goafs connected directly or indirectly to actively moving headings as well as questions of leaky reservoirs of methane and other gases were studied in research papers and experiments marginally and fragmentarily. The major reasons for that were metrological difficulties concerning the measurements of contents, concentrations and flows of goaf gases and difficulties resulting from calculating complicated model systems.

Considerable progress in this field has been in the papers of Dziurzyński 1981, 1985, 1988, 1996; Dziurzyński et al. 1988, 1992, 1993, 1995; Roszkowski et al. 1992, 1997, 1999; Pawiński et al 1974, 1979, 1989; J. Szlązak 1980, 2000; N. Szlązak et al. 1987, 1990; Sułkowski 1987, 1996; Trutwin 1972, 1973.

In their papers published so far, the authors have dealt generally with the question of the influence of the flow of natural methane, ventilation and methane drainage on the distribution of goaf gases' concentrations in the context of fighting the methane, explosion and fire hazards.

A limited scope of applying inert gases (Bystroń et al. 1998; Batko et al. 1985; Buchwald et al. 1976; Dziurzyński et al. 1996), and methane (Nawrat 1999; Nawrat et al. 1991) in fire and explosion preventive actions has resulted mainly from an unsatisfactory number of installations and a lack of solutions to a number of theoretical and practical problems determining a complete safety of the invasive influence of gases on the gas environment in goafs.

2. Possibilities of regulating composition and concentrations of gases in sealed headings and goafs

The composition and concentrations of gases in sealed headings and goafs undergo changes in space and time under the influence of the following factors:

- natural factors — the inflows of methane and carbon dioxide from rock mass; their quantitative and qualitative parameters result from a seam's geophysical conditions; possibilities of regulating them are basically limited,
- internal factors — the inflows and outflows of goaf gases and the inflows of the products of oxidation and coal burning in goafs whose quantitative and qualitative parameters can be regulated by means of ventilation and methane drainage, particular methods of mining (e.g. leaving coal in goafs), backfilling goafs with sand or power plant wastes, applying water to lower the temperature of rocks, and other methods,
- external factors — the inflows of air to goafs and outflows of goaf gases as a result of ventilation and methane drainage to headings with operating ventilation whose quantitative and qualitative parameters can be regulated,
- external invasive factors — the supply of inert gases to sealed goafs and headings in the form of nitrogen, carbon dioxide, argon or a gas mixture of methane and air (coming from methane drainage in other parts of the coal mine); such gases are supplied to goafs by means of invasive installations whose quantitative and qualitative parameters can be regulated to a considerable extent.

2.1. External regulation of gas concentrations

By regulating external ventilation parameters, it is possible to cause changes in the concentrations of gases in sealed headings and goafs. The method and scope of such actions can have a local character (a selected area of goafs) or a global character (selected groups of goafs or all goafs in a given coal mine).

2.2. Inertization method

The method of inertization consists in a regulated supply of mixtures of inert (inflammable) gases of low oxygen concentrations. As a result of such an invasive action, the original composition of gases changes and the final result is a gas mixture of a very limited oxygen concentration. It has an essential influence on reducing the processes of oxidation or coal burning as well as methane or other flammable gas explosion hazards. Inert gases used mainly in coal mining are low-oxygen steam and gas mixtures and nitrogen.

Low-oxygen steam and gas mixtures

Low-oxygen steam and gas mixtures are the result of burning liquid fuel with air in special burning chambers. The result of burning, e.g. aviation fuel, in a ring combustion chamber is a mixture of dry combustion gases with an oxygen concentration of 14—16%. An additional fuel injection in a so-called afterburner chamber causes the afterburning of oxygen, which reduces the oxygen concentration in exhaust gases to about 2%. The rest of exhaust gases is made up of CO_2 — from 13% to 16%, $H_2 + CO$ — about 1%, N_2 — a complement to 100%. Next, dry combustion gases are cooled with water which evaporates and causes that water vapour constitutes 60% of the volume at the outlet of moist gases. A Gas Fire Extinguisher Unit has been developed in Poland; it has been used in some fire-fighting operations.

Gaseous and liquid nitrogen

The arduousness of applying liquid nitrogen and carbon dioxide transported in gas cylinders to their place of application in coal mines as well as inconvenience and danger connected with using steam and gas mixtures have caused that the most intensively developing method of inertization of the gas environment in sealed headings and goafs is inertization by means of gaseous nitrogen produced on the surface from the atmospheric air or liquid nitrogen, which is later transported to headings and goafs by means of pipelines, or through holes.

Gasification of liquid nitrogen

There are two methods of using liquid nitrogen in coal mines.

In the first one, liquid nitrogen delivered to the mine is first pumped into a special tank, and then into a gasification installation. Installation type UZA-1, used in the gasification of liquid nitrogen in an atmospheric heat exchanger, is characterized by the following technical parameters:

- working temperature — about –196°C,
- working pressure — 0,65 MPa, 0,25 MPa,
- temperature of gasified nitrogen — about 10°C below ambient temperature,
- capacity of gaseous nitrogen — 2000 m^3 /h,
- maximum distance of pumping gaseous nitrogen in a coal mine — up to 4000 m.

Installations for the gasification of liquid nitrogen are situated on the surface, possibly the closest to the pit in which liquid nitrogen is to be transported underground by means of pipelines.

The second method consists in pumping liquid nitrogen from cisterns to special tanks in installation AUG-2 which are transported underground close to the pumping station.

The station's installation pumps liquid nitrogen from the tanks to a head equipped with nozzles spraying nitrogen to the sealed area.

Installation AUG-2 has the following technical and working parameters:

- tank's working capacity — 1020 dm^3,
- average volume stream of liquid nitrogen pumped by means of a three-nozzle head — 180 dm^3 /min,
- time of pumping and spraying liquid nitrogen from 12 tanks — about 1.5 h.

Production of gaseous nitrogen from atmospheric air

In obtaining gaseous nitrogen from the atmospheric air, Poland's coal mining industry uses membrane installation HPLC produced by MESSER, which has constituted a part of the equipment of the Central Mine Rescue Station in Bytom since 1998. It is the first and so far the only such installation owned by Poland's mine rescue services. The installation to obtain nitrogen from the atmospheric air has been produced as a movable installation operating on the surface.

Installation HPLC consists, among others, of the following elements:

- air compressor,
- multistage air cleaning system,
- membrane modules,
- regulating apparatus.
- The main technical data of installation HPLC:
- capacity 600 m^3 N_2/h,
- excess pressure at outlet — minimum 10.5 bars.

In the process of obtaining nitrogen, first the atmospheric air is compressed and then cleaned by means of appropriate filters. Next, it passes on to the membrane part. The membrane part is the major element of the installation. It consists of a large number of parallel fibres in which, thanks to diffusion, the air's components are separated.

Consequently, at the end of the membrane part we receive a mixture of nitrogen with the concentration of above 97% and oxygen with the concentration of below 3%. This low-oxygen mixture of gases is commonly called nitrogen. The remaining air enriched with oxygen (35–40% of O_2) is released to the atmosphere. The underground installation consists of pipelines whose ends, situated close to the place where nitrogen is introduced to the sealed headings and goafs, are equipped with a sounding pipe and a set of valves.

2.3. Invasive methane filling method

In order to effect fire and explosion preventive measures, the Rybnik-Jastrzębie Coal Mining Holding has developed an invasive method of filling sealed headings and goafs with methane. The method consists in a controlled loading of a determined amount of the methane-air mixture recovered from a methane drainage installation by means of a water-circulating pump (Fig. 1).

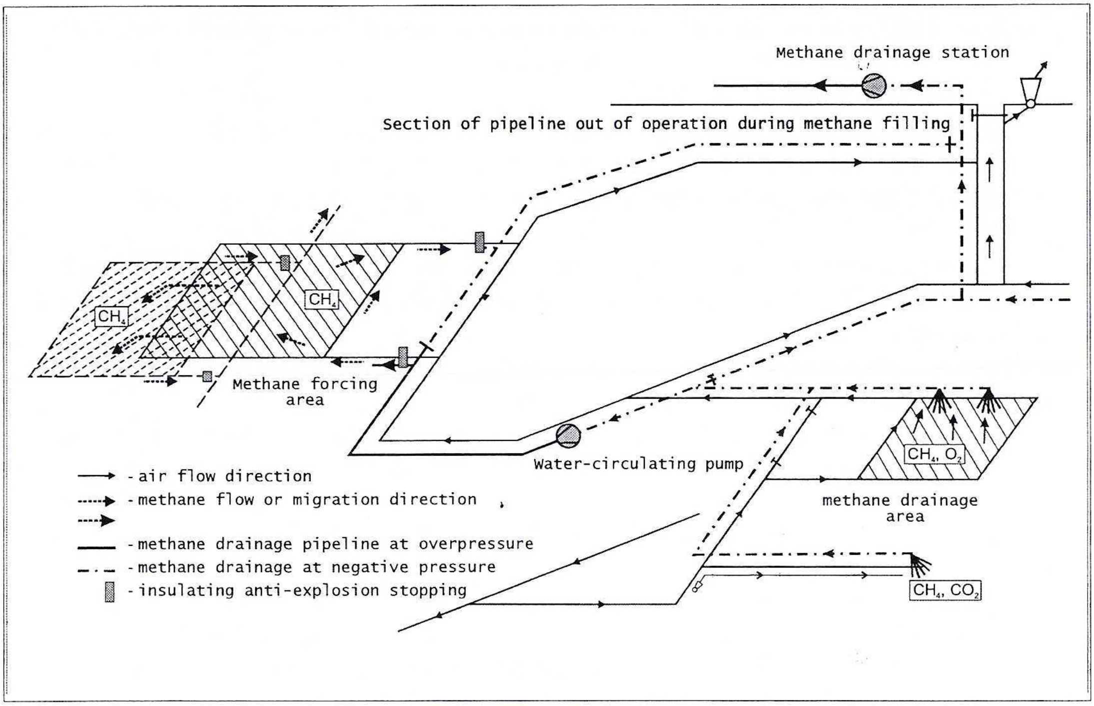


Fig. 1. Schematic diagram of filling sealed goaf and gases with methane

Rys. 1. Schemat ideowy wypełniania metanem otamowanych wyrobisk i zrobów

The methane filling method can be used exclusively in coal mines equipped with operating underground methane drainage installations. It makes it possible to fill sealed headings and goafs with very great amounts of gas, which enables to change significantly the composition of goaf gases in a short period of time.

The utilization of the method is also limited by a strict dependence of the methane concentration in supplied gas on the methane concentration in the underground methane drainage installation. It has been proved in practice that the method can be useful in controlling explosion and fire hazards. The basic machinery used in the process of forcing methane into sealed headings and goafs is a mobile gas pumping station. It is based on a gas compressor with rotating water-rings, commonly known as a water-circulating pump. Currently, Methane Drainage Plant "ZOK", Ltd. in Jastrzębie owns such a station based on water-circulating pump PP 7.14.9.4.

Major technical data:

- maximum value of subatmospheric pressure — 800 hPa,
- maximum value of overpressure — 300 hPa,
- maximum capacity — 15 m^3 /min,
- power demand — 44 kW.

3. Applications of the invasive method of filling sealed headings and goafs with methane

Because of its high effectiveness in terms of reducing the hazards connected with fires and explosions of fire gases, the methane filling method was used on many occasions in the coal mines of the Jastrzebie Coal Mining Holding in the years 1978–1998

This article presents the results obtained during firefighting in longwall B-6a seam 360/1 in the "Pniówek" coal mine where the method of filling a fire field with methane was applied.

Longwall B-6a seam 360/1 was being worked in the lengthwise system with caving in the direction away from the field. It was fully mechanized.

The longwall had the following parameters: seam thickness: 1,8–2,0 m; average inclination: 5°; length of longwall: 150 m; methane hazard — category IV; dust hazard — class B; coal self-ignition — group I (Szb = 50°C/min); absolute methane bearing capacity — 17.5 m^3CH_4 /min (in which methane drainage –10 m^3CH_4 /min); outlay of air — 800–900 m^3/min.

The fire in the area of longwall B-6a occurred on 23 August 1987 as a result of igniting methane during shooting works conducted to cause the caving of roof rocks. The layout of headings in the area of longwall B-6a with regard to the state of ventilation after closing the fire field is presented in Fig. 2. Before the fire occurred, the wall had been ventilated in system "Z", and fresh air was supplied to the wall by means of belt gangway B-9, airway B-8 and airway B-6. Used air was moved by means of gangway B-2 to ascending cross-cut S-2. Gangway B-2 behind the front of the longwall was maintained using wooden cribs filled with stone and anhydrite.

The fire-fighting operation lasted from 23 to 28 August 1987. The fire field was sealed with four anti-explosion stoppings: T-1 in gangway B-2, near ascending cross-cut S-2; T-2 in airway B-8, near gangway B-4; T-3 in gangway B-8, near belt gangway B-8; T-4 in belt gangway B-9, near belt gangway B-8.

In order to obtain relatively quickly a non-explosive mixture of gases in the fire field, a decision was made to fill the field with methane. In order to effect this a hole ϕ65 mm was drilled from gangway B-10 seam 361 to the upcut of longwall B-8 seam 360/1. A water-circulating pump was installed in the area of the cross-cut to the dip road to level 830 m.

Two methane lines ϕ100 mm were attached to the pump, i.e. a suction line, from the pipeline in the directional east cross-cut, level 705 and a forcing line, installed in the dip road to level 830 m and in gangway B-10 seam 361 to the above mentioned hole ϕ65 mm.

Filling the fire field with methane started on 28 August 1987. The starting parameters were the following: mixture capacity — 7.8 m^3/min; methane concentration — 64%.

On 30 August 1987 the filling parameters were increased to the following average values: mixture capacity — 13.2 m^3/min; methane concentration — 66%.

The course of changes in the average methane concentration behind stoppings T-1, T-2, T-3 i T-4 in the period from 27 August to 13 October 1987 is presented in Fig. 3.

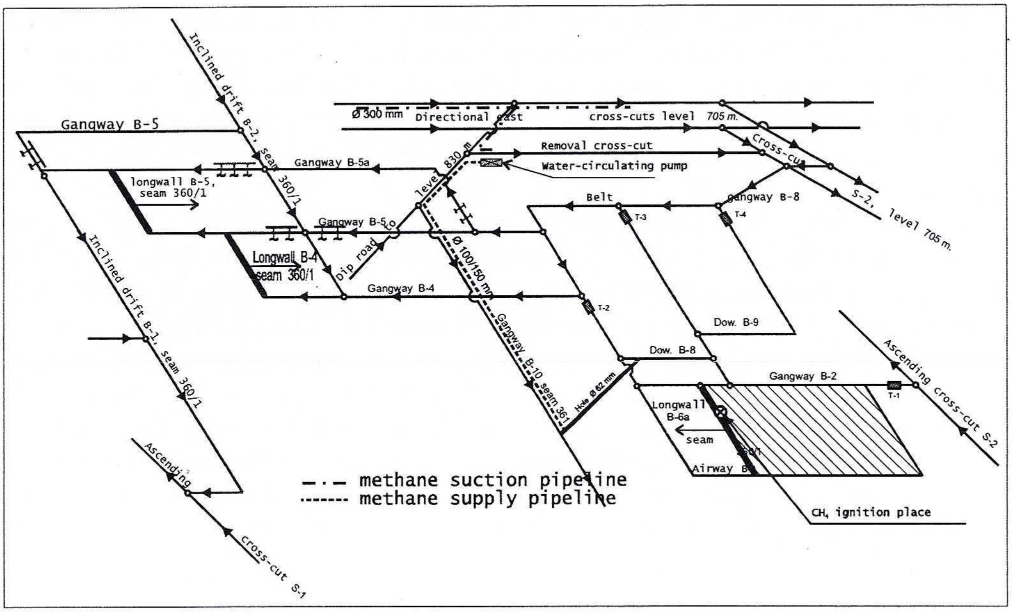


Fig. 2. Diagram of sealed area of lingwall B-6a, seam 360/1, "Pniówek" coal mine

Rys. 2. Schemat otamowanego rejonu ściany B-6a pokł. 360/I KWK „Pniówek"

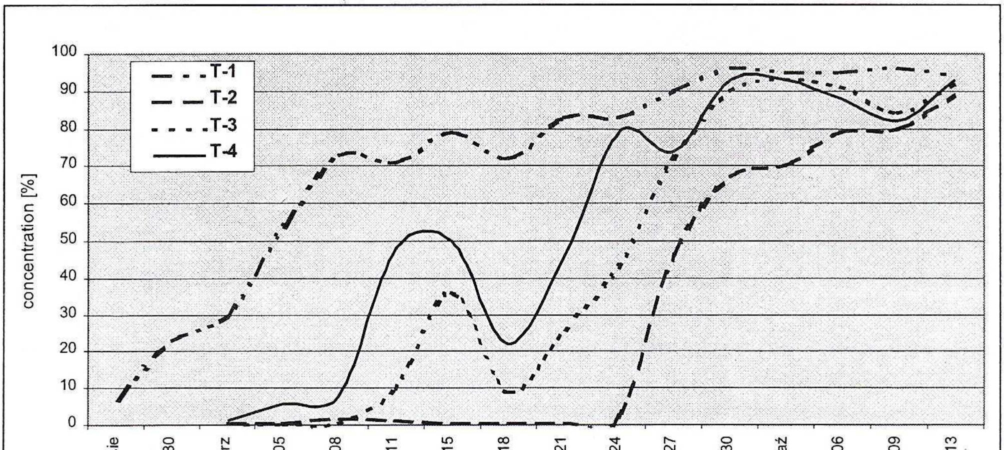


Fig. 3. Methane concentration in the area of longwall B-6a, seam 360/1 behind stoppingsT-1, T-2, T-3 and T-4 (27.08–13.10.1987)

Rys. 3. Stężenie metanu w rejonie ściany B-6a pokł .360/1 za tamami T-1, T-2, T-3 i T-4 (27.08–13.10.1987)

Apart from few breaks connected with breakdowns of the installations or other reasons, filling the fire field with methane was conducted continuously until 11 October 1987. The total amount of the loaded mixture reached 926 700 m^3, of which methane constituted 620 900 m^3. After the state of the fire was assessed and it was ensured that it had been extinguished, on 20 November 1987 work on the fire field recovery was started.

After opening the fire field and conducting a thorough inspection of the headings and machinery installed in them, fire fighters identified traces of explosions inside. Although it cannot be univocally ascertained if the explosion was connected with methane filling, such a hypothesis should not be rejected. However, this case indicates that methane filling can also be connected with a danger of explosion inside a fire field. It sets very strict requirements for anti-explosion fire stoppings. The scale of the explosion hazard is closely connected, among others, with the period of the occurrence of the methane-air mixture capable of exploding. Filling high concentration methane enables a maximum shortening of this period, which is illustrated in Fig. 4 by the

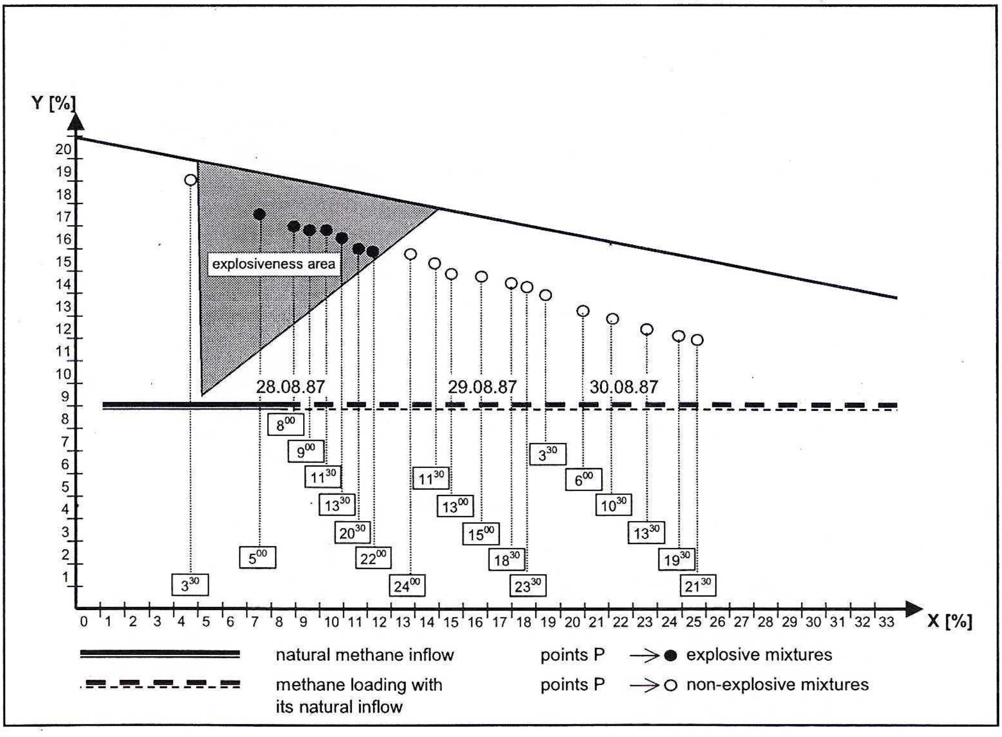


Fig. 4. Diagram of explosiveness with the course of pointsP(X,Y) air-methane mixtures in the area of longwall B-6a seam 360/1 behind stopping T-1
(during methane loading in the period 28.08–30.08.1987)

Rys. 4. Diagram wybuchowości z przebiegiem punktów P(X, Y) charakteryzujących mieszaniny metanowo-powietrzne w rejonie ściany B-6a pokł. 360/1 za tamą T-1
(w czasie podawania metanu w okresie 28.08–30.08.1987)

movement of the point representing the gas mixture (behind stopping T-1) beyond the explosion area of the explosiveness diagram.

After about 16 hours from the beginning of methane filling, the gas mixture behind stopping T-1 became non-explosive because of the increase in the share of flammable gases (methane). As their concentration was rising, the gas mixture was becoming safer and safer, which is illustrated by the successive movements of the point symbolizing the parameters of the gas mixture away from the explosion area.

If the fire field had not been filled with methane, the end effect, i.e. the movement beyond the explosion area, would probably have been achieved only after a few, or more than ten days. Taking into consideration a bigger number of fire stoppings and a more widespread fire field, the acceleration in the occurrence of a non-explosive mixture in a field by means of methane filling could take weeks and months, especially in the case of a low methane bearing capacity of a fire field.

A fast achievement of a methane-air mixture with a high methane concentration shortens considerably the time of extinguishing fire centres.

4. Experimental research

In order to acquire a full knowledge on the course of filling sealed headings and goafs with methane, experimental research has been conducted in normal conditions in sealed

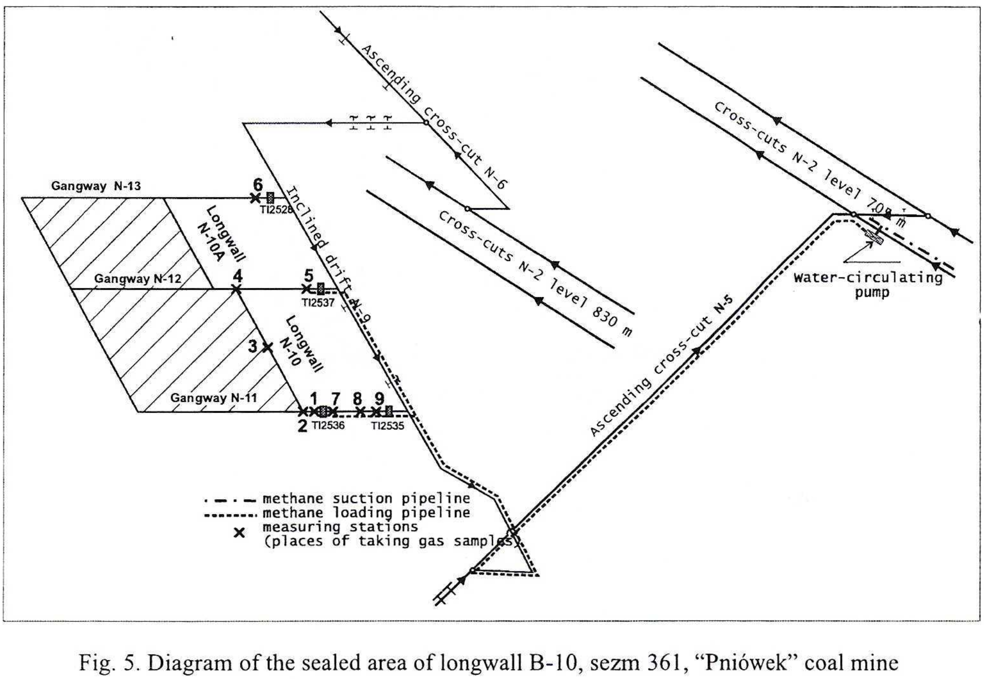
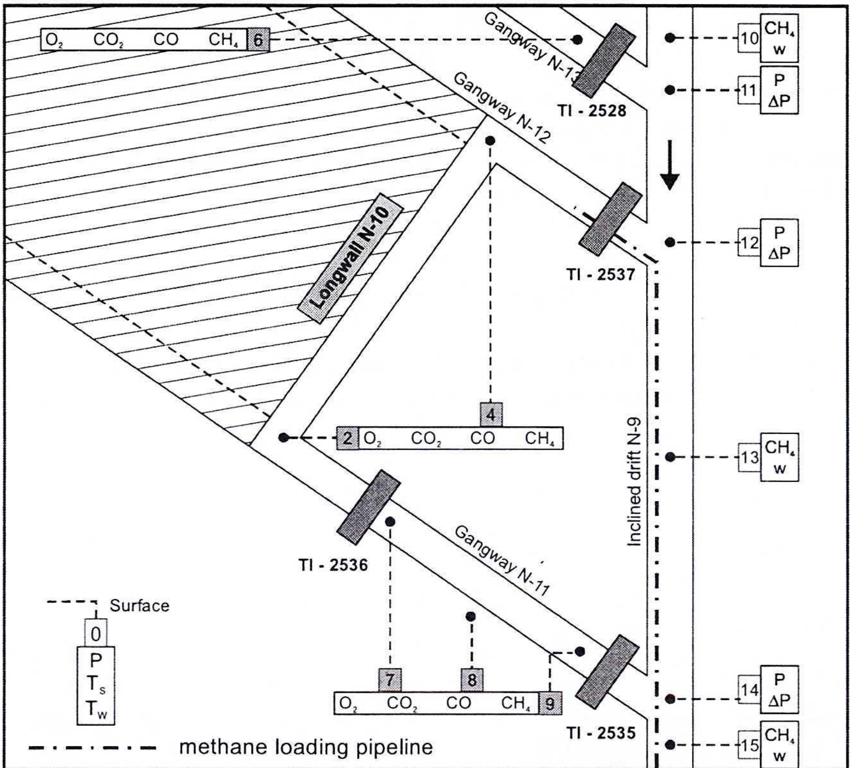


Fig. 5. Diagram of the sealed area of longwall B-10, sezm 361, “Pniówek” coal mine

Rys. 5. Schemat otamowanego rejonu ściany N-10 pokł. 361 KWK „Pniówek” areas of longwalls in the "Pniówek" and "Zofiówka" coal mines, which are characterized by the greatest absolute methane bearing capacities among Poland's coal mines.

Because of a considerable similarity between research conducted in the two mines, the article presents only research carried out in the area of longwall N-10 seam 361 in the "Pniówek" coal mine (Fig 5).

Longwall N-10 has the height of 2 m, length of 200 m and inclination of 2.5°. When its exploitation was finished and all machinery was moved out, the longwall was sealed with anti-explosion stoppings TI-2537 and TI-2535.



List of measuring stations places of taking gas samples

2	Gangway N-11, seam 361 sample from crossing with longwall N-10
4	Gangway N-12, seam 361 sample from crossing with longwall N-10
6	Gangway N-13, seam 361- sample from behind stopping 2528
7	Gangway N-11, seam 361 sample from before stopping TI-2536
8	Gangway N-11, seam 361 sample from the middle of gangway
9	Gangway N-11, seam 361 sample from behind stopping TI-2535

All insulating stoppings presented in the figure are anti-explosive stoppings

Fig. 6. Measuring stations in the area of longwall N-10, seam 361

Rys. 6. Stacje pomiarowe w rejonie ściany N-10 pokład 361

During the period of its exploitation the longwall was characterized by the following methane hazard and ventilation parameters: methane hazard — category IV; dust hazard — class B; coal self-ignition — group II; incubation period — 78 days; absolute methane bearing capacity — 9.7 m^3 CH_4/min during exploitation and 2,6 m^3 CH_4/min during liquidation; air capacity 1 360 m^3/min during exploitation and 510 m^3/min during liquidation.

The area of longwall N-10 was equipped with measuring devices (Fig. 6) enabling to measure air pressure, air capacity and gas concentrations.

Gangway N-12 (Fig. 5 and 6) was equipped with a pipeline ϕ100 mm through which gas from methane drainage was supplied by means of a water-circulating pump.

Findings

A. In the period from 1 August 1998 7.00 a.m. to 2 August 1998 8.00 p.m., about 26 700 m^3 of the methane-air mixture (14 200 m^3 of methane) were supplied to the sealed headings and goafs in the area of longwall N-10. The concentration equalled 53–54%, and the capacity of the supplied mixture — from 10.1 to 15.6 m^3/min — Fig. 7.

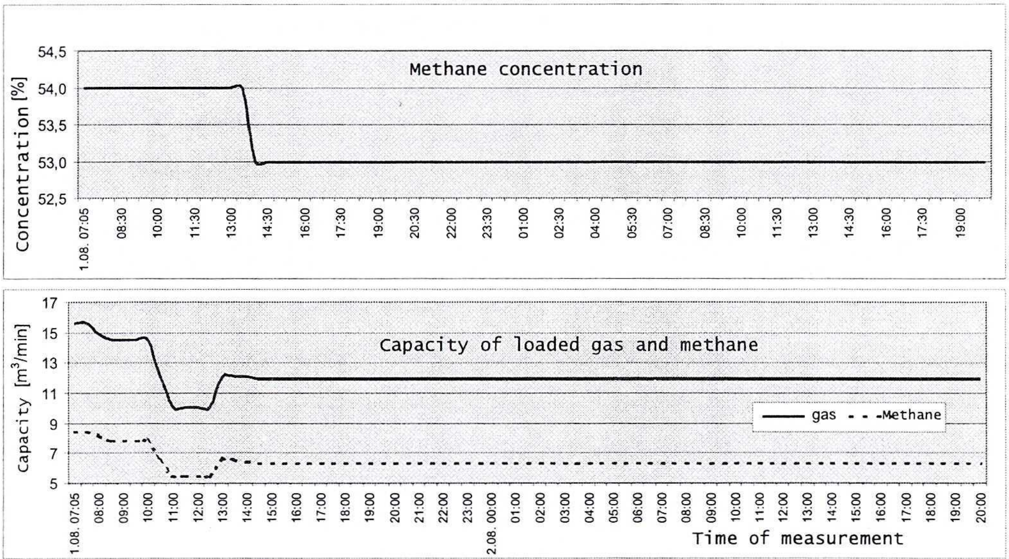


Fig. 7. Parameters of loaded gas (1.08–2.08.1998)

Rys. 7. Parametry podawanego gazu (1.08–2.08.1998)

B. In the final stage of methane filling, the measuring stations were indicating the following maximum methane concentrations: 14% behind TI-2528 in gangway N-13; 49% behind TI-2537 in gangway N-12; 47% in longwall N-10 and in gangway N-11 behind TI-2536 — Fig. 8.

In the case of all stations situated in gangway N-11, within a few days after completing methane filling, the methane concentration was still rising as a result of its natural inflow. In the same period of time in the other stations, there was a fall in the methane concentration — it was the fastest behind the inflow stoppings in gangways N-12 and N-13.

The average gas flow velocity in longwall N-10 measured by means of tracer gas equalled 0.86 m/min, i.e. 0.014 m/s.

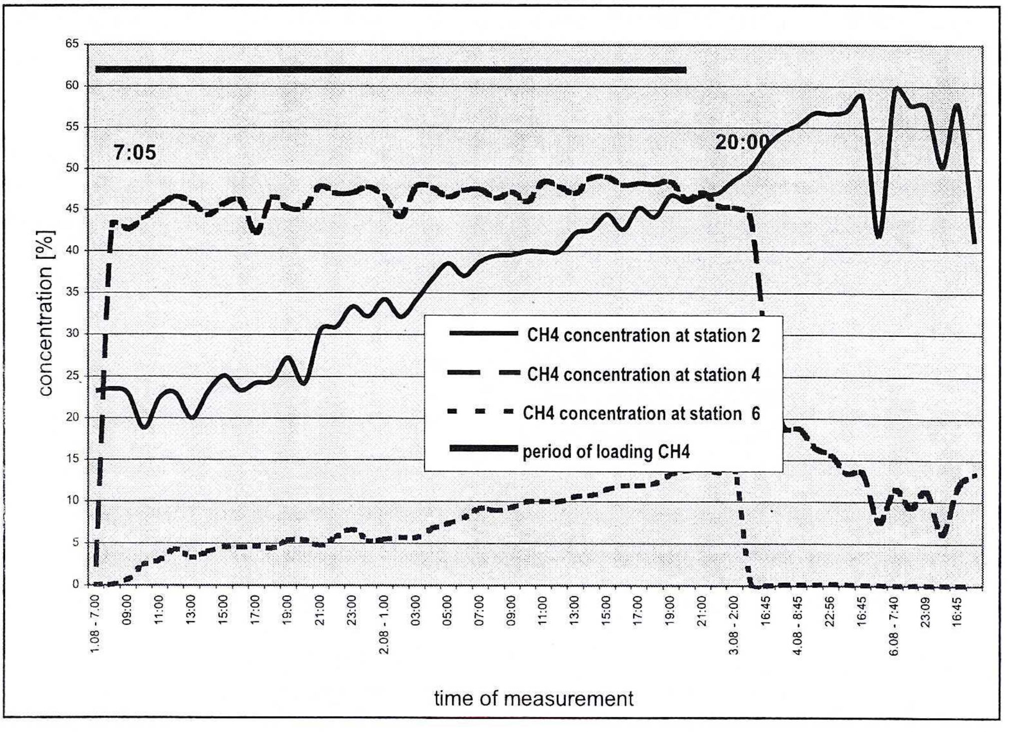


Fig. 8. Changes in methane concentration in sealed headings in the area of longwall N-10 seam 361 (1.08.98–7.08.1998)

Rys. 8. Kształtowanie się stężeń metanu w otamowanych wyrobiskach rejonu ściany N-10 pokł. 361 (1.08–7.08.1998)

C. During the process of methane filling in the wall there occurred non-explosive mixtures because of excess methane; the loading of methane accelerated considerably the occurrence of non-explosive mixtures, which is especially important in the context of work safety — Fig. 9.

D. During the research the oxygen content was falling proportionally to the increasing methane concentration, which had an advantageous influence on reducing the hazard of endogenic fires in the goafs of longwall N-10.

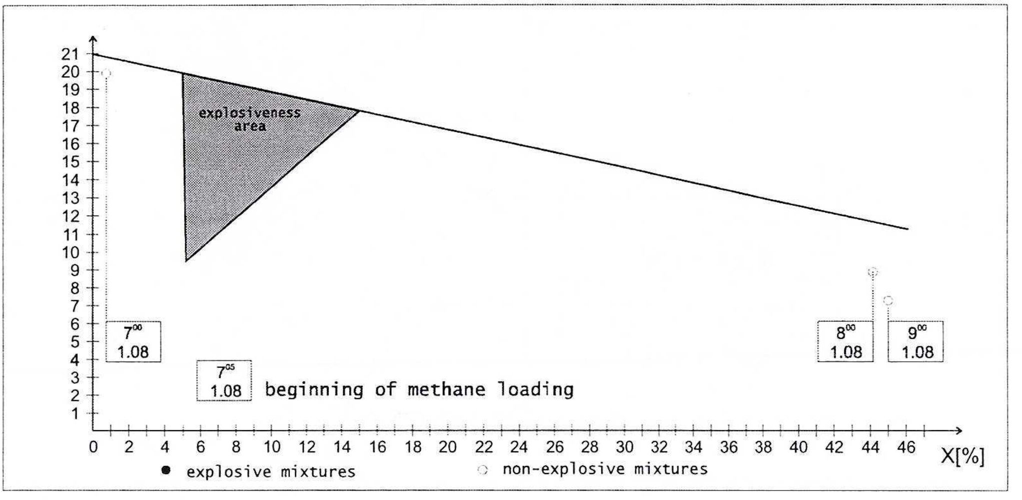


Fig. 9. Diagram of explosiveness for air-methane mixtures sampled in gangway N-12, seam 361 behind stopping TI-2537 (between 7.00–9.00 on 1 August 1998)

Rys. 9. Diagram wybuchowości dla mieszanin metanowo-powietrzych pobranych w chodniku N-12 pokł. 361 za tamą TI-2537 (w okresie od 700 do 900 w dniu 1.08.1998)

5. Model testing

For designing the methane filling process for sealed headings and goafs, and especially for the evaluation of changes in gas concentrations and safety, a mathematical model has been developed. Such a mathematical model, supported by computer calculations, enables to carry out simulations of the influence of parameters on the effectiveness of the process.

5.1. Assumptions

In the development of the mathematical model for a given arrangement of sealed headings and goafs (Fig. 10), the following phenomena have to be considered:

- flow of air-methane mixture in headings,
- flow of air-methane mixture in goafs,
- inflow of methane to goafs,
- inflow of air-methane mixture from goafs to headings,
- filling sealed headings and goafs with air-methane mixture by means of a water-circulating pump,
- flow of components of air-methane mixture in headings and goafs.

Similarly to papers dealing with the descriptions of the phenomena occurring in ventilation networks and goafs by means of mathematical models (Dziurzyński 1988;

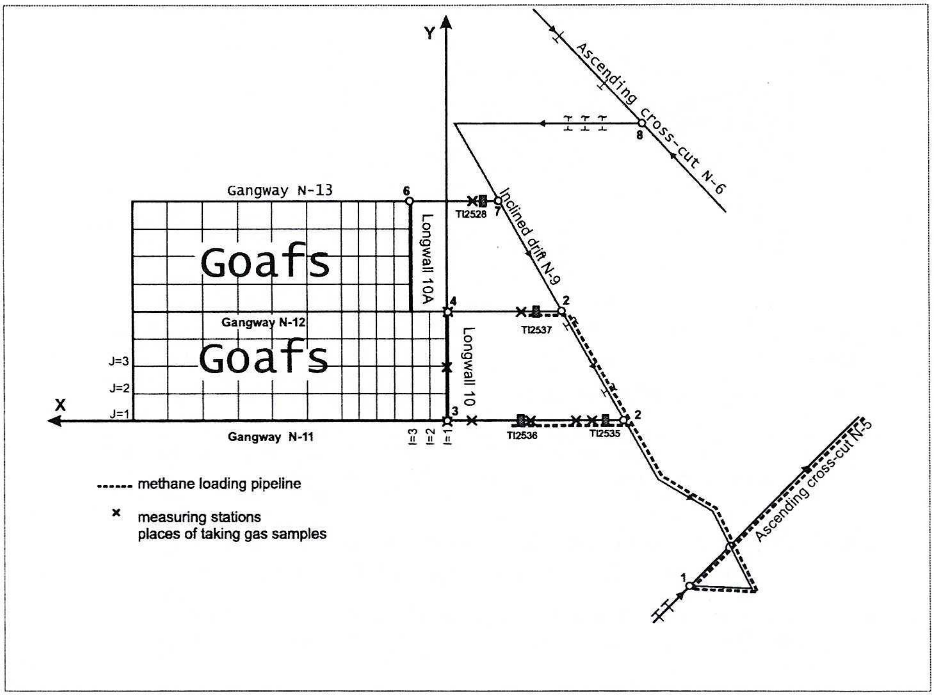


Fig. 10. Ventilation network and goaf area diagram of connections between headings, substitute air strips and points connecting goaf sub-area, adopted co-ordinate system

Rys. 10. Sieć wentylacyjna i obszar zrobów — schemat połączenia wyrobisk, bocznic zastępczych i punktów łączących podobszar zrobów, przyjęty układ współrzędnych

Nawrat 1989; Trutwin 1972) a series of simplifying assumptions have been made. It has been assumed that the object of the research is an area of a longwall consisting of headings making up a ventilation network. The longwall is mined by caving, which results in goafs. The area of the goafs and headings under consideration is under the influence of natural depression and the mine's main ventilation fan.

Inside the goafs, which are assumed to be a porous medium (Litwiniszyn 1949; J. Szązak et al. 1990) the filtration flow of the air-methane mixture is considered according to the linear Darcy equation. The tested area of the goafs and headings together with the accepted coordinate system is presented in Fig. 10.

5.2. Equations of the flow of the air-methane mixture in the analysed model

5.2.1. The flow of air and methane in headings

The flow of the air-methane mixture in the mining heading is described by a system of equations of motion, continuity and state which, in accordance with the accepted assumptions, is given in the following form (Litwiniszyn 1951; Nawrat 1989; Turtwin 1972):

- equation of motion for a stationary state:

$$v\frac{\partial(v\rho)}{\partial s}+\frac{\partial p}{\partial s}+g\rho\frac{dz}{ds}+j+j_{s_n}\delta(s-s_{rt})=h_w\delta(s-s_w) \tag{1}$$

- equation of continuity:

$$\frac{\partial(v\rho)}{\partial s}=0 \tag{2}$$

- equation of state:

$$\rho=\rho(C_{\mathrm{CH_4}}) \tag{3}$$

where:

s — space coordinate measured along a heading's axis [m],
t — time [s],
z — upward height coordinate [m],
$v(s,t)$ — mixture flow velocity [m/s],
$p(s,t)$ — absolute pressure [Pa],
$\rho(C_{\mathrm{CH_4}})$ — density of air-methane mixture [kg/m^3],
$C_{\mathrm{CH_4}}(s,t)$— methane mass concentration in mixture, given by the following formula:

$$C_{\mathrm{CH_4}}=\frac{\rho_{\mathrm{CH_4}}}{\rho} \tag{4}$$

$\rho_{\mathrm{CH_4}}$ — partial density of methane [kg/m^3],
j_{s_n} — pressure losses from local resistance [Pa],
s_{rt} — coordinate of loss occurrence place ,
$\delta(s-s_{rt})$ — Dirac delta function [1/m],
$\delta(s-s_w)$ — Dirac delta function [1/m],
h_w — ram effect caused by ventilation fan [Pa],
s_w — coordinate of fan's position,
$j=j(s,t)$ — hydraulic gradient [Pa/m], given by the following formula:

$$j=\frac{\lambda\rho O_b}{8A} \tag{5}$$

λ — dimensionless resistance coefficient,
O_b — heading's perimeter [m],
A — heading's cross-section area [m^2].

After inserting (5) into (1) and after additional transformations, we receive the following:

$$v\frac{\partial(v\rho)}{\partial s}+\frac{\partial p}{\partial s}+g\rho\frac{dz}{ds}+\frac{\lambda\rho O_b}{8A^3r^2}vA\rho|v|A\rho+j_{s_n}\delta(s-s_{rt})=h_w\delta(s-s_w) \tag{6}$$

In the consideration of the incompressible flow it has been assumed that:

$$\frac{\partial\rho}{\partial p}=0$$

therefore the mixture's density will be expressed in dependence on the methane concentration only.

Thus the equation of state (3) at the constant pressure and temperature for the air-methane mixture has the following form:

$$\rho=\frac{p_o}{T[R_p+(R_{CH_4}-R_p)C_{CH_4}]} \tag{7}$$

where:

- R_p — air's gas constant $R_p = 287.11$[J/kgK],
- R_{CH_4} — methane's air constant $R_{CH_4} = 518.37$ [J/kgK],
- $T =$ const — temperature of air-methane mixture [K],
- p_o — reference pressure.

and the following equation is also true:

$$C_p=1-C_{CH_4} \tag{8}$$

where:

- $C_p=C_{O_2}+C_{N_2}$ — air's mass concentration in mixture,
- C_{O_2} — oxygen's mass concentration in mixture,
- C_{N_2} — nitrogen's mass concentration in mixture,
- C_{CH_4} — methane's mass concentration in mixture,

We assume in simplification that the air consists of oxygen and nitrogen only and that in the mass unit of the air there is 0.23 of oxygen's mass and 0.77 of nitrogen's mass, and that incoming methane displaces uniformly oxygen and nitrogen in proportion to their shares in the air. Therefore the oxygen concentration can be calculated from the following simplified formula:

$$C_{O_2}=0.23(1-C_{CH_4}) \tag{9}$$

In order to determine changes in the methane concentration during the flow of the mixture in the heading, the following form of the equation of continuity is accepted:

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho v)}{\partial s}=0 \tag{10}$$

and for methane — a component of the mixture [29],

$$\frac{\partial \rho_{CH_4}}{\partial t} + \frac{\partial (\rho_{CH_4} v)}{\partial s} = 0 \tag{11}$$

Taking into consideration the equation (10) and the formula (4), the equation (11) can be transformed to the following form:

$$\frac{\partial C_{CH_4}}{\partial t} + \frac{\partial (C_{CH_4})}{\partial s} = 0 \tag{12}$$

Equations (1), (2), (3) and (12) form a mathematical model of the flow of methane and air in a mining heading.

Because of the application of the numerical method, we integrate the equation (1) along length L_i^w of the i-th heading. Taking into consideration the continuity equation (2), we can write:

$$\int_0^{L_i^w} \frac{\partial p_i}{\partial s} ds + \int_0^{L_i^w} g\rho_i \frac{dz_i}{ds} ds + \int_0^{L_i^w} \frac{\lambda_i \rho_i O_{b,i}}{8A_i^3 \rho_i^2} v_i A_i \rho_i |v_i| A_i \rho_i ds + \tag{13}$$

$$+ \int_0^{L_i^w} j_{i,s_n} \delta(s - s_{rt}) ds = \int_0^{L_i^w} h_{w,i} \delta(s - s_w) ds$$

after further transformations we obtain:

$$[p_i(L_i^w) - p_i(0)] + \frac{R_i}{\rho_i^{s2}} Q_m^w \left| Q_m^w \right| + g\rho_i^s [z_i(L_i^w) - z_i(0)] + j_{i,s_{rt}} = h_{w,i} \tag{14}$$

where it is assumed:

$\rho_i^s = \frac{1}{L_i^w} \int_0^{L_i^w} \rho ds$ — average density,

$Q_m^w = v_i A_i \rho_i$ — mass capacity of flow of mixture in heading [kg/s],

$R_i = \frac{\lambda \rho_i^s O_{b,i} L_i^w}{8A_i^3}$ — heading's aerodynamic resistance [kg/m^7].

Taking into consideration the mesh equations for the ventilation network and introducing a matrix notation of the network's structure (Litwiniszyn 1951), we obtain:

$$\sum_{i=1}^{N} \alpha_{m,i} \left[\frac{R_i}{\rho_i^{s2}} Q_m^w \left| Q_m^w \right| + g\rho_i^s [z_i(L_i^w) - z_i(0)] + j_{i,s_{rt}} = h_{w,j} \right] = 0 \tag{15}$$

$m = 1, 2, ..., M,$
$i = 1, 2, ..., N,$

where:

$\alpha_{m,i}$ — elements of mesh-air split coincidence matrix,
$M = N - P + 1$ — number of independent meshes in ventilation network,
N — number of air splits in ventilation network,
P — number of nodes in ventilation network,

For the ventilation network, the node equation in the following form is valid too:

$$\omega^{w}_{CH_4,k} + \sum_{i=1}^{N} \varepsilon_{k,i} Q^{w}_{m,i} = 0 \tag{16}$$

where:

$k = 1, 2, ..., P$,
$i = 1, 2, ..., N$,
$\omega^{w}_{CH_4,k}$ — inflow of methane to the k-th node [kg/s],
$\varepsilon_{k,i}$ — elements of node-air split coincidence matrix.

5.2.2. The flow of methane and air in goafs

It has been assumed that the movement of the air-methane mixture in the headings is described by the equations of motion, continuity and state (Litwiniszyn 1949; Trutwin 1972). According to the assumptions, the following system of equations has been accepted (Nawrat 1989):

- the equation of motion for the mixture given for two components:

$$v_x = -\frac{k}{\mu}\left(\frac{\partial p}{\partial x} + \rho g \frac{\partial z}{\partial x}\right) \tag{17}$$

$$v_y = -\frac{k}{\mu}\left(\frac{\partial p}{\partial y} + \rho g \frac{\partial z}{\partial y}\right) \tag{18}$$

- the equation of continuity for the mixture:

$$mh\frac{\partial p}{\partial t} + \frac{\partial(\rho v_x h)}{\partial x} + \frac{\partial(\rho v_y h)}{\partial y} = \omega^{z}_{CH_4} \tag{19}$$

- the equation of state:

$$\rho = \rho(C^{z}_{CH_4}) \tag{20}$$

where:

$x,\ y$ — axes of cartesian coordinate system [m],
v_x — component of flow velocity in direction of axis x [m/s],

v_y — component of flow velocity in direction of axis y [m/s],
$k = k(x,y)$ — permeability of area of headings under consideration [m^2],
$m = m(x,y)$ — porosity of area of headings under consideration,
$h = h(x,y)$ — height of area of headings under consideration,
μ — absolute viscosity of mixture [kg/ms],
$\omega^z_{CH_4}$ — inflow of stream of methane mass to area of goafs, per 1 m^2 of goafs [kg/sm^2],
$C^z_{CH_4}(x,y,t)$ — mass concentration of methane in mixture, which equals:

$$C^z_{CH_4} = \frac{\rho_{CH_4}}{\rho} \tag{21}$$

Accepting the equation of continuity (19) for the flow of the mixture in goafs and conducting transformations similar to those for the equation of continuity in the heading (10) and (11) and taking into consideration (21), we obtain an equation determining changes in the methane concentration in the goafs:

$$m\frac{\partial C^z_{CH_4}}{\partial t} + v_x\frac{\partial C^z_{CH_4}}{\partial x} + v_y\frac{\partial C^z_{CH_4}}{\partial y} = \frac{\omega^z_{CH_4}}{\rho h}(1 - C^z_{CH_4}) \tag{22}$$

In order to obtain a solution of the accepted system of the equations of motion (17) and (18), we approximate derivatives $\frac{\partial p}{\partial x}, \frac{\partial p}{\partial y}, \frac{\partial z}{\partial x}, \frac{\partial z}{\partial y}$ by means of a difference quotient and multiply both sides of the equation by the density of the flowing mixture and the height of the goafs in the element of the goaf sub-area under consideration, eventually we obtain:

$$v_x\rho h = -\frac{k}{\mu}h\rho\left(\frac{\Delta p}{\Delta x} + \rho g\frac{\Delta z}{\Delta x}\right) \tag{23}$$

$$v_y\rho h = -\frac{k}{\mu}h\rho\left(\frac{\Delta p}{\Delta y} + \rho g\frac{\Delta z}{\Delta y}\right) \tag{24}$$

where:

Δx, Δy — the length of the element of the goaf sub-area [m] along axis x and axis y,

Because of applying the numerical method, we integrate the equation (23) along axis Δy on length of the goaf sub-area and the equation (24) along axis Δx on length of the goaf sub-area. Now we obtain:

$$\int_{y_0}^{y_0+\Delta y} v_x \rho h dy = -\int_{y_0}^{y_0+\Delta y} \rho \frac{k}{\mu} h \left(\frac{\Delta p}{\Delta x} + \rho g \frac{\Delta z}{\Delta x} \right) dy \tag{25}$$

$$\int_{x_0}^{x_0+\Delta x} v_y \rho h dx = -\int_{x_0}^{x_0+\Delta x} \rho \frac{k}{\mu} h \left(\frac{\Delta p}{\Delta y} + \rho g \frac{\Delta z}{\Delta y} \right) dx \tag{26}$$

Now we obtain:

$$Q_{my} = -\frac{1}{\upsilon} \int_{y_0}^{y_0+\Delta y} kh \left(\frac{\Delta p}{\Delta x} + \rho g \frac{\Delta z}{\Delta x} \right) dy \tag{27}$$

$$Q_{my} = -\frac{1}{\upsilon} \int_{y_0}^{y_0+\Delta y} kh \left(\frac{\Delta p}{\Delta y} + \rho g \frac{\Delta z}{\Delta y} \right) dx \tag{28}$$

where:

$Q_{mx} = \int_{y_0}^{y_0+\Delta y} v_x \rho h dx$ — mass capacity of air-methane mixture flowing in goafs in direction of axis x [kg/s],

$Q_{my} = \int_{x_0}^{x_0+\Delta x} v_y \rho h dx$ — mass capacity of air-methane mixture flowing in goafs in direction of axis y [kg/s],

$\upsilon = \frac{\mu}{\rho} = \text{const}$ — kinematic viscosity, which is assumed to have constant value [m^2/s] (Pawiński et al. 1979):

For the sake of clarity, in the following part we present consecutive transformations of the equation (27). We obtain:

$$\frac{\upsilon Q_{mx}}{\int_{y_0}^{y_0+\Delta y} khdy} = \frac{\Delta p_x}{\Delta x} - g \frac{\Delta z}{\Delta x} \frac{\int_{y_0}^{y_0+\Delta y} kh\rho dy}{\int_{y_0}^{y_0+\Delta y} khdy} \tag{29}$$

We integrate the equation (29) along length Δx (axis x).
After transformations we obtain:

$$\left(\upsilon \int_{x_0}^{x_0+\ddot{A}x} \frac{dx}{\int_{y_0}^{y_0+\ddot{A}y} khdy} \right) Q_{\max} = -(p_{x_0+\ddot{A}x} - p_{x_0}) - g\frac{\ddot{A}z}{\ddot{A}x} \int_{x_0}^{x_0+\ddot{A}x} \frac{\int_{y_0}^{y_0+\ddot{A}y} kh\rho dy}{\int_{y_0}^{y_0+\ddot{A}y} khdy} dx \tag{30}$$

Designating:

$$R_{zx} = \upsilon \int_{x_0}^{x_0+\ddot{A}x} \frac{dx}{\int_{y_0}^{y_0+\ddot{A}y} khdy} \tag{31}$$

$$h_{zx} = g\frac{\ddot{A}z}{\ddot{A}x} \int_{x_0}^{x_0+\ddot{A}x} \frac{\int_{y_0}^{y_0+\ddot{A}y} kh\rho dy}{\int_{y_0}^{y_0+\ddot{A}y} khdy} \tag{32}$$

And introducing the designations (31) and (32) into the equation (30) we can write:

$$R_{zx}Q_{mx} + (p_{x_0+\ddot{A}x} - p_{x_0}) + h_{zx} = 0 \tag{33}$$

Conducting transformations analogous to those for the equation (27), we obtain the equation (28) in the following form:

$$R_{zy}Q_{my} + (p_{y_0+\ddot{A}y} - p_{y_0}) + h_{zy} = 0 \tag{34}$$

where:

$$R_{zy} = \upsilon \int_{y_0}^{y_0+\ddot{A}y} \frac{dy}{\int_{y_0}^{x_0+\ddot{A}y} khdx} \tag{35}$$

$$h_{zy} = g\frac{\ddot{A}z}{\ddot{A}y} \int_{y_0}^{y_0+\ddot{A}y} \frac{\int_{y_0}^{x_0+\ddot{A}x} kh\rho dx}{\int_{y_{x0}}^{y_{x0}+\ddot{A}x} khdx} dy \tag{36}$$

The obtained formulas (31), (35) enable us to calculate the value of the substitute aerodynamic resistance for the linear flow of the air-methane mixture through the goaf subarea in the direction of axis x and axis y. The formulas (32), (36) determine the value of pressure resulting from the existence of the gravity forces and the distribution of the density of the flowing mixture. A method of determining the value of these parameters is presented in the chapter describing the application of the numerical method.

Because of applying the numerical method, we take into consideration the mesh and node equations for a ventilation network and introduce the notation of a network's structure in a matrix form (Trutwin 1972). We obtain the node equations for the goaf sub-areas from the equation of continuity:

$$\frac{\partial(\rho v_x h)}{\partial x} + \frac{\partial(\rho v_y h)}{\partial y} = \omega^z_{\mathrm{CH}_4} \tag{37}$$

We integrate the equation (37) on the volume of the sub-area and obtain:

$$\int_V \left(\frac{\partial(\rho v_x h)}{\partial x} + \frac{\partial(\rho v_y h)}{\partial y} \right) dV = \int_V \omega^z_{\mathrm{CH}_4} \, dV \tag{38}$$

From Gauss and Ostrogradzki's theorem for integrals we obtain in (38):

$$\sum_{l=1}^{L} Q_{m,l} = \Omega^z_{\mathrm{CH}_4} \tag{39}$$

where:

$l = 1, 2, ..., L$ — consecutive number of inflow or outflow,

L — total number of inflow and outflow to goaf sub-area under consideration,

$\sum_{l=1}^{L} Q_{m,l} = \Omega^z_{\mathrm{CH}_4}$ — inflow of methane mass to goaf sub-area under consideration [kg/s],

Accepting inflow $\Omega^z_{\mathrm{CH}_4}$ as a side inflow and introducing a matrix notation of a node-air split coincidence for the network, we obtain:

$$\Omega^z_{\mathrm{CH}_4,k} + \sum_{i=1}^{N} \varepsilon_{k,i} [u_i Q_{mx,i} + (1-u_i) Q_{my,i}] = 0 \tag{40}$$

where:

$u_i = 1$ — for a substitute air split of a goaf sub-area in the direction of axis x,

$u_i = 0$ — for a substitute air split of a goaf sub-area in the direction of axis y.

Using a mesh equation for (33) and (34) and for the notation of the structure of a ventilation network in the form of a matrix of a mesh-air split coincidence (Trutwin 1972), we obtain:

$$\sum_{i=1}^{N} \alpha_{m,i}[u_i(R_{zx,i}Q_{mx,i} + h_{zx,i}) + (1-u_i)(R_{zy,i}Q_{my,i} + h_{zy,i})] = 0 \quad (41)$$

$m = 1, 2, ..., M,$
$i = 1, 2, ..., N,$

where:

$u_i = 1$ — for substitute air split of goaf sub-area in direction of axis x,
$u_i = 0$ — for substitute air split of goaf sub-area in direction of axis y.
N — a total number of air splits resulting from the sum of the number of headings and the division of a goaf area into sub-areas Δx and Δy,
M — a total number of independent meshes for a network consisting of headings and a goaf area.

The obtained form of the system of linear algebraic equations (41) is useful in the calculation of the flow of the air-methane mixture in a goaf area.

5.3. Initial and boundary conditions

The presented systems of equations describing the flow of the air-methane mixture in a heading and goafs are conjugate with each other through initial conditions and boundary conditions.

Initial conditions

We assume that for $t \leq 0$ the flow of the air-methane mixture is steady. The values of the capacity of the flow in the headings result from the measurements of the parameters characteristic for the flow under consideration taken in the mine. For the goaf area, the parameters of the model are determined on the basis of the formulas (31), (35) presented in the paper and on the basis of the results of experimental research (J. Szlązak 1980) and theoretical considerations (Dziurzyński 1988; J. Szlązak et al. 2000; N. Szlązak 1990).

For the equation determining changes in the methane concentration in the heading (12), we assume that methane concentrations at all inlets to the area are known, e.g. they are measured in the mine.

For the equation determining changes in the methane concentration in the goafs (22), we assume that the distribution of the methane concentration corresponds to the solution of the system of equations (17), (18), (20), (22) for $t \leq 0$ in the conditions of the stationary state.

Boundary conditions:

The systems of equations for the determination of the capacity of the flow of air and methane for the headings (15), (16) and for the goafs (40), (41) were expressed by means of the matrix of ventilation network structure. In the considered area of the headings and goafs, we make the following assumptions for the equations:

- there is no change of momentum in any node, then pressure in the node is the same; in the nodes having contact with the atmosphere, pressure is equal to atmospheric pressure,
- the mass conservation law applies also to the components of the methane mixture; besides, according to the assumption that instantaneous mixing occurs in a node connecting headings, we can write:

$$\sum_{d=1}^{D} Q_m C_{CH_4} = C_{CH_4} \sum_{od=1}^{OD} Q_m \tag{42}$$

where:

$d = 1, 2, ..., D$	— numbers of consecutive inflows to the k-th node,
D	— maximum number of inflows to the k-th node,
$od = 1, 2, ..., OD$	— numbers of consecutive outflows from the k-th node,
OD	— maximum number of outflows from the k-th node.

The equation above indicates that the concentration of methane flowing out of the node is the same in all outflow air strips (in the headings) and in the goafs.

- the inflow of methane mass to the ventilation node created by the headings; besides, we assume that such a source corresponds to the so-called side inflow (as presented by Barczyk) for which the inflow of methane mass was determined by a function characterized by a given inflow capacity Q_{CH_4} and methane concentration C_{CH_4}.

The distribution of the methane concentration in the goafs is determined by the equation (22). For this equation we assume:

- for the boundary having contact with the heading ventilated by means of a circulating current, we have:

$$C^{Z}_{CH_4}(x,0,t) = C_{CH_4}(s,t) \tag{43}$$

$$C^{Z}_{CH_4}(0,y,t) = C_{CH_4}(s,t)$$

- for the boundary not having contact with the headings ventilated by means of a circulating current, we have:
  - for the boundary parallel to axis y

$$\frac{\partial C^{z}_{CH_4}}{\partial x} = 0 \tag{44}$$

  - for the boundary parallel to axis x

$$\frac{\partial C^{z}_{CH_4}}{\partial y} = 0 \tag{45}$$

5.4. Numerical method

The system of equations accepted for solving is quasi-static. Within this system, we can separate solutions concerning the outflow of the air-methane mixture from solutions concerning the distribution of methane concentrations. The first type of equations concerns the flow of the air-methane mixture for the stationary state, allowing for the boundary conditions (Chapter 5.3.). The second type of equations contains a derivative with regard to time and it is necessary to solve them in consecutive time steps.

In order to determine the flow of the air-methane mixture in the headings and goafs we solve the algebraic system of the non-linear equations (15) and the linear equations (33), (34). Solving this system of equations we applied the modified Cross method. The classical iterative Cross method of approximate solutions concerns non-linear systems of equations (Cross 1936; Pawiński et al. 1979). It can be shown easily that it is also true for a mixed system of equations where some equations are linear (the goaf area) and some non-linear (the headings). The Cross method uses the determination of corrections for mesh capacities. For linear equations, the correction formula given by Cross is modified allowing for the form of the equations (33) and (34). We can write:

$$\Delta Q_m = \frac{\sum_{i=1}^{N} \alpha_{m,i} w_i f_{z,i} + \sum_{i=1}^{N} \alpha_{m,i}(1-w_i) f_{w,i}}{\sum_{i=1}^{N} \alpha_{m,i} w_i \frac{df_{z,i}}{dQ} + \sum_{i=1}^{N} \alpha_{m,i}(1-w_i)\frac{df_{z,i}}{dQ}} \tag{46}$$

$m = 1, 2, ..., M,$

$n = 1, 2, ..., N,$

where:

$w_1 = 1$ — for substitute air strips in goaf sub-area,

$w_i = 0$ — for air strips (in headings).

$$f_{z,i} = u_i \sum_{b=1}^{B} (\alpha_{i,b} R_{zx,i} Q_{mx,i} + h_{zx,i}) + (1-u_i)\left(\sum_{b=1}^{B} \alpha_{i,b} R_{zy,i} Q_{my,i} + h_{zy,i}\right)$$

$$\frac{df_{z,i}}{dQ} = u_i R_{zx,i} + (1-u_i) R_{zy,i}$$

$u_1 = 1$ — for substitute air strip in goaf sub-area in direction of axis x,

$u_1 = 0$ — for substitute air strip in goaf sub-area in direction of axis y,

$$f_{w,i} = \frac{R_i}{\rho_i^{s2}} \sum_{b=1}^{B} \alpha_{i,b} Q_m^w \left| \sum_{b=1}^{B} \alpha_{i,b} Q_m^w \right| + g\rho_i^s [z_i(L_i^w) - z_i(0)] + j_{i,s_n} - h_{w,i}$$

$$\frac{df_{w,i}}{dQ}=2\frac{R_i}{\rho_i^{s2}}\sum_{b=1}^{B}\alpha_{i,b}Q_m^w-\frac{dh_{w,i}}{dQ}$$

ΔQ_m — correction in the m-th mesh,

$\alpha_{i,b}$ — matrix resulting from transposition of mesh-air strip coincidence matrix $\alpha_{m,i}$ for $m = b$, $b = 1, 2, ..., B$

The calculated correction should be added to the accepted capacity in the first iterative step. The calculations of the flow of the mixture for given parameters have indicated that a convergence of the modified Cross method has been achieved.

The equations (33) and (34) contain parameters R_{zx}, R_{zy} and h_{zx}, h_{zy} whose values are determined in the following way. We approximate the value of integrals in the dependences (31) and (35) by means of the sum:

$$R_{zx}=\upsilon\sum_{0}^{IP}\frac{\Delta px}{\sum_{0}^{JP}(kh)_{(x_0+ip\Delta px,\,y_0+jp\Delta py)}\Delta py} \tag{47}$$

and

$$R_{zy}=\upsilon\sum_{0}^{IP}\frac{\Delta py}{\sum_{0}^{JP}(kh)_{(x_0+ip\Delta px,\,y_0+jp\Delta py)}\Delta px} \tag{48}$$

We approximate the value of the integrals in the dependences (32) and (36) by means of the sum:

$$h_{zx}=g\frac{\Delta z}{\Delta x}\sum_{0}^{JP}\frac{\sum_{0}^{JP}(kh\rho)_{(x_0+ip\Delta px,\,y_0+jp\Delta py)}\Delta py}{\sum_{0}^{JP}(kh)_{(x_0+ip\Delta px,\,y_0+jp\Delta py)}\Delta py}\Delta px \tag{49}$$

and

$$h_{zy}=g\frac{\Delta z}{\Delta y}\sum_{0}^{JP}\frac{\sum_{0}^{IP}(kh\rho)_{(x_0+ip\Delta px,\,y_0+jp\Delta py)}\Delta px}{\sum_{0}^{IP}(kh)_{(x_0+ip\Delta px,\,y_0+jp\Delta py)}\Delta px}\Delta py \tag{50}$$

where:

$ip = 1, 2, ..., IP$,

$jp = 1, 2, ..., JP$,

Δpx — length of step in direction of axis x, for sub-area of length Δx,

Δpy — length of step in direction of axis y, for sub-area of length Δy,

$IP = \dfrac{\Delta x}{\Delta px}$ — total number of steps for sub-area of length Δx,

$JP = \dfrac{\Delta y}{\Delta py}$ — total number of steps for sub-area of length Δy,

Both in (48) and (49) in the numerator there occurs mixture density $\rho[C_{CH_4}(x,y,t)]$, whose value in goaf sub-area Δx and Δy we determine by the approximation based on six contiguous points in the goaf sub-area. We accept a second-order polynomial approximating changes in density in the following form:

$$\rho = a_0 + a_x x + b_0 y + b_x xy + c_0 y^2 + c_x xy^2 \tag{51}$$

According to Fig. 11, for the function (52) the following dependencies are true; on their basis we calculate particular coefficients of an approximating function. We can write:
for $x = 0$ and $y = 0$:

$$\alpha_0 = \rho_{i,j} \tag{52}$$

for $x = \Delta x$ and $y = 0$:

$$a_x = \frac{\rho_{i+1,j} = \rho_{i,j}}{\Delta x} \tag{53}$$

for $x = 0$ and $y = +\Delta y$:

$$\rho_{i,j+1} = \rho_{i,j} + b_0 \Delta y + c_0 \Delta y^2 \tag{54}$$

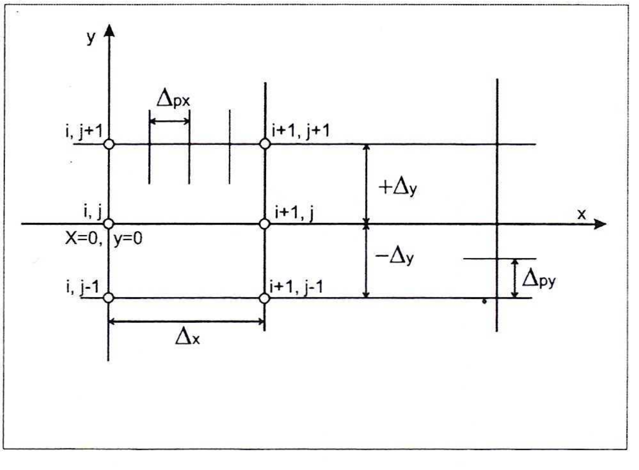


Fig. 11. Numerical diagram of dividing fragmenst of goafs into sub-areas

Rys. 11. Schemat numeryczny podziału fragmentu zrobów na podobszary, oznaczenia i wskazówki for $x = 0$ and $y = -\Delta y$:

$$\rho_{i,j-1} = \rho_{i,j} - b_0 \Delta y + c_0 \Delta y^2 \tag{55}$$

for $x = \ddot{A}x$ and $y = +\ddot{A}y$:

$$\rho_{i+1,j+1} = \rho_{i,j} + a_x \Delta x + b \Delta y + b_x \Delta x \Delta y + c_0 \Delta y^2 + c_x \Delta x \Delta y^2 \tag{56}$$

for $x = \Delta x$ and $y = -\ddot{A}y$:

$$\rho_{i+1,j-1} = \rho_{i,j} + a_x \Delta x - b \Delta y - b_x \Delta x \Delta y - c_0 \Delta y^2 + c_x \Delta x \Delta y^2 \tag{57}$$

Subtracting the equation (55) from (54) after further transformations we obtain:

$$b_0 = \frac{\rho_{i,j+1} - \rho_{i,j-1}}{2\Delta y} \tag{58}$$

Adding the equation (55) to (54) after transformations we obtain:

$$c_0 = \frac{\rho_{i,j+1} + \rho_{i,j-1} - 2\rho_{i,j}}{2\Delta y^2} \tag{59}$$

Adding the equation (57) to (56) after transformations we obtain:

$$c_x = \frac{\rho_{i+1,j+1} + \rho_{i+1,j-1} + \rho_{i,j} - \rho_{i,j-1} - \rho_{i,j+1} - \rho_{i+1,j}}{2\Delta x \Delta y^2} \tag{60}$$

Subtracting the equation (57) from (56) after transformations we obtain:

$$b_x = \frac{\rho_{i+1,j+1} - \rho_{i+1,j-1} + \rho_{i,j-1} - \rho_{i,j+1}}{2\Delta x \Delta y^2} \tag{61}$$

where:

$i = 1, 2, ..., I$ — index of position of point in goaf sub-area in direction of axis x,
$j = 1, 2, ..., J$ — index of position of point in goaf sub-area in direction of axis y,

The formulas presented above enable to calculate the values of substitute resistance $R_{m,x}$ and $R_{m,y}$ and values $h_{z,x}$ and $h_{z,y}$, which result from the existence of the gravity forces and the distribution of density of the flowing mixture. These formulas were used in a computer program.

We have presented above the method of solving a system of algebraic equations, from which we have obtained the values of the capacity of the flow of the air-methane mixture both in the headings and the goaf area. Next, having this solution, we can proceed to obtain a solution leading to determining the distribution of the methane concentration in the headings and goafs. First we determine the values of the velocity of the flow of the air-methane mixture using the current values of density and geometrical measurements of the heading and given goaf sub-area.

The equation concerning the distribution of the methane concentration in the heading and goafs is a partial differential equation. In solving the equation (11) concerning the distribution of the methane concentration in the heading, the finite difference method is used and the derivatives in the equation are approximated by means of a secret differential diagram (Dziurzyński 1985; Nawrat 199). The selection of this method resulted, among others, from the division of the goafs into sub-areas of lengths Δx and Δy. The approximation formula for the equation (11) has the following form:

$$\frac{C^{t+1}_{\mathrm{CH_4},k+1} - C^{t}_{\mathrm{CH_4},k}}{\Delta t} + v_i^{k+1} \frac{C^{t+1}_{\mathrm{CH_4},k+1} - C^{t+1}_{\mathrm{CH_4},k}}{\Delta s} = 0 \tag{62}$$

where:

t — consecutive time step,

Δt — length of time step,

$k = 1, 2, ..., K$ — consecutive step along coordinate s,

$K = \dfrac{L}{\Delta s}$ — total number of steps for air strip of length L, while for the headings having contact with the goafs $L = \Delta x$,

Δs — length of spatial step along coordinate s,

v_i^k — velocity of flow of air-methane mixture in the i-$^{\text{th}}$ air strip,

After the transformation of (62) we obtain:

$$C^{t+1}_{\mathrm{CH_4},k+1} = \frac{1}{1 + \dfrac{v_i^k \Delta t}{\Delta s}} \left[C^{t}_{\mathrm{CH_4},k} + 1 + \frac{v_i^k \Delta t}{\Delta s} C^{t+1}_{\mathrm{CH_4},k} \right] \tag{63}$$

In order to solve the distribution of the methane concentration in the goafs (22) we use the method of "against-current" approximation. This method is used successfully in solving this type of equations.

It results in establishing a balance of the mass of the air-methane mixture flowing in and flowing out of the volume of the goaf sub-area; we assume that the methane concentration flowing out of the considered sub-area to other sub-areas is the same.

Using this method enables to take into consideration the solutions of the equation (63) on a common boundary where the headings have a contact with the goafs.

The approximation formula for the equation (22) has the following form:

$$\frac{C^{z,t+1}_{\mathrm{CH_4},i,j} - C^{z,t}_{\mathrm{CH_4},i,j}}{\Delta t} + v_{x,i-1,j} \frac{C^{z,t+1}_{\mathrm{CH_4},i,j} - C^{z,t+1}_{\mathrm{CH_4},i-1,j}}{m_{i-1,j}\Delta x} + v_{y,i,j-1} \tag{64}$$

$$\frac{C^{z,t+1}_{\mathrm{CH_4},i,j} - C^{z,t+1}_{\mathrm{CH_4},i-1,j}}{m_{i,j-1}\Delta y} = \frac{\omega^{z,t+1}_{\mathrm{CH_4},i,j}}{\rho^{t}_{i,j} h}(1 - C^{z,t+1}_{\mathrm{CH_4},i,j})$$

After further transformations we obtain:

$$C^{t+1}_{\mathrm{CH_4},i,j} = \frac{1}{W}\left(\frac{C_{\mathrm{CH_4},i,j}}{\Delta t} + \frac{\omega^{t+1}_{\mathrm{CH_4},i,j}}{\rho^{t}_{i,j} m_{i,j} h_{i,j}} + \frac{v^{t+1}_{x_{i-1,j}}}{m_{i-1,j}} \frac{C^{t+1}_{\mathrm{CH_4},i-1,j}}{\Delta x} + \frac{v^{t+1}_{y_{i,j-1}}}{m_{i,j-1}} \frac{C^{t+1}_{\mathrm{CH_4},i,j-1}}{\Delta y} \right) \tag{65}$$

where:

$$W = \frac{1}{\Delta t} + \frac{v^{t+1}_{x_{i-1,j}}}{m_{i-1,j}\Delta x} + \frac{v^{t+1}_{y_{i,j-1}}}{m_{i,j-1}\Delta y} + \frac{\omega^{t+1}_{\mathrm{CH_4},i,j}}{\rho^{t}_{i,j} m_{i,j} h_{i,j}} \tag{66}$$

On determining the distributions of the methane concentration in the heading and the points of the goaf sub-area which contain mass $\int_V m\rho h dx dy$, in accordance with formula (9), we calculate the distribution of the oxygen concentration and the density of the air-methane mixture in accordance with the equation of state given in the form (7).

In order to verify the convergence of the obtained results, during numerical calculations we have conducted calculations using another division into sub-areas or a changed time step. If obtained results have not been very much different, they have been accepted for further considerations.

On the basis of the presented numerical methods and approximation formulas as well as boundary and initial conditions, a computer program has been developed. It enables a numerical simulation of the phenomena connected with the movement of methane in a sealed space in the changeable conditions of ventilation and methane inflow.

5.5. Verification of the adapted mathematical model

5.5.1. A computer simulation program

The presented mathematical model of the flow of air and methane in a sealed space constitutes a basis for a computer program simulating the phenomena under consideration which is named METAN.

5.5.2. A computer simulation of the influence of filling sealed space with methane — verification of the model

In chapter 4, we have presented the results of the experimental research conducted in longwall N-10 seam 361 in the "Pniówek" coal mine.

Using the results included in research papers (Dziurzyński 1985, 1988; J. Szlązak et al. 1987; N. Szlązak 1990) we have accepted the distributions of permeability *k(x,y)*, porosity *m(x,y)* and the height of the goafs *k(x,y)*. According to the formula given in chapters 5.3 and 5.4, data, adjusted to the mining and geological conditions, has been prepared for each case under consideration. The data concerning the values of the parameters describing the flow in headings has been accepted on the basis of measurements taken in the factual conditions of the experiment. Besides, the results of the research on the flow of marker SF_6 in a sealed space have been taken into consideration in preparing the data and determining the initial flow in the examined area (Babicz et al. 1983).

5.5.3. The simulation — the "Pniowek" coal mine, longwall N-10, seam 361

The area of longwall N-10 in the "Pniówek" coal mine has been selected for the simulation. The spatial diagram of the area is presented in Fig. 5. The following data has been accepted for the determination of the parameters of the mathematical model of the longwall N-10 area:

- the length of longwall N-10 equals 200m, the accepted life of the longwall equals 1000 m,
- the length of longwall N-10 A equals 100 m,
- the thickness of seam 361 equals from 1.6 to 2.1 m, 2 m have been accepted,
- roof rock — shale clay and arenaceous shale, class of roof — 3–4,
- absolute methane bearing capacity — during exploitation — 9.7 m^3/min, during the liquidation of the longwall — 2.6 m^3/min,
- the length of the division of the goafs into sub-areas $\Delta y = 25$ m in the direction of axis *y*, in the direction of axis *x*, a changing length of the division has been accepted:
  - from 0 to 100 m of the longwall's life $\Delta x = 25$ m,
  - from 100 to 200 m of the longwall's life $\Delta x = 50$ m,
  - from 200 to 600 m of the longwall's life $\Delta x = 100$ m,
  - from 600 to 1000 m of the longwall's life $\Delta x = 200$ m,
- the distributions of permeability, porosity and the goafs' height have been accepted according to the principles presented in paper (Dziurzyński 1988) and applied to roof rocks and the thickness of seam 361.

The spatial diagram (Fig. 12), which is a screen dump taken during the simulation, presents the initial state in the flow of the air-methane mixture in the sealed area of longwall N-10.

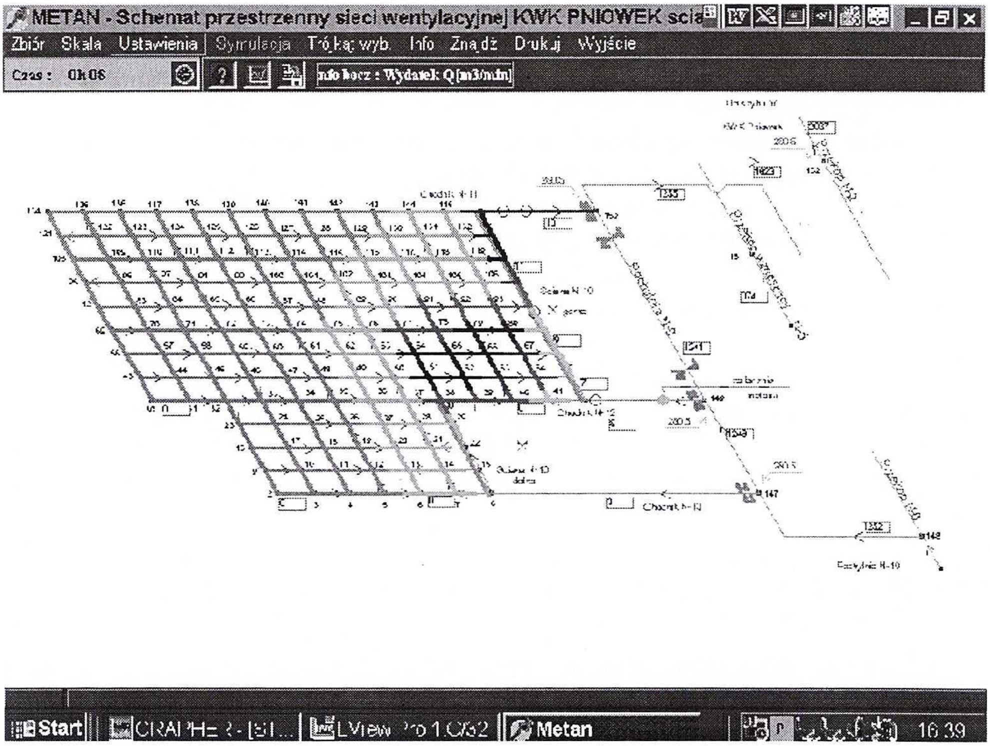


Fig. 12. Initial state flow of air-methane mixture in the area of longwall N-10 seam 361

Rys. 12. Stan początkowy — rozpływ mieszaniny powietrza i matanu w rejonie ściany N-10 pokł. 361 — symulacja komputerowa

Fig. 12 shows the results of the calculations of the capacity of the flow of the air-methane mixture in the headings of the area under consideration and the distribution of the methane concentration in the goafs; the value of the methane concentration has been indicated according to the accepted color scale. For such an initial state, a simulation of the influence of loaded methane on the distribution of the concentration of methane and oxygen in the tested area has been carried out. Methane has been delivered to gangway N-12 (air strip 149-42), according to the characteristic presented in Fig. 7.

Thanks to the simulation possibilities of the program, measuring points have been established in the tested area where methane and oxygen concentration sensors have been positioned. These places correspond to particular measuring stations accepted during the experimental research. It concerns:

- a methane sensor at measuring station 5 in gangway N-12,
- a methane sensor at measuring station 3 in longwall N-10 — in the middle of its length,
- methane and oxygen sensors at measuring stations 1 and 2 in gangway N-11 (before stopping TI-2536, from the direction of longwall N-10),

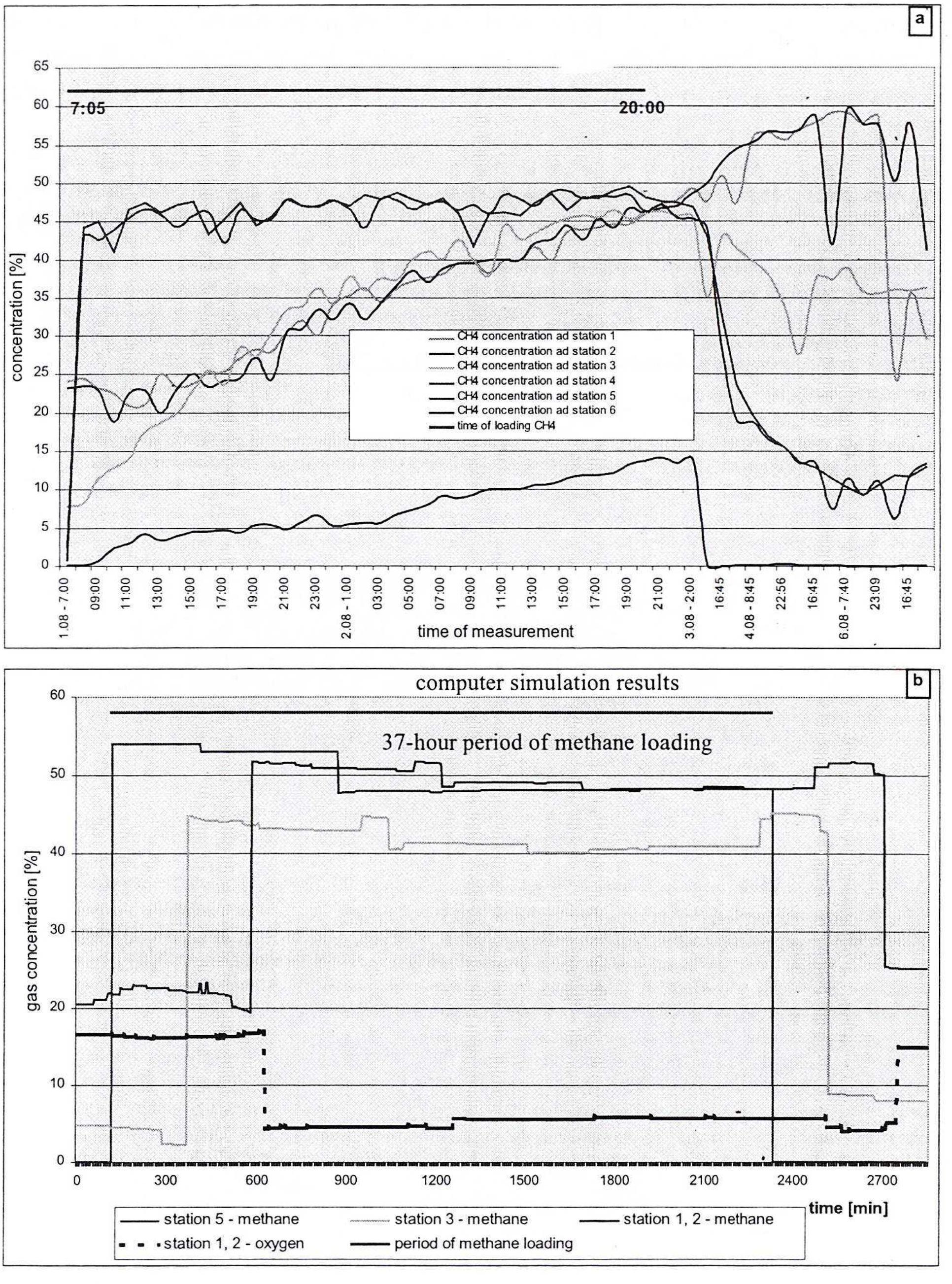


Fig. 13. Changes in methane concentrations in sealed headings of the area of longwall N-10 seam 361 (1.08.98–7.08.1998) — results of experimental research

Rys. 13. Kształtowanie się stężeń metanu w otamowanych wyrobiskach rejonu ściany N-10 pokł. 361 (1.08–7.08.1998)

In order to verify the correctness of the accepted mathematical model, simulation calculations have been conducted for the parameters of the model which have been accepted as if for a situation with conditions corresponding to those occurring during the experiment.

In comparing the consistency of the results obtained in the simulation and the results obtained during the experiment, the diagram of changes in the methane concentration in the sealed area has been taken into consideration. The diagram is presented in Fig. 13.

The presented solution allows to ascertain a similar character in the course of changes in the methane concentration in the sealed area of longwall N-10 obtained experimentally and theoretically from the simulation. For example, observing the course of changes in the methane concentration, a continuous curve — (station 2), in the phase after switching off the delivery of methane we can notice a further slight increase in the methane concentration.

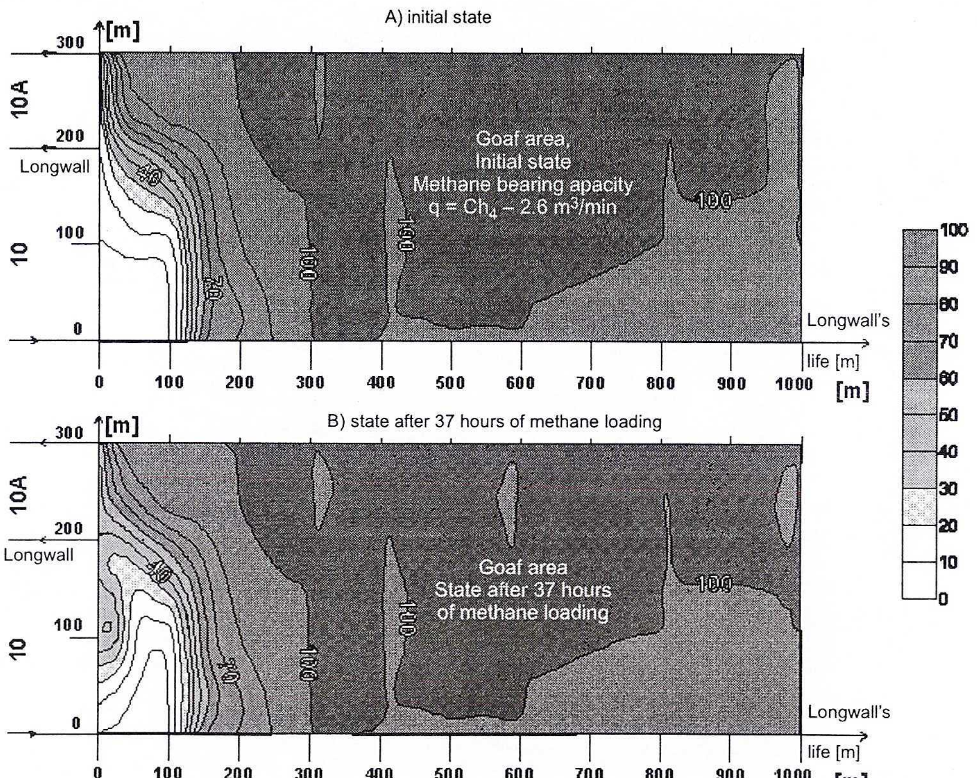


Fig. 14. Distribution of methane concentration in goafs of longwall N-10, seam 361 — computer simulation

Rys. 14. Rozkład stężenia metanu w zrobach ściany N-10 w pokł. 361— symulacja komputerowa

Similar results have been obtained during the experimental research where the level of the values of the methane concentration measured in the consecutive measuring points is close to the values obtained from the calculations.

The following Figures present the distribution of the methane and oxygen concentrations in the goafs of longwall N-10.

Fig. 14 presents the distribution of the methane concentration in the goafs of longwalls N-10 and N-10A. Two solutions are presented: the first solution for the initial state refers to the period after blocking the area and before delivering methane; the second solution refers to the state 37 hours after delivering methane — just before switching it off.

The presented solutions enable to notice changes in the distributions of the methane and oxygen concentrations (Fig. 15) between the state concerning the phase before

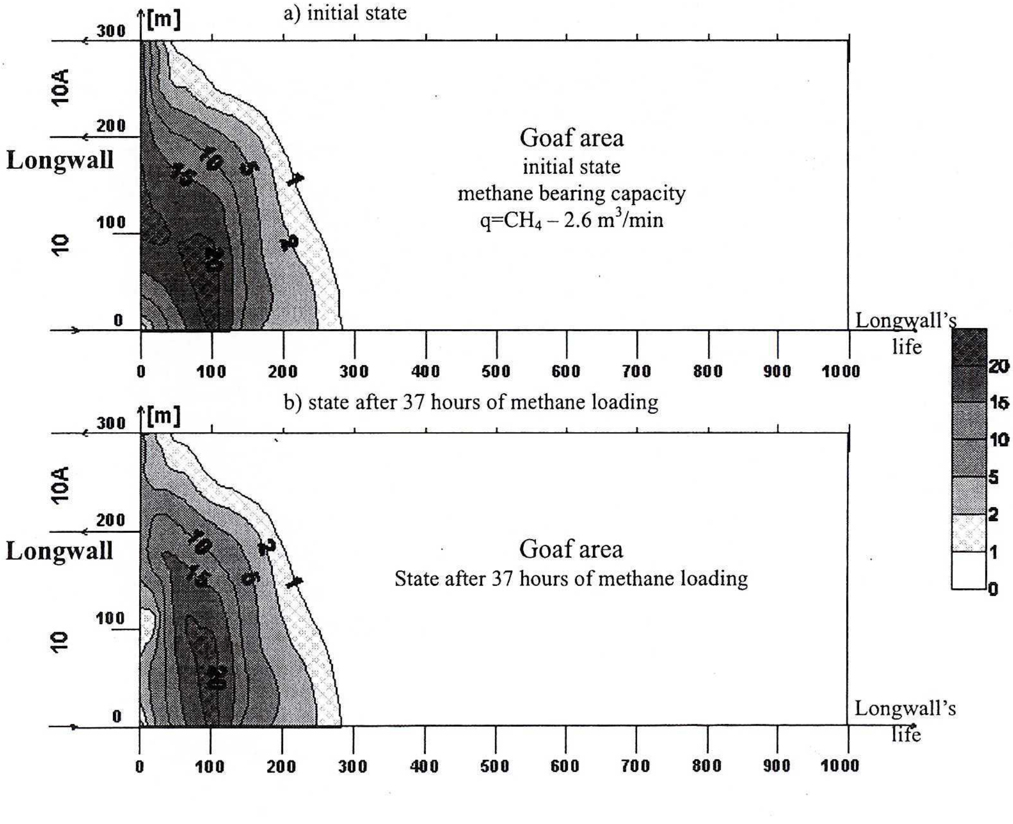


Fig. 15. Distribution of methane concentration in goafs of longwall N-10, seam 361 — computer simulation

Rys. 15. Rozkład stężenia tlenu w zrobach ściany N-10 w pokł. 361 — symulacja komputerowa delivering methane and the state of the goaf area after the period of 37 hours. It can be ascertained that the goaf area is being slowly filled with a mixture of a low oxygen content.

6. Findings and conclusions

The analytical material, practical experiences as well as experimental and model research presented in this paper enable to formulate the following findings and conclusions:

1. A very important problem in coal mines is the control and regulation of gaseous states in sealed headings and goafs, especially in terms of the endogenic fire hazard and methane or fire gas explosion hazard.

2. In coal mines, the composition and concentration of gases in sealed headings ana goafs can be changed under the influence of the following factors:

- natural factors — inflow of gases — methane or carbon dioxide — from rock mass,
- internal factors — the inflow and outflow of goaf gases and inflow of the products of oxidation and coal burining in goafs,
- external factors — the inflow of air as a result of ventilation and methane drainage,
- external invasive factors — the supply of inert gases or air-methane mixtures and goaf gases mixtures by means of invasive installations.

3. The methods of influencing the composition of gases in sealed headings and goafs differ first of all on technical parameters and the degree of safety and effectiveness in time, the safest technology being the use of inert gases.

4. The author has participated in the development of the invasive method of filling sealed headings and goafs with the air-methane mixture recovered from the underground methane drainage network in the coal mines of the Jastrzębie Coal Mining Holding. The application of this method requires the fulfilment of many conditions, especially in the field of safety.

5. The method of filling sealed headings and goafs with methane has been applied on numerous occasions in the coal mines of the Jastrzębie Coal Mining Holding ("Morcinek", "Pniówek" and "Zofiówka"). Its practical usability has been confirmed.

6. It has been shown experimentally that the application of the method of filling sealed headings and goafs with methane enables:

- to regulate within a specific range the composition and concentration of gases, especially the concentration of methane and oxygen,
- to change in a controlled way the composition and concentration of gases — the air-methane mixture — with a view to reducing its explosiveness,
- to reduce the oxygen concentration, i.e. to reduce considerably the possibility or velocity of the process of coal self-ignition or endogenic fires.

7. In the "Pniówek" and "Zofiówka" coal mines experimental research has been carried out which enables to monitor precisely the process of gasodynamic changes

in the sealed headings and goafs while the methane filling method has been used. The applied measuring equipment enables to document the course of changes in the methane and oxygen concentrations and the velocity of the gas flow. It has been confirmed that:

- as a result of filling the goafs with methane, an significant increase in the methane concentration and decrease in the oxygen concentration occurs,
- the dynamics of the course of changes in the methane and oxygen concentrations depends on:
  - the efficiency of the installations delivering methane from the methane drainage network,
  - the composition of the air-methane mixture delivered to the goafs and obtained from the methane drainage network,
  - the topological structure and gas permeability of the sealed headings and goafs,
  - the influence of external factors, mainly ventilation and methane drainage.

8. The original results of the experimental research carried out in the conditions of an operating coal mine have been the basis for the development of a mathematical model. So far this problem has not been studied extensively enough. A simple mathematical model has been developed, and appropriate boundary conditions and numerical methods have enabled to develop a computer simulation program. On the basis of this program, a series of simulations have been carried out concerning the distribution of the methane and oxygen concentrations in the case of delivering methane to the goafs of longwall N-10 in the "Pniówek" coal mine.

Alternative simulation calculations have been done for various values of the absolute methane bearing capacity of the area as well as the capacity and concentration of methane delivered to the area.

9. In the simulation calculations, a considerable similarity between the results of the experimental research and the model research has been obtained, which enables to analyse qualitative and time courses. The developed computer simulation program METAN is a useful tool in coal mining. A series of alternative research on the simulation of the influence of methane delivered to the sealed area enables:

- to determine the distribution of the methane or oxygen concentration in the sealed area and the areas with the mixtures of explosive gases,
- to observe the influence of the concentration and capacity of delivered methane on the gas parameters of the area, and first of all to get to know the dependence between the parameters of delivered methane, the area's methane bearing capacity and the distribution of the methane concentration,
- to determine a zone characterized by a low oxygen concentration, i.e. an area where the process of coal burning is considerably limited.

10. This paper is a contribution to the development of the scientific principles of the invasive filling of seale dheadings and goafs with gases in order to regulate the composition and concentration of goaf gases with respect to limiting the fire and explosion hazards, which consequently will result in the improvement of work safety in coal mines.

REFERENCES

Babicz W., Broś E., Lasa J., Nawrat S., Sachs F., Stobiński J., Śliwka I., 1983: Application of electronegative markers in identification research on ventilation networks in underground mines. Mining Review no. 6.

Batko S., Ragus E., 1985: Application of liquid carbon dioxide and nitrogen in fire-fighting operations in the Lenin coal mine. Work Safety in Coal Mining. no. 3.

Buchwald P., Kajdasz Z., 1998: Inertization with application of nitrogen. Mine Rescue Work no. 3.

Bystroń H. et al., 1976: Technology of extinguishing fires in methane fields with industrial verification of applying a gas extinguishing unit. IBG "Barbara".

Cross H., 1936: Analysis of flow in networks conduits or conductors, engineering experiment station. Biul. no 286. University of Illinois.

Czechowicz J., 1972: Fire-fighting in methane coal mines. "Śląsk" Publishing House, Katowice.

Ćwięk B., 1987: Principles of organizing rescue operations and methods of fire-fighting in underground mining. Training materials of SITG, Katowice.

Dziurzyński W., 1981: Digital simulation of the systems of regulating mine ventilation networks in the presence of methane emission from old goafs. Archives of Mining Scienes vol. 26, is. 3.

Dziurzyński W., 1985: Unsteady conditions in a mine ventilation network caused by exogenic fire. Ph.D. Thesis, Academy of Mining and Metallurgy, Kraków.

Dziurzyński W., 1988: Forecasting the process of deep mine ventilation in the conditions of underground fire, Studies, Theses, Monographies No.56, Institute of Mineral Resources and Energy Management, Polish Academy of Sciences, Kraków.

Dziurzyński W., Nawrat S., 1995: Optimal choice of the parameters for ventilation and methane drainage in a longwall face with caving. Proceedings of the 7th US Mine Ventilation Symposium, USA.

Dziurzyński W., 1996: Underground fire in the conditions of methane inflow — a mathematical model, Archives of Mining Scienes vol. 36, book. 3.

Dziurzyński W., Nawrat S., 1993: Influence of ventilation on methane drainage in a longwall face with caving, Archives of Mining Scienes vol. 38, book. 2.

Dziurzyński W., Tracz J., Trutwin W., 1988: Simulation of mine fires. Proceedings of Fourth International Mine Congress, Brisbane, Australia.

Dziurzyński W., Tracz J., Trutwin W., 1992: Computer simulation of transients in mine ventilation. Proceedings of the Fifth International Mine Ventilation Congress, Marshalltown, South Africa.

Dziurzyński W., Nawrat S., Roszkowski J., 1992: On the influence of ventilation parameters on the effectiveness of the methane drainage system. Proceedings of the Fifth International Mine Ventilation Congress, Marshalltown, South Africa.

Dziurzyński W., Nawrat S., Roszkowski J., Trutwin W., 1995: Mine ventilation disturbed by outbursts. Intern. Symposium cum Workshop on Management and Control of High Gas Emissions and Outbursts in Underground Coal Mines. Wollongong, NSW, Australia.

Dziurzyński W., Nawrat S., Roszkowski J., Trutwin W., 1996: Computer simulation of mine ventilation disturbed by fires and the use of fire extinguishers. Proceeding of the 6th International. Mine Ventilation Congress, USA.

Frycz A., Kozłowski B., 1979: Ventilation of methane coal mines. "Śląsk" Publishing House, Katowice.

Grębski Z., Kozłowski B., 1982: Methane drainage of rock mass in coal mines. "Śląsk" Publishing House, Katowice.

Konarski A., 1978: Influence of roof control on methane hazard in a longwall heading. Mining News no. 11.

Litwiniszyn J., 1949: Stationary flows in heterogenously unisotropic mediums. Annales de la Societe Polonaise de Mathematique vol. XXII.

Litwiniszyn J., 1951: A problem of dynamic of flow in conduit networks. Bulletin of Academy Polonaise Science vol. 1, no. 3.

Litwiniszyn J., 1957: Flow with the exchange of mass, momentum and energy. Applied Mechanics Archives vol. 9, is. 2.

Matuszewski J., 1976: Changeability in methane concentration in goafs behind a longwall face. Scientific Symposium on "Fighting Methane and Coal Dust Explosion Hazards in Coal Mining" Katowice.

Michaylow M., Vlasseva E., 1995: On void aerodynamics in a porous media of a job area. Proceedings of the 7th US Mine Ventilation Symposium, Lexington, USA.

Myszor H., 1974: Methane emission from longwalls of intensive exploitation. Mining Review no. 5.

Nawrat S., 1989: Influence of ventilation on methane drainage in a caving longwall. Ph.D. Thesis, Academy of Mining and Metallurgy, Kraków.

Nawrat S., Żyła W., 1991: Methane filling of sealed fire fields in coal mines. Mining News no. 4.

Nawrat S., 1999: Experimental and model research on the process of methane filling of sealed headings in coal mines. EMAG Scientific, Research and Implementation Papers. 1(11).

Nguyen Huyen Dien, 1994: A method of forecasting distribution of methane concentration in goafs of caving longwalls. PhD Thesis, Silesian University of Technology, Gliwice.

Pawiński J., Roszkowski J., 1974: Movement of methane in serially connected elements of methane drainage networks of different characteristics. Archives of Mining Scienes no. 4.

Pawiński J., Roszkowski J., Szlązak N., at al., 1989: Analysis of explosion hazards in headings and goafs and applied preventive measures. Unpublished paper. Kraków — Rybnik.

Pawiński J., Roszkowski J., Strzemiński J., 1979: Mine ventilation. Silesian Technical Publishing House, Katowice.

Roszczynialski W., Wacławik J., 1983: Mining aerology. National Scientific Publishing House. Warszawa.

Roszczynialski W., Trutwin W., Wacławik J., 1992: Mine Ventilation Measurements. "Śląsk" Publishing House, Katowice.

Roszkowski J., Szlązak N., Szlązak J., 1997: Methane drainage as a means of fighting explosion hazard and methane utilization in coal mines. Mining News. no. 10.

Roszkowski J., Szlązak N., 1999: Selected problems of methane drainage in coal mines. Academic Publishing House. Kraków.

Staroń T.: Mining of coal seams with roof caving in the vicinity of fire fields. "Śląsk" Publishing House. Katowice.

Strumiński A., 1987: Fighting underground fires in coal mines. Polish Academy of Sciences Publishing House, Wrocław.

Sułkowski J., 1996: Hazard connected with the presence of methane in longwall goafs leading away from a field. Research paper GIG Ser. Konf. no. 14.

Sułkowski J., Nguyen H.Dieu, 1994: Location of zones with explosive concentration of methane in caving wall goafs with diagonal ventilation. Scientific conference "Methane Hazard in Coal Mining".

Szlązak J., 1980: Influence of sealing wall gangways on air flow through goafs. Ph.D. Thesis, Academy of Mining and Metallurgy, Kraków.

Szlązak J., 2000: Air flow through a longwall caving area in the light of theoretical and experimental research. Academy of Mining and Metallurgy, Academic Publishing House.

Szlązak J., Szlązak N., 1987: Determination of aerodynamic resistance on caving longwall goafs. Archives of Mining Scienes vol. 32, is. 4.

Szlązak J., Szlązak N., 1987: Air escape through caving longwall goafs ventilated with system C — to boundaries. Archives of Mining Scienes vol. 32, is. 4.

Szlązak N., 1990: Evaluation of fire hazard in caving goafs on the basis of ventilation intensity. Archives of Mining Scienes vol. 35, is. 3.

Szlązak J., Szlązak N., 1990: Effectiveness of sealing longwall gangways and flow through caving longwall goafs. Archives of Mining Scienes vol. 35, is. 4.

Trutwin W., 1972: Digital simulation of nonstationary states of the process of ventilation and regulating a mine ventilation network. Mining Research Papers vol. 10, is. 2.

Trutwin W., 1973: Influence of ventilation conditions on methane concentration in mine headings. Mining Research Papers vol. 11, is. 2.

Wasilewski S., 1997: Systems of monitoring and controlling ventilation hazards. Mining Mechanization and Automation no. 6/7.

REVIEW BY: PROF. DR HAB. INŻ. JANUSZ ROSZKOWSKI, KRAKÓW

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