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INVESTIGATIONS ON METHANE EMISSION FROM FLOODED WORKINGS OF CLOSED COAL MINES

Eugeniusz Krause[1*], Zbigniew Pokryszka[2]

[1] *Department of Energy Saving and Air Protection, Experimental Mine "Barbara", Central Mining Institute (Katowice, Poland)*
[2] *National Institute for Industrial Environment and Risks (INERIS) (Verneuil-en-Halatte, France)*
* Corresponding author: ekrause@gig.eu, tel. +48 32 32 46 501, fax: +48 32 202 87 45

Abstract
The migration of methane towards the surface, within mining areas of closed mines, can be a danger to public safety for many of years after the process of liquidation has been finished. The liberation of methane from undisturbed coal seams, and those destressed through earlier mining has not been fully recognised so far. Knowledge of the effect of the presence of water, along with hydrostatic pressure, on the intensity of methane desorption from destressed seams is necessary in determining the approximate volume of methane inflowing, within a period of time, into a closed mine. Laboratory tests on these relationships have been carried out in accordance with proper research methodology by the National Institute for the Environment and Industrial Hazards (INERIS), France with the Central Mining Institute, Katowice, Poland. The results have facilitated determining the effect of hydrostatic pressure variation of water on the intensity of methane desorption from flooded coal. These results has been practically applied in predicting the emission of methane into closed mines, and in orienting the rules of methane hazard control, both during the process of mine closure, and on the surface of post-mining areas.

Keywords
methane desorption, flooded mines, closed mines

1. INTRODUCTION

The migration of methane towards the surface takes place for many years following the closure of a mine. The emission of methane accompanies the liquidation process of the underground infrastructure (areas, levels and shafts), until the hazard appears on the surface of the closed mine.

Following the closure of a mine, the emission of methane from non-extracted methane-bearing seams occurs, typically for a period of approx. 15 years.

As a consequence of the water table rising as a result of mine flooding, the following phenomena occur:

- a drop in the intensity of methane desorption resulting from the effect of increased hydrostatic pressure and filling gas migration with water (residual voids, pores, fissures)
- increase of free gas pressure in the workings over the water level, the so-called "piston effect".

The increase of mine gas pressure creates conditions for the migration of methane through fissures towards the surface of post-mining areas.

The methane release on the surface is a very complex effect that depends on many factors related, among other things, to the structure and permeability of the overburden strata, the methane desorption rate from the unexploited gassy coal seams, destressed as a consequence of earlier mining, and the spatial location of these unexploited coal seams in relation to the water level in the flooded mine (Krause, Skiba 2010).

The evaluation of the released methane volume in the conditions of mine flooding is of importance when assessing methane hazard in post-mining areas. In some countries it is imposed by operative legislation and is an integral part of the methodology enabling authorities to assess gas hazard in post-mining areas (Tauziede, Pokryszka, Barriere 2002; Pokryszka at. al 2005).

At the same time it should be noted that, in spite of carrying out over more than ten years of investigations and monitoring of gas emissions following the closure of mines in Europe (Burrel, Friel 1996; Kral, Platenik, Novotny 1998; Pokryszka, Tauziede 2000; Robinson 2000; Nowotny et al. 2001; Prokop 2001; Besnard, Pokryszka 2005; Krzystolik et al. 2002), the question of methane released and migrating from non-degassed and flooded coal seams is still poorly addressed. The underground investigations conducted in Polish mines, together with the results of laboratory tests carried out in France and Poland, have however, enabled us to work out specified conclusions concerning this matter.

2. EMISSION OF METHANE INTO NON-FLOODED POST-MINING AREAS

Investigations conducted by the Central Mining Institute on the emission of methane from a distressed strata into the post-mining goaf of active or liquidated longwalls, have enabled us to work out a model which in turn facilitates identifying the prognostic determination of the volume of methane released into the goaf.

The development of the model of methane release has been based on the results of investigations on methane emission into goafs, conducted from 1994–2000, and on the results of computations of methane emission into the workings. The results were based on airflow along the workings in the vicinity of stoppings isolating the goaf, and the increments of methane in the air in those workings. During the process of mining, and after its completion, three periods occur that are characterised by different courses of methane release:

- mining period in which, after the longwall advance has been started, the absolute methanity rises to the value corresponding with the gas conditions of the extracted seam and its surroundings
- longwall liquidation period of 1 to 3 months, with the methane emission flow rate decreasing to the value from the range of 40% to 20% in relation to the absolute value during the period of mining exploitation
- post-liquidation period, lasting for approx. 15 years, in which the release of methane into post-mining goafs successively vanishes

In the course of mining, the release of methane into the longwall environment takes place, depending on:

- the length and slope of the longwall that influences the range of the mining-induced stress relief zone in which the degassing of the seams takes place
- the degree of degassing of undermined and overmined seams, which depends on the height of the extracted longwall, the distance of those seams from the mined seam, and on the method of mining (caving, filling).

The range of the desorption zone for longwalls with different lengths is determined by mathematical relationships (Krause, Łukowicz 2002; Krause 2008), which facilitate constructing the nomograms shown in Fig. 1.

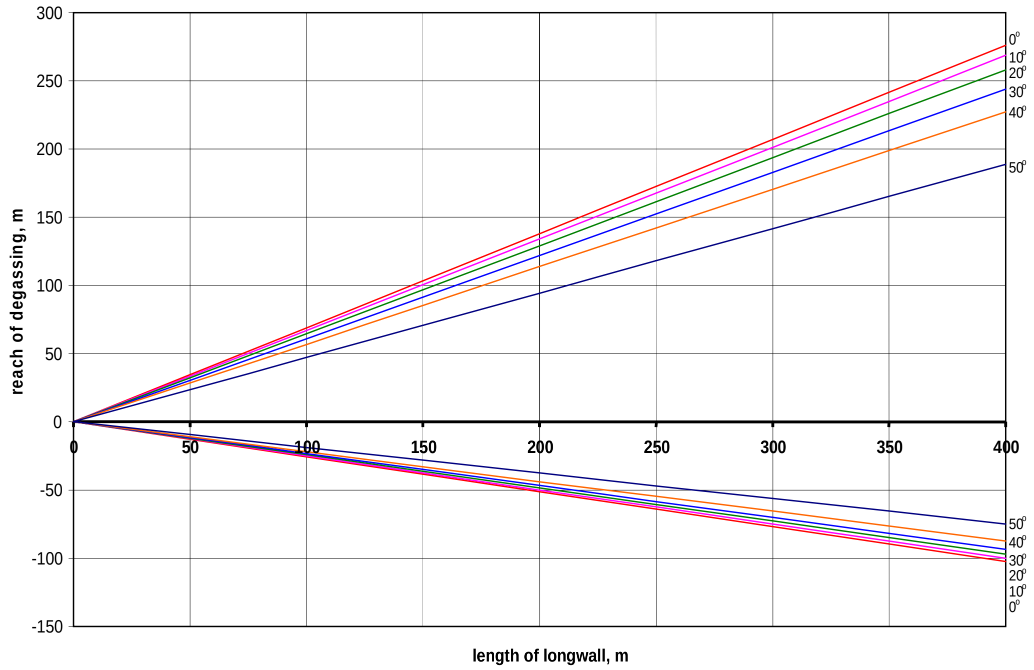

Fig. 1. Dependence of the degassing reach of undermined and overmined seams on the and slope of the longwall

When predicting methane emissions into planned longwalls, and then the post-mining emissions, one should take into account the range of stress relief, which, to a considerable extent, influences the volume of methane released into the goaf, as a result of degassing the undermined and overmined seams.

Figure 2 presents approximate values of the degassing degree of undermined and overmined seams depending on their distance from the seam extracted by the longwall carving method. The curves of the degassing degrees for under- and overmined seams (blue colour) have been plotted in comparison with the depth distribution of the initial methane content of seams.

Methane released from undermined and overmined strata migrates into the environment of the mined longwall, which, as a consequence, generates a decrease of the initial methane content in these seams to the M_{wt} value. The post-mining value of the methane content, M_{wt} of the seams, is the difference between the initial content, M_o and the direct desorbable methane content – M_{des} ($M_{wt} = M_o - M_{des}$). After the process of mining has finished, the emission of methane from the seams corresponding to gas available quantity, M_{wt} occurs and lasts for approximately 15 years (Krause E. 2009).

Based on research carried out by the Central Mining Institute, a model of methane emission into the longwall goaf has been developed (Fig. 3). The longwall mining operations lasts 1 year on average. The period of longwall closure lasts for 1–3 months, while the post-mining period of methane emission into the goaf has a duration of approx. 15 years. During longwall operation and the dismantling of mining equipment, degassing of undermined and overmined coal seams takes place, up to the available methane content M_{wt}, followed by a long period of methane desorption from these seams, with lower emission kinetics.

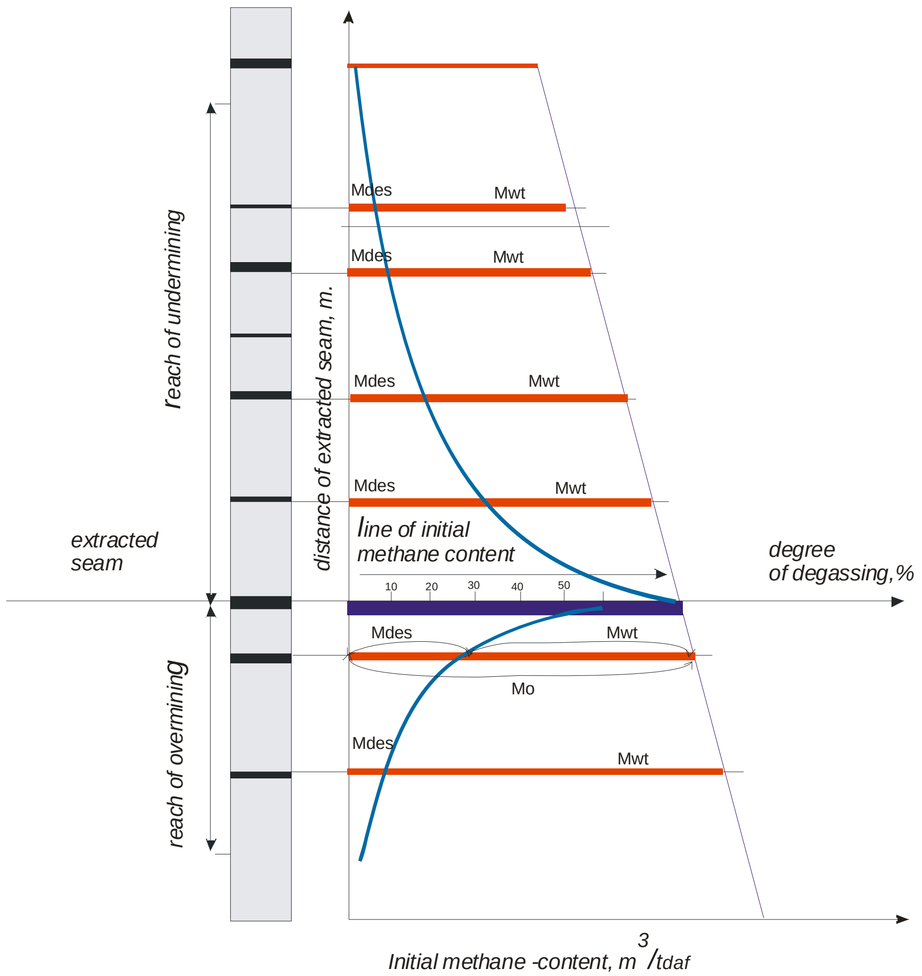

Fig. 2. Degree of degassing of undermined and overmined coal seams around an exploitation by longwall caving

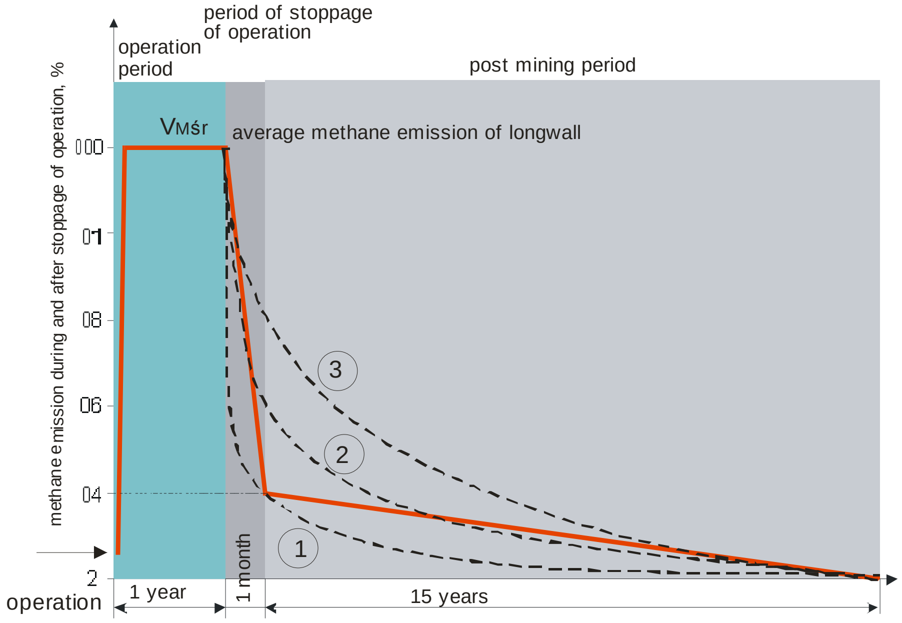

Fig. 3. Model of methane emission to the longwall goaf during and after mining operation

The release of methane during the post-mining period depends on the contribution of methane originating from undermined and overmined seams in the total emission of methane during mining operations.

The course of curves 1, 2 and 3 (depicted in Fig. 3 with dotted lines) reflects the approximate quantities of methane emitted into the goaf from under- and overmined seams, after activities have stopped. The position of curve 1, at the closest distance from the X axis, justifies a small contribution of methane inflowing to the goaf as a result of degassing undermined and overmined seams. In the case of such a characteristic of methane emission into the goaf of the operated longwall, the contribution of methane liberated from the mined seam in the course of longwall advance prevailed over methane liberated from undermined and overmined seams.

In the case when in the range of mining-induced stress relief areas, there are no undermined and overmined seams, the inflow of methane into post-mining zones can be approximately zero. The course of curves 2 and 3 points at a substantial contribution of methane emitted into a post-mining goaf from undermined and overmined seams destressed in the course of mining. Based on the results of underground field tests on methane emissions into the goaf, considerable diversification of methane release was found, confirmed also in a geological analysis of the mining surroundings.

On the basis of the model described above, it is possible to estimate the emission of methane into the longwall goaf after mining operations, in the form:

$$\dot{V}_Z = 0{,}2\,\dot{V}_{M\,\acute{s}r}\left(1-\frac{u}{15}\right),\ \mathrm{m^3CH_4/min} \qquad (1)$$

where:

$\dot{V}_{M\ \acute{s}r}$ – average methane flow rate during mining operations, m^3CH_4/min

u – the number of years since longwall exploitation was stopped

In the view of statistical data gathered from Polish coal mines, the emission of methane from the longwall goaf, after mining is stopped, equals approx. 20% of the average methane flow rate during the mining period.

A total emission of methane in a closed coal mine can by approximately estimated as a sum of methane emission flow rates from longwalls operated within the previous 15 years:

$$\dot{V}_{zlik} = \sum_{i=1}^{n} \dot{V}_{z_i},\ \mathrm{m^3CH_4/min} \qquad (2)$$

where:

$\dot{V}_{z_i}$ – methane emission flow rate into the goaf of the "*i*" – the mined out longwall, m^3CH_4/min

n – the number of longwalls exploited in the period of the previous 15 years before the closure of the mine, *i* = 1 to n.

It should be noted that methane emission into principal underground infrastructure of the mine (access and development workings) does not exceed 6% of the total volume of methane released into the mine.

3. EMISSION OF METHANE FROM FLOODED UNEXPLOITED COAL SEAMS

Field experience from the flooding operations of abandoned gassy mines have shown that the presence of water and hydrostatic pressure limits related to it result in the desorption and migration of methane from the unexploited seams destressed by mining. However, in scientific literature, there is no information, being of importance from the point of view of mining practices, concerning the detailed description of the mechanisms involved.

In connection with the above, from 2004–2005, the INERIS Institute (France) and Central Mining Institute (Poland) carried out joint laboratory tests aimed at determining the relationships in the "coal-gas-water" system in the context of flooding unexploited gassy coal seams in abandoned mines.

The tests included the following main stages:

- Determining the sorption capacity of coal in a dry-air state through determining the isotherm of methane sorption on a coal sample taken from an analysed coal seam.

Determining the sorption isotherms enables evaluating, with considerable accuracy, the volume of gas contained in the coal for a given level of sorption equilibrium pressure, and then to determine the quantity of the desorbable gas V_{des} from the specified mass of coal, at the drop of pressure up to the atmospheric pressure level (Fig. 4).

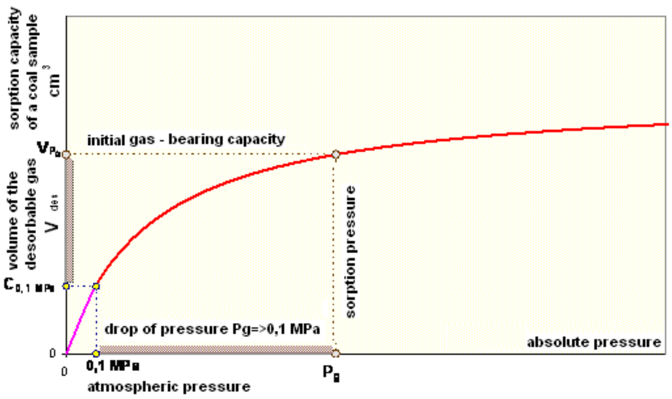

Fig. 4. Isotherm of gas sorption on a coal sample

- Saturating the coal sample with methane at a specified sorption equilibrium pressure.

Coal samples in dry-air state, with grain size of 0.5–1 mm were saturated with methane in the conditions of various levels of gas pressure, that is between pressure related to strongly degassed seams (relative pressure < 0.1 MPa) and pressure close to the level of *in situ* pressure in non-degassed seams (relative pressure > 1 MPa).

The experiment was performed in autoclaves, in the conditions of controlled temperature and pressure (Fig. 5).

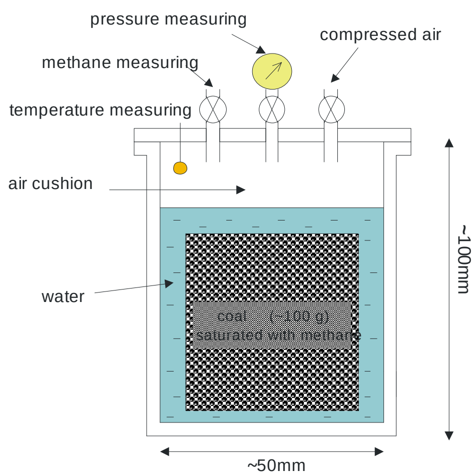

Fig. 5. Autoclave used in the tests

- Flooding the coal samples with water and applying a given level of hydrostatic pressure.

The samples of coal saturated with methane were rapidly flooded with water in such a way that coal should be entirely covered with a layer of water 1 cm-deep. Next, a given level of pressure was set in the upper part of the autoclave, through pumping up compressed air over the water level. This pressure was transferred to coal in the form of hydrostatic pressure (Fig. 5). In the course of a given series of experiments, hydrostatic pressure was set at lower, equal and higher levels, in order to produce various combinations in relation to methane sorption pressure in coal.

Methane emission was observed by measuring methane concentration in the air cushion with a specified volume over the level of water covering the coal sample. For most tests, the stabilisation of methane concentration in the air cushion was observed after 14 to 30 days. The tests were conducted on several coal samples originating from the Upper Silesia (Poland) and Lorraine (France) Coal Basins, for various combinations of sorption pressure Ps and hydrostatic pressure Ph, which provided more precise, quantitative determination of the effects of water and hydrostatic pressure on the intensity of methane emission from coal. For comparison, tests of methane emission from dry samples were also made.

As an example, Fig. 6 presents the intensity of methane emission observed for various coal samples collected in the Albert seam in the Lorraine Basin, depending on the relative overpressure of the adsorbed gas in relation to the hydrostatic pressure.

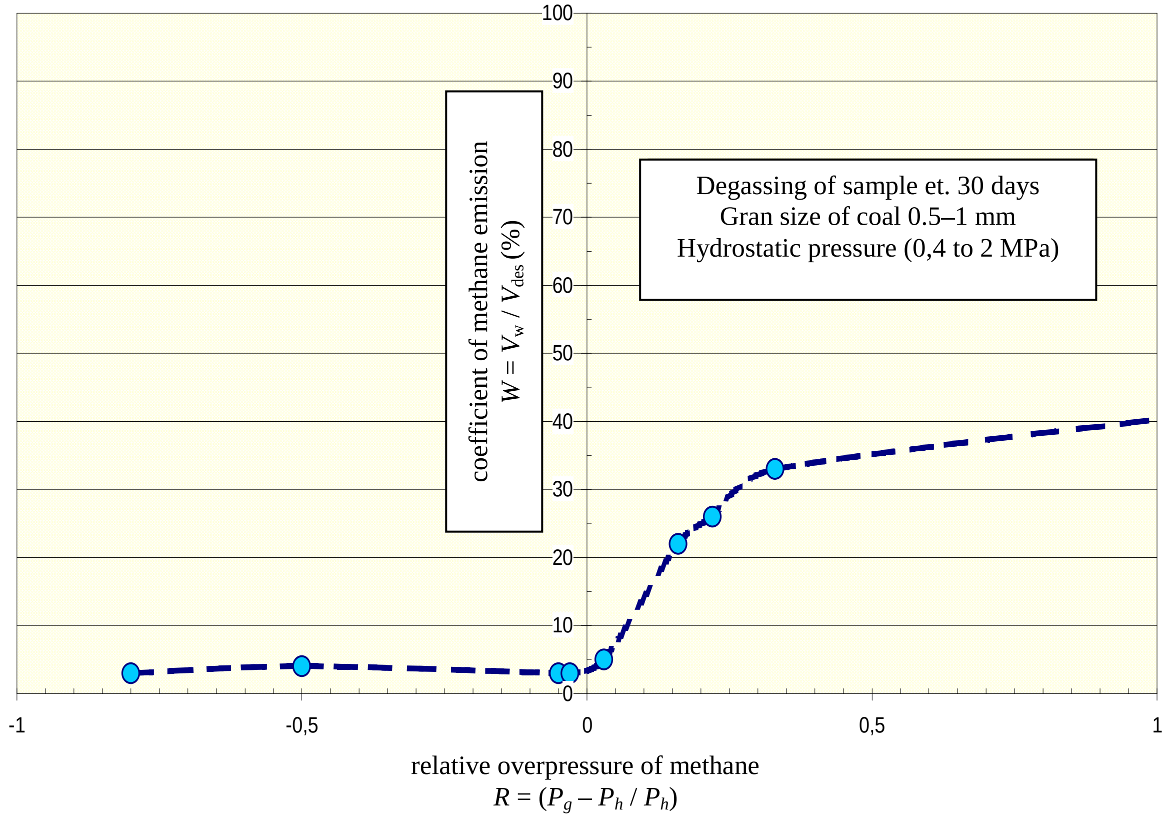

Fig. 6. An example of the hydrostatic pressure effect on emission of the methane from a sample of flooded coal. Coal taken from the Albert seam, Lorraine Basin

- Observing methane emission from flooded coal.

Coefficient W of methane emission from coal is given by:

$$W = V_w/V_{des}$$

where:

V_w – the volume of methane emitted from coal of a specified sample

V_{des} – the volume of methane desorbable at the pressure drop from a specified initial pressure to atmospheric pressure shown in Fig. 4.

The relative overpressure of methane R is given by the relationship:

$$R = (P_g - P_h)/P_h$$

where:

P_g – the initial absolute pressure of methane in coal corresponding with sorption equilibrium pressure

P_h – the absolute hydrostatic pressure of water covering the methane-containing coal sample

The results of the tests presented above, and of tests on other Polish and French coal shows that the hydrostatic pressure of water considerably reduces the emission of methane from coal. This effect increases with increasing water pressure in relation to the initial sorption equilibrium pressure of methane in coal.

The value of the gas emission coefficient becomes a minimum in the case of equilibrium between hydrostatic and gas pressures. Then, it remains approximately constant, in spite of the increasing predominance of hydrostatic pressure in relation to gas pressure. In this range of hydrostatic pressure, the volume of gas released in the experiments conducted remained less than 10% of the theoretical desorbable volume.

The kinetics of gas desorption from coal and the quantity of the desorbed methane are also limited by the presence of water, without the important effect of hydrostatic pressure. Fig. 7 presents the results of tests on methane emissions conducted on a sample of dry coal collected from seam No. 361 of the Pniówek mine, and on samples flooded with water at various levels of hydrostatic pressure (0; 0.2; 0.4 and 0.5 MPa), at identical initial pressure of gas sorption equilibrium (0.4 MPa).

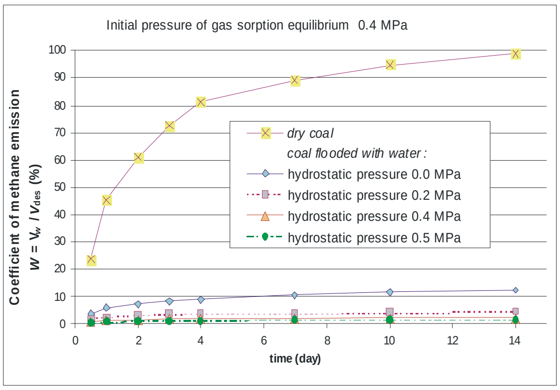

Fig. 7. Comparison of methane emission from the sample of dry coal and coal samples flooded with water at various hydrostatic pressures. Coal taken from No. 361 seam of Pniówek mine

The results of tests have shown that the intensity of methane emission from coal flooded with water, without the effect of hydrostatic pressure, was, in similar conditions, approximately 9 times lower than that from dry coal, and substantially decreased, in accordance with the results from Fig. 6, on applying hydrostatic pressure of a considerable value.

4. CONCLUSIONS

1. During and after closure of a coal mine, the rise of methane concentration and pressure takes place in the isolated post-mining voids, and creates a possibility of further gas migration into the surface trough overburden strata or directly connected workings.
2. In the conditions of flooding closed methane mines, the presence of water and related hydrostatic pressure limits the desorption and migration of methane from unexploited gassy coal seams, and thereby contributes to the reduction of methane migration to the surface of post-mining areas.
3. The presented results of investigations performed with the aim to determine the relationships present in the coal-gas-water systems, in view of closed coal mines can be used to predict the emission of methane into flooded coal mines, and in elaborating the rules of methane hazard control, in the course of mine closure and on the surface of post-mining areas.

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