The determination of methane resources from liquidated coal mines

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Abstract. The article refers to methane presented in hard coal seams, which may pose a serious risk to workers, as evidenced by examples of incidents, and may also be a high energy source. That second issue concerns the possibility of obtaining methane from liquidated coal mines. There is discussed the current methodology for determination of methane resources from hard coal deposits. Methods of assessing methane emissions from hard coal deposits are given, including the degree of rock mass fracture, which is affected and not affected by mining. Additional criteria for methane recovery from the methane deposit are discussed by one example (of many types) of methane power generation equipment in the context of the estimation of potential viable resources. Finally, the concept of "methane resource exploitation from coal mine" refers to the potential for exploitation of the resource and the acquisition of methane for business purposes.

1. Introduction
Methane in the nature occurs mainly in natural gas deposits – as its primary ingredient – and in hard coal deposits – as adsorbed gas. In the first case, it is the sought after and desirable high-energy fuel, in the second, after release, poses a serious threat to people and the environment in which methane-air mixture may form.

Coal deposits in the Upper Silesian Coal Basin are, apart from its northern part, strongly methane-bearing. By the mid-1950s, methane found in underground mines was not a significant problem, although it was noted in the history of the Polish mining industry by such catastrophic incidents as those in the mines: Brzeszcze-Silesia (10.06.1945 – 9 victims), Marcel (06.11.1947 – 5 victims), Mysłowice (4.12.1951 – 7 victims), methane explosion and coal dust in Jankowice mine (04.05.1950 – 29 victims).

Beginning in the 1950s the mining works, which prepared the exploitation of the southern part of the GZW in the Rybnik Coal Region, as well as the exploitation of ever deeper coal seams in the remaining part of the GZW, caused that the methane threat, or more precisely, the methane explosion hazard became a very common occurrence (outside the northern part of the GZW). This is evidenced by such mine disasters as: [1]: methane explosions in mines Moszczenica (08.04.1959 – 14 fatalities), Silesia (28.06.1974 – 34), Halemba (10.01.1990 – 9 victims), Śląsk (18th of December 1990 – 4), Sośnica (07.11.2003 – 3), Borynia (04.06.2008 – 6), Wujek Ruch (06.10.2014 – 5), or methane and coal dust explosions in mines: Halemba (21.11.2006 – 23) and Wesoła (13.01.2008 – 2). There were also methane and rocks’ outbursts in Zofiówka (22.11.2005 – 3).

Combating methane hazard until the seventies of the last century practically consisted in ventilations works. In the following years, after the previous tests, the use of methane drainage has become more and more often used to improve safety, which over time has become mandatory for use...
under certain conditions [2]. This was treated as a significant step in the fight against the explosion, which indeed was, and still is, a great success despite the disasters associated with methane. It should be emphasized that less methane flows in the mine air, posing a risk of explosion (other than places designated for this purpose), as methane can be captured. However, methane was not treated for a long time as a fuel – it was either discharged into the ventilation air – even underground, or directly into the atmosphere – from the surface methane pump station.

It was only in the 21st century that methane derived from hard coal was started as a valuable fuel and a factor which improves the economics of coal production [3]. Methane removed by methane drainage method is used as a low-methane fuel in various types of heating and power plants, eg in boiler houses with gas or coal-fired boilers and with gas turbine engines and turbines, or in gas-fired boilers. Following this, in the context of an ever-increasing number of liquidated mines, including methane mines, it was thought to take methane of such former mines and also about its economic use in heating and power plants. It just started to treat it as a business idea, which forced the alignment of legislation to document methane deposits from hard coal deposits as a primary mineral, as well as the granting and succession of concessions to entrepreneurs/mines, which are transferred to the structures that are involved in the restructuring of mines.

It is worth to note the data from the Ministry of the Environment (for example: [4]), which indicates that the size of the documented methane resource reserves in the Upper Silesian Basin is estimated at over 90 billion cubic meters. in 60 deposits. These resources are increasing, as more and more reconnaissance work is being done, resulting in new documentation of methane deposits from hard coal deposits. Only in 2015, the stock of methane from hard coal deposits increased by nearly 4 billion cubic metres, in the connection with documenting new three deposits. There is also an increase in the size of industrial reserves, which in the case of 27 deposits fluctuated within 6 billion cubic meters. At the end of May 2017, the searching for and the exploration of methane deposits from coal seams was conducted in Poland on the basis of eight concessions granted by the Ministry of Natural Resources and the extraction of this gas – on the basis of three concessions.

2. Methane in hard coal deposits
Methane in the coal deposits is divided into the accompanying mineral – the methane exploitation is possible during coal mining - and the main mineral that can be extracted either independently of the coal or in the post-mining period, ie exploiting the methane bed from the hard coal mines. According to the subject of this article, the next part of this article will cover the last case.

The occurring of methane in coal, as it is commonly accepted, is associated with the formation of coal. In low carbon coals methane was formed as a result of microbial activity, and in coals with a higher degree of carbonation – as a result of the organic matter processes [5] accumulated in the marshes as a residue of various vegetation growing on Earth in hot and compressed climates. The chemical and physical reactions that have caused them have led to the formation of coal, as well as methane, carbon dioxide, nitrogen and water. As the deposits of organic matter exploded, the pressure and temperature increased, resulting in an increased degree of carbonation of the material and an increase in the methane content.

It is characteristic for methane, found in coal seams, that it contains small amounts of carbon dioxide and nitrogen, and does not contain hydrogen sulphide (so methane is so-called "sweet" gas). This means that methane does not require special preparation before use. In addition, it is extracted at a much lower pressure than methane from conventional deposits.

Methane contained in coal [6, 7] is adsorbed (in micropores less than 2 mm in diameter), in form of free gas trapped in gaps and cracks and dissolved in water in coal. In the carbon matrix it is trapped by weak van der Waals bonds, characterized by the attraction between noble gases and between non-polar molecules.

As practice shows, methane in coal occurs in varying amounts, and the amount of sorbed methane depends on many factors. The main ones are the sorption properties of coal, the temperature and the
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Coal has a specific sorbent capacity for certain values: pressure, temperature and humidity. The amount of hydrocarbons that can be absorbed results inter alia from petrographic composition and degree of coagulation [8, 9]. However, due to the complexity of the problem, there is no clear correlation between methane content and the factors that form it. The reason for this is that some of the organic matter has evaporated in the carbonizing process, and some have evaporated in the areas of tectonic disturbances. Disturbances can, in certain circumstances, be a convenient way of migration, and in others create sealed screens that prevent degasification.

The phenomenon of adsorption occurring on the solid-gas phase boundary is a big issue, so the theory on the subject is a lot. One of the most commonly used models to describe sorption processes is the Langmuir model, where the amount of adsorbed methane in coal is characterized by the equation [5]:

\[
p = \frac{1}{a} + \frac{p}{a_m} K \cdot a_m
\]

where:
- \(p\) – equilibrium pressure [MPa],
- \(a\) – amount of adsorbed methane per unit mass of coal \([\text{m}^3/\text{Mg}]\),
- \(a_m\) – the amount of adsorbed methane assuming the one-molecule layer \([\text{m}^3/\text{Mg}]\),
- \(K\) – adsorption equilibrium constant, determined experimentally.

An example of the course of changes in the amount of adsorbed methane in coal, as a function of temperature change – with constant moisture content, light fractions, pure carbon and ash – is shown in figure 1.

![Figure 1. The examples of methane adsorption isotherms in coal for different temperatures, with a constant content of: moisture – 1.4%, light fractions – 24%, pure carbon – 67%, ash – 7.5% [5].](image)

In practice, the amount of gas (including methane) \(G\) \([\text{m}^3]\) contained in the coal seam is calculated from the dependence:

\[
G = A \cdot h \cdot r_c \cdot G_s,
\]

where:
- \(A\) – surface of coal seam \([\text{m}^2]\),
- \(h\) – average thickness of the coal seam \([\text{m}]\),
- \(r_c\) – average coal density \([\text{Mg/m}^3]\),
- \(G_s\) – amount of adsorbed methane \([\text{m}^3/\text{Mg}]\).
In turn, the amount of adsorbed methane in the coal mass unit \( G_s [m^3] \) is calculated as [5]:

\[
G_s = (1 - f_a - f_m) \frac{V_L \cdot P}{P_L + P},
\]

where:
- \( f_a \) – percentage of ash [%],
- \( f_m \) – percentage of moisture [%],
- \( V_L \) – volume of Langmuir [m³],
- \( P_L \) – Langmuir pressure [MPa],
- \( P \) – pressure [MPa].

As it turns out, the determination of the amount of methane that can be adsorbed from the coal seam is the more accurate when the well-known values of the parameters are taken into account.

3. Factors characterizing the methane deposit from coal deposits of liquidated mines

As it is already mentioned, the coals show a certain sorption capacity. Under given conditions of pressure, temperature and humidity, they can absorb the right amount of hydrocarbons, resulting from, among other things, the petrographic composition and degree of carbonation. As these processes are very complex, one can not expect a clear correlation between methane content and the factors that form it. Significant amount of gas produced by the process of carbonation of the organic matter has evaporated, and therefore the conditions for re-generation of the gas have to occur. Probably methane migrating from a deeper subsoil was absorbed by the coals to which it had come.

The methane bed found in the coal deposits of the liquidated mine is:
- free methane, which filled post-mining goaf, non-caved areas and/or not in bad repair excavations, as well as pores and gaps in coal seams and porous barren rock;
- methane sorbed, that is physico-chemically bound to coal mineral matter of coal seams and dispersed in barren rocks.

The methane drainage from such a deposit usually occurs when the developed business plan confirms the profitability of the project. The business plan is usually based on the geological and investment documentation of the methane deposit in the hard coal deposit, which must be prepared on the basis of the geological and investment documentation of the hydrocarbon reservoir [10]. For its preparation, quite extensive knowledge is needed – mainly in the field of geology, including:
- hard coal deposits in the given area, their range of methane content, porosity, ash content, humidity or density,
- barren rocks deposits in strata, mainly relating to their porosity and methane content,
- the structure of mining excavations,
- the method of development of coal deposits in individual seams,
- the coal mining made in individual seams,
- the rock tectonics, including downthrows, upthrows, faults,
- the vicinity of the deposit, which may affect the inflow or outflow of free methane, water, other gases,
- methane depletion in the period from the preparation of the coal deposit to exploitation, through the period of mining plant operation until its physical liquidation – including depletion by ventilation or methane drainage,
- the parameters of free gas in the free space of the deposit.

Practice shows that the knowledge of hard coal deposits in a given area is relatively accurate, as the documentation of hard coal deposits has been based on the results of research on coal and rock samples, in terms of methane content, porosity, moisture, and coal samples also in terms of ash content and density. In turn, the development of the deposit and the exploitation of the given coal seam based
on the specific structure of the excavation knowledge has deepened and expanded due to i.e. rock tectonics.

The formation of soil or the neighborhood of a given deposit may not be accurately identified – an accurate and extensive knowledge of the neighboring mining area is not always known. It is also difficult to accurately determine the amount of methane loss in the entire earlier desorption period and therefore it is estimated. The knowledge of the parameters of gases creating a free gas is the most accurate, as it results from the in situ research needed to carry out a concession for the exploration and discovery of methane deposits from coal deposits.

In the abandoned mines, the original methane content system of the coal seams has changed many times. The sorption and desorption processes were repeated with the coal mining, which was usually accompanied by the methane drainage, which at the end of mining formed a new spatial distribution of methane content. Its role in this is the mutual arrangement of a sorbed gas - a free gas that determines many of the physico-chemical factors arising, inter alia, from geological conditions, as well as from the migration of gases outside the given area (e.g. to the surface, adjacent areas with active mining, etc.). Therefore the fall of the deposit pressure causes the gas desorption from the seams to cracked and porous rocks, goaf, and especially to the post-extraction workings.

Due to the fact that in Poland – in a decisive part – it is made exploitation of coal seams by longwall working system, in the rock there are formed large cavities that are the residues after the extracted coal - the goaf. The caving zone (figure 2) includes approximately 2.5 to 3.5 times the extracted coal seam \([11]\) \(h_b – \text{in figure 2}\), and the high caving zone includes to 5 times \([12]\) \((h_b + h_i – \text{in figure 2})\) and even up to 6-7 times \([13, 14, 15]\). The area around the longwall face is characterized by very high values of filtration and permeability coefficient.

Figure 2. A diagram of the relaxed rock mass around the caving longwall face \([12]\).

Another important factor for the methane deposit is the convergence of both goaf and mining excavations: close to longwall, air workings and rock drifts \([12]\).

4. Identification of methane resources from hard coal deposits

The methane bed of the hard coal mine requires, as already mentioned, documentation of what is being done during exploration-identification work. The scope of such work is usually specified in the concession for the exploration and identification of methane from hard coal. Once completed,
appropriate documentation shall be prepared in accordance with the Geological and Mining Law [16] and the Implementing Regulations [17, 18, 19, 20, 10, 21, 22].

On the other hand, the classification categories for the deposit are based on the qualification rules for the documentation of hard coal methane, as set out in the Balancing Criteria and the Principles for Calculation of Methane Resources in Coal Seams [23] and the Principles for Documenting Oil, Natural Gas and Methane in the seams of coal [22]. Accordingly, the methane deposit, as primary mineral, is eligible depending on the surface area for which one drainage hole is made, in which methane content tests were performed, which are required to determine the industrial resources, ie:

- in category C if at least 1 hole/8 km$^2$,
- in category B, at least 1 hole/2 km$^2$,
- to category A, includes the methane resources documented by exploited exploitation holes using the mass balance method or statistical methods.

It is also important to determine the methane boundaries of the given area, which, in addition to, as already mentioned, account for the presence of methane sorbed in the bed and free methane in the free space must take into account the methane in the barren rocks. As the lower limit is usually the level (depth) of rock deposits, and the upper limit for the occurrence of methane sorbed on carbon deposits is usually the Carboniferous roof, located below the impermeable forms of Miocene clay.

In the case of liquidated coal mines where coal remains unextracted, it is important to identify the methane deposit from this part of the coal bed. This is done in terms of balance resources and off-balance resources. The balance resources consist of sorbable methane, which is physicochemical-bound to carbonaceous material and dispersed in barren rocks, and methane free that fills post-mining goaf, free spaces in narrow workings, as well as pores and cracks in coal seams and porous rocks. Off-balance resources consist of non-sorbable methane.

Significant, from the point of view of the future methane drainage from the liquidated mine, is to determine the size of the dynamic resources of methane sorbed on the coal seams, which are partly a potential source of methane to the open space - eg non-liquidated excavations, goaf. It is a sorbed methane, which is released from a part of the rock covered by previous mining works in the area and, if so, carried out in the area of the adjacent coal bed. Also important is the recognition of the tectonics of the rock, because in the tectonic region strongly disturbed is the diversity of methane content, even within one seam. There are also - in certain conditions - the possibility of methane inflow even from more distant areas and deposits through these disturbances, and in others - they can create sealed screens that prevent degassing.

Depending on the specific methane conditions prevailing in the coal bed methane and in the goaf, an appropriate method of calculating the methane content of coal in the reservoir is chosen. Typically, aggregate resources of methane from coal in the deposit ($Q_m$) are composed of static methane free ($Q_g$) resources filling the anthropogenic reservoir and the dynamic resources of the sorbed methane ($Q_d$) in the hard coal deposits formed to the depth assumed as the bottom boundary:

$$Q_m = Q_g + Q_d \ [Nm^3]$$

4.1. Static resources of methane deposits
Assessment of the amount of static resources of free methane ($Q_g$) accumulated in the anthropogenic reservoir – collector created in the rock cavities – what are post-mining gobs and dammed workings, including main workings, non-liquidated workings, made in the barren rock (left as full-scale but converged) and workings made in coal deposit (left in reduced dimensions and converged), workings partially liquidated (eg by stowing) by volume method, using the formula:

$$Q_g = V_k \cdot p \cdot C \cdot wT \ [Nm^3]$$

where:

$V_k$ – volume of collector within free gas accumulation [m$^3$].
The gas pressure coefficient determining the deposit pressure relative to the normal pressure, 
$p$ – the gas pressure coefficient determining the deposit pressure relative to the normal pressure,

$m$ – the gas pressure coefficient determining the deposit pressure relative to the normal pressure,

$C$ – content average – CH₄ in gas [%],

$wT$ – conversion factor from m³ to Nm³ (Nm³ – normal m³, for normal conditions, ie pressure 101,325 kPa, temperature 273.15 K, coefficient of compressibility 1).

$$V_k = V_{W_{sk}} + V_{W_w} + V_{W_p} + V_{Zr} \ [m^3]$$  \hspace{1cm} (6)

The volume of the collector is calculated as the sum of the individual available gas volumes for the free space - ie non-liquidated excavations $(V_{W_x})$ and goaf:

$$V_{W_x} = L \cdot A \cdot C_x \ [m^3]$$  \hspace{1cm} (7)

where:

$L$ – the length of non-liquidated excavations of a given type - separately: excavations made in the $L_{sk}$ barren rock, excavations made in the $L_w$ coal seam, excavations made in the coal seam close to longwall $L_p$ \ [m],

$A$ – cross section of the narrow working corridor of a given type - separately: excavations $A_{sk}$ made in the barren rock, excavations made in the coal seam $A_w$, excavation made in the coal seam close to longwall $A_p$ \ [m²],

$c_x$ – capacity coefficient of free space for a given type of excavation, assuming that mine work has been retreated for a minimum of 20 years back – separately: for excavations made in barren rock $c_{sk} = 0.8$; for excavations made in the coal seam $c_w = 0.5$; excavation made in the coal seam close to longwall $c_p = 0.3$).

On the other hand, the volume of goaf is calculated according to the formula:

$$V_{Zr} = \sum (P_x \cdot g_{px} \cdot c_{Zr}) \ [m^3]$$  \hspace{1cm} (8)

where:

$P_x$ – the surface of each extracted seam \ [m²],

$g_{px}$ – average thickness of each exploited seam \ [m],

$c_{Zr} = 0.15$ – the capacity factor of the goaf, assuming that mine work has been retired a minimum of 20 years back.

4.2 Dynamic resources of methane deposits

The amount of sorbed methane $(Q_d)$ is taken for the coal deposits from the Carboniferous roof to the depth assumed as the limit. The methodology most commonly used is:

- estimation of pure coal mineral matter resources $(csw)$ at individual levels in the separated parts of coal deposit,

- calculation of the mean methane content of the seams in those parts, which is calculated from the results of the tests at the different levels of the separated part of the deposit,

- multiplying the amount of pure coal mineral matter resources $(csw)$ by the average methane content minus the residual methane content value, which is calculated by indirect analytical method, due to lack of direct measurements. In $csw$ estimation, documented coal resources are corrected by
multiplying it by the increase factor for undocumented, thin seams and coal inserts with a thickness of 0.1 m and a reduction factor for moisture and ash content in coal.

Generally, the assessment of the dynamic resources of methane in the bed \((Q_d)\) is made using the formula:

\[
Q_d = Q_w \cdot K1 \cdot K2 \cdot (G - Gr) \text{[m}^3]\]

(9)

where:
- \(Q_w\) – documented coal resources [Mg],
- \(G\) – average methane content [m\(^3\) CH\(_4\)/Mgcsw],
- \(K1\) – increase factor for undocumented coal inserts (depending on their total thickness - usually within the range of 3.0-6.0),
- \(K2\) – reduction coefficient due to moisture and coal ash (usually within the range of 0.75-0.85),
- \(Gr\) – residual methane content [m\(^3\) CH\(_4\)/Mgcsw], which is calculated for coals using an analytical method for the determination of residual (non-desorbable) regression equation:

\[
Gr = a_0 + a_1 \Delta P_2
\]

(10)

where: \(a_0, a_1\) – coefficients of regression equation.

5. Limitations of methane drainage potential

As already mentioned, in the second decade of the 21st century, the exploitation of methane from the hard coal deposits from liquidated mines was increased. Most methane is used to produce electricity in cogeneration engines, to which methane is supplied from pumping stations. The pumping station sucks gases, including methane, from the methane bed through a borehole made from the surface to an anthropogenic reservoir (usually to the goaf of the just extracted top seam; below the top seam there are situated the gobs of bottom seams) and transfers them to the cogeneration engine.

The methane mining from hard coal to dry up completely is not possible. The first reason is the limitations that result from the parameters of pumping stations. This concerns the vacuum that could be generated. The amount of vacuum created \((P_{gr})\), depending on the operating parameters of the device used to drain the methane from the coal bed is usually the pressure level of approx. \(P_{gr} = -35\) kPa. This is the limit pressure for the emission of desorbable gas. At such pressure, the equilibrium between the pressure of the gas in the coal deposit and the vacuum produced and the possibility of further methane operation are terminated. These quantities of methane remaining in the deposit are non-industrial resources \((Q_{np})\), which together with industrial resources \((Q_p)\) are the total methane resources of hard coal methane \((Q_m)\).

The second reason for limiting the potential for full exploitation of methane resources is the need to ensure the safe operation of the cogeneration engine.

For example, the Caterpillar 3516 1.136 MW engine for optimum operation and production of electric current requires 4.7 m\(^3\) of CH\(_4\) at a concentration of 100%. Engine operation is possible with a minimum methane concentration in the engine gas of \(Cs_{min} = 33\) % CH\(_4\). When the concentration drops below this value, the motor is automatically immobilized. This means that at this limit concentration the gas should be delivered at 15 m\(^3\)/min.

These acts make it necessary, from a business point of view, to introduce the concept of “methane exploitation resources” from the hard coal mine \(- Q_E\), which can be completely used to produce electricity. These resources are defined as

\[
Q_E = Cs_{min} \cdot Qm \cdot 0.01 \text{[m}^3]\]

(11)

As a consequence, this reason is more important because it determines the amount of resources that can be exploited.
6. Summary
Methane from hard coal deposits can be of two kinds: typical, that is, creating a methane explosion hazard in active mines and less typical – using it for electricity production – where as an energy fuel increases its share in the energy balance.

Estimating methane resources in the hard coal deposit requires detailed analysis of the geological and operation documentation both from the period of coal exploration and mine exploration, particularly methane content research.

The use of cogeneration engines for methane combustion and electricity generation creates concrete limitations in the potential for complete exhaustion of industrial methane from hard coal deposits – the operation below the specified methane concentration in the combusted gas engine is not possible.

From the business point of view, it was necessary to take into account the limitations resulting from the performance of the cogeneration engine in determining the amount of resources to be used, which led to the introduction of the term “methane exploitation resources” from the hard coal mine deposits.

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