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Hard coal mining in India and the opportunities for application of foregoing demethanization in Moonidih colliery

Introduction

India is gradually becoming a global superpower, with the population approximating the one of China. The population growth dynamics for China and India is, respectively, ca. 7 million per year and 17 million per year. Should the tendency hold, India is expected to become – in more or less three years – the most populous country in the world. At the same time, India is one of the world's poorest countries, with over 300 million people lacking access to electricity (Ferris 2014). Still, the country is regarded as another developing superpower and destination for large industrial output hubs (Pappas and Chalvatzis 2017). The growing population, along with the dynamic increase in power-consuming output is forcing India to undertake actions aiming at stepping up its energy security. India's economic growth is directly connected with the increased energy consumption (Narayan 2016). If the country wants to effectively compete with the regional leader in the field of energy production, i.e. China, it has to boost its own power output. At present, differences in energy consumption per capita between the two states are huge: in China, this consumption is 4.6 times bigger than in India (World Bank 2015). India's goal by 2030 is to become, along with China, the biggest energy consumer in absolute terms.

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The main reason for power insufficiency in India is the hard coal deficit facing the country's power plants, as hard coal is India's major energy resource. The state's hard coal resources, located at the depth of up to 1,200 m, are at present estimated at 306.6 billion tons (Singh and Kumar 2016), but, under the present economic and technological circumstances, not all of them can be successfully tapped into. The documented resources, with extraction volume estimated at 60.6 billion tons, are able to deliver coal for over 100 years, given the current state of production (Shankar 2014).

India is the world's third hard coal producer, after China and the US. In the years 2000–2015, the output grew by over 60%, from 340 million tons to 565 million tons. India's ambition is to increase the output further, to 1.5 billion tons in 2020, and supplying the electrical energy to the 300 million people that have so far been living without electricity. The current increase in output is, however, failing to match the rising demand for electrical energy, which has grown from 370 TWh to over 900 TWh in 2000–2015. This rise in demand is connected with the speedy development of the Indian economy, the average growth of which in the last decade stood at over 8% a year. If we compare the hard coal consumption per capita for Poland and India, it will turn out to be ca. 1.2 Mg for the former and 0.4 Mg for the latter. This difference will become even more striking if we take the brown coal output into account, which in Poland stands at 60 million tons, and in India at a mere 24 million tons (1.6 Mg and 0.02 Mg per capita, respectively).

The world's biggest company dealing with hard coal extraction is Coal India Limited (CIL). CIL has over 450 mines, employs over 400,000 people, and extracts ca. 430 million tons of hard coal from 471 mining facilities. CIL's extraction growth dynamics is presented in Fig. 1. The company's average annual output growth stands at almost 30 million tons.

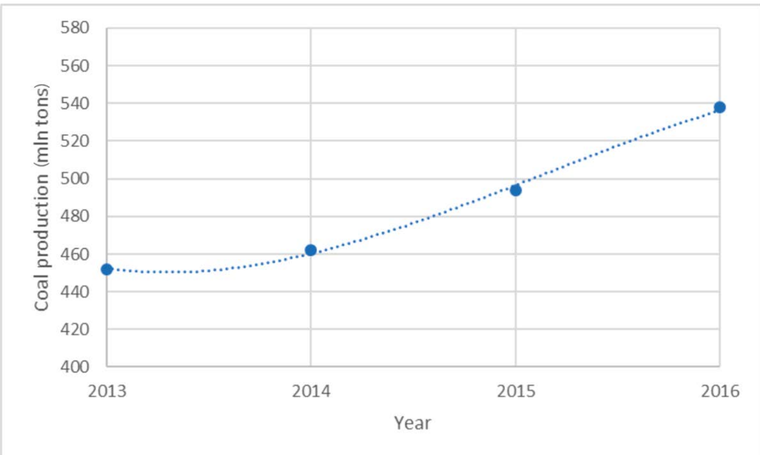

Fig. 1. Hard coal extraction at Coal India Limited
(based on: https://www.coalindia.in/en-us/performance/physical.aspx)

Rys. 1. Wydobycie węgla w Coal India Limited
(na podstawie: https://www.coalindia.in/en-us/performance/physical.aspx)

Regardless of such huge output, CIL also has to act as an importer of coal. In 2014, India was the world's second largest coal importer (after China and ahead of Japan), bringing over 200 million tons of the resource from Indonesia, South Africa and Australia by sea. Hard coal output in India can be limited due to the occurrence of various threats, including the methane threat, much like in Poland. The amount of methane deposited in coal beds, estimated at 400 BCM (Singh 2016), speaks to the scale of this hazard. As a result, Indian engineers, together with their more experienced partners from Australia, the US, Poland, Germany and some other countries, are working on projects aiming at the demethanization of India's coal beds.

1. The methane threat in Indian mines as illustrated by the example of the Moonidih mine

India's underground hard coal mines are classified under one of the three methane threat categories. The 1st category, or degree, includes excavations in which the methane release from coal is lower than 1 m^3/t, and the concentration of explosive gases in the air is below 0.1%. The 2nd category encompasses excavations in which the methane release from coal falls within the range 1–10 m^3/t, and the concentration of explosive gases is below 1%. The 3rd category includes areas in which the methane-bearing capacity exceeds 10 m^3/t. The biggest methane threat occurs in the mines in the Jharia basin, located in East India, 300 kilometers north-west of Calcutta (the Jharkhand province) – cf. Fig. 2. The geological map of the Jharia basin can be found in works by (Singh et al. 2013; Kumar et al. 2015).

Fig. 2. A map of India with the city of Moonidih marked on it

Rys. 2. Mapa Indii z zaznaczonym miastem Moonidih

According to the information provided in the work by (Kumar et al. 2015), the average methane content of c∞oal seams in the Jharia basin area is very high and stands at 17.98 m^3/Mg. As the quoted authors claim, the methane content increases with the depth and the degree of coalification. One of the mines classified under the 3rd category of the methane threat is the Moonidih mine, located on the outskirts of the city of the same name, and equipped – to a large extent – by the Polish company Kopex. At present, the mine authorities are planning to carry out a foregoing demethanization procedure, along with using methane in gas engines. In order to evaluate the potential of extracting methane from the mine's coal bed No. XVI, laboratory research into the collected coal samples was conducted with the aim of determining the sorption isotherm and the effective diffusion coefficient. The next step was to estimate the kinetics of the coal bed demethanization, conducted with the application of numerical methods on the basis of the value of the coal diffusion coefficient.

2. Theoretical foundations of the issue

Let us assume that the methane occurring in coal is the sum of the sorbed gas, bonded with the inner surface of coal (*a*) and the "free" gas occurring in the coal's pores and cracks (*w*). For the sorbent-sorbate system (in our case, the coal-methane system) in the state of equilibrium, the size of sorption (*a*) depends on the temperature (*T*) and the pressure (*p*) of gas in a free phase, and can be described by means of a sorption isotherm in the following form: $a = f(p,T)$. The equation which is the most frequently used to describe the sorption of methane in coal is Langmuir's equation:

$$a = a_m \frac{bp}{1+bp} \tag{1}$$

↳ a – the amount of methane sorbed under a given equilibrium pressure p, m^3CH_4/Mg,
a_m – the maximum size of the sorption, when $p \to \infty$, m^3CH_4/Mg,
b – the constant characteristic of the coal-methane system, MPa^{-1},
p – the pressure of the free gas (in the volume stage), MPa.

Let us assume that the amount of "free" gas in the pore area of coal is the function of temperature is described by the following linear equation:

$$w = \frac{\varepsilon}{\rho_{He}} \frac{P}{P_0} \cdot \frac{298}{T} \tag{2}$$

↳ w – the amount of free methane under a given equilibrium pressure p, m^3CH_4/Mg,
ε – porosity,
P – the absolute pressure of the free gas, MPa,

p_0 – the atmospheric pressure, MPa,
T – the absolute temperature of the rock mass, K,
ρ_{He} – the real density of coal, Mg/m^3.

The kinetics of the process of methane accumulation/release from coal, called sorption/ /desorption kinetics, can be described by means of the solution to the 2nd diffusion equation, with the application of a number of simplifying assumptions, listed in the work by (Crank 1975). The solution can be found in some scientific sources, including (Timofeev 1967; Pillalamarry 2011). It looks as follows:

$$\frac{v(t)-v(\infty)}{v(0)-v(\infty)} = \frac{6}{\pi^2}\sum_{1}^{\infty}\left[\frac{1}{n^2}\exp\left(-\frac{n^2\pi^2 D_e t}{r^2}\right)\right] \tag{3}$$

D_e – the effective diffusion coefficient,
r – the grain radius,
$v(0)$ – the initial mass of gas accumulated in a coal sample,
$v(\infty)$ – the limit to which the mass of gas remaining in the sample tends with times.

By solving the above equation in a numerical way and comparing the results with the results of the gravimetric measurement procedure, determining the value of the effective diffusion coefficient becomes possible. In the present paper, the method of the least differences between the squares of the measured and calculated values was applied.

3. The research results

3.1. The technical analysis of coal

The content of the volatile matter, moisture and ash was determined according to the Polish Norm. Density was determined by using the helium pycnometry and quasi-liquid pycnometry, with the application of AccuPyc and GeoPyc instruments (Viana et al. 2002). The results of the technical analysis of coal are presented in Table 1.

Table 1. The results of the technical analysis of coal

Tabela 1. Wyniki analizy technicznej węgla

Volatile matter content	Moisture content	Ash content	Real density	Apparent density
$V_{daf}^{r} = 29.63$	$W_t^r = 1.23\%$	$A^a = 21.31\%$	$\rho_{He} = 1.640$ g/cm^3	$\rho_p = 1.498$ g/cm^3

3.2. The microscopic analysis

For the microscopic analysis, material collected from a gallery's working face was chosen. The studies were conducted on coal grains of the size of 2.5–5.0 mm. The research material was used to create – via grinding and polishing – microsections, which were subsequently analyzed under a microscope. The AXIOPLAN microscope produced by ZEISS was used in the research, along with an XYZ computer-controlled mechanical table. The image from the optical microscope was transmitted to the computer screen by means of a CCD camera. The research stand at which the measurements were carried out is shown in Fig. 3.

Fig. 3. The microscopic research stand

Rys. 3. Stanowisko mikroskopowe

The investigated coal is characterized by a medium degree of coalification (the volatile matter content is ca. 30%). The coal bed has a high content of inflammable minerals, seen in the microscopic image taken at the magnification of 500× – cf. Fig. 4. The coal material represents the strip coal, with the dominant share of vitrinite. The analysis of the maceral content of coal was carried out at the optical magnification of 500×. The results of the analysis were as follows: vitrinite – 50.28%, inertinite – 33.96%, liptinite – 6.86%, minerals – 8.90%.

3.3. Methane sorption capacity of coal

Studies into methane sorption on the coal collected from the Moonidih mine were carried out by means of the gravimetric method, using the IGA-001 instrument, under the temperature of 25°C. The 0.20–0.25 mm grain fraction was investigated. The subgrain (fines) from a 0.20 mm sieve was used in the technical analysis of coal.

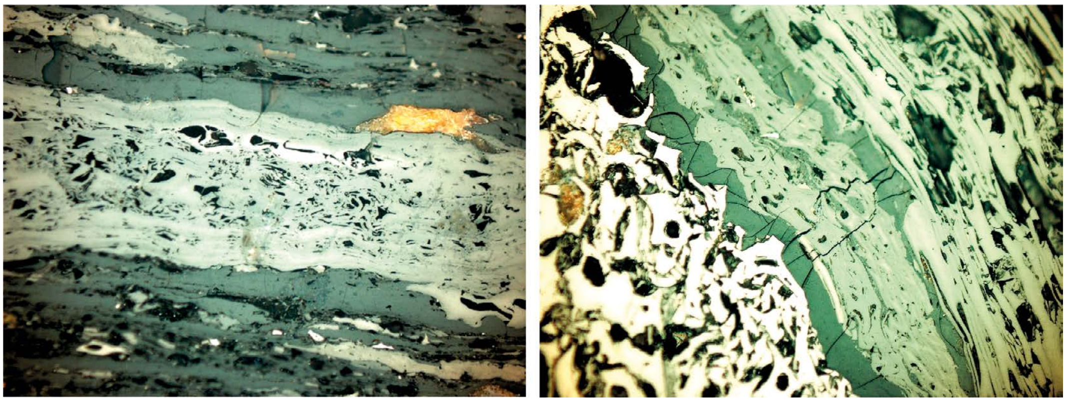

Fig. 4. Examples of coal structures from the Moonidih mine as seen under an optical microscope.
Reflected light, immersion, optical magnification of 500×

Rys. 4. Przykłady struktur węgla z kopalni Moonidih pod mikroskopem optycznym.
Światło odbite, imersja, powiększenie optyczne 500×

The measurement procedure encompassed the following stages:

- sieving the 0.20–0.25 mm grain fraction,
- weighing the coal sample,
- outgassing the sample under the pressure of 3×10^{-7} bar, for 24 hours,
- measuring the course of the sorption process on coal for the following pressure values: 1 bar, 4 bar, 15 bar, along with recording the kinetics of the process.

The temporal course of methane sorption/diffusion on the investigated coal is shown in Fig. 5. The measurement points and the adjusted Langmuir's sorption isotherm (1) are shown in Fig. 6.

As a result of the conducted research, the following values of the sorption properties of the coal bed were obtained:

- sorption capacity under barometric pressure: $a_{1bar} = 2.85$ cm^3/g$_{csw}$.
- the maximum sorption capacity in the Langmuir equation (1): $a_m = 18.31$ cm^{3}CH$_4$/g$_{csw}$,
- the inverse of the half-pressure in the Langmuir equation (1): $b = 0.163$ bar^{-1}.

The research was conducted under laboratory temperature. An increase in temperature reduces methane sorption on coal. A drop in the Langmuir sorption is a linear function of temperature. The following formula may therefore be developed:

$$a_m(\mathrm{T}) = a_m(\mathrm{T} = 0) - \mathrm{c} \cdot \mathrm{T}$$

The value of the *c* coefficient for hard coal equals ca. 0.075 cm^{3}g^{-1}K^{-1} (Wierzbicki 2013). Under these assumptions, the maximum Langmuir sorption for the investigated coal will be:

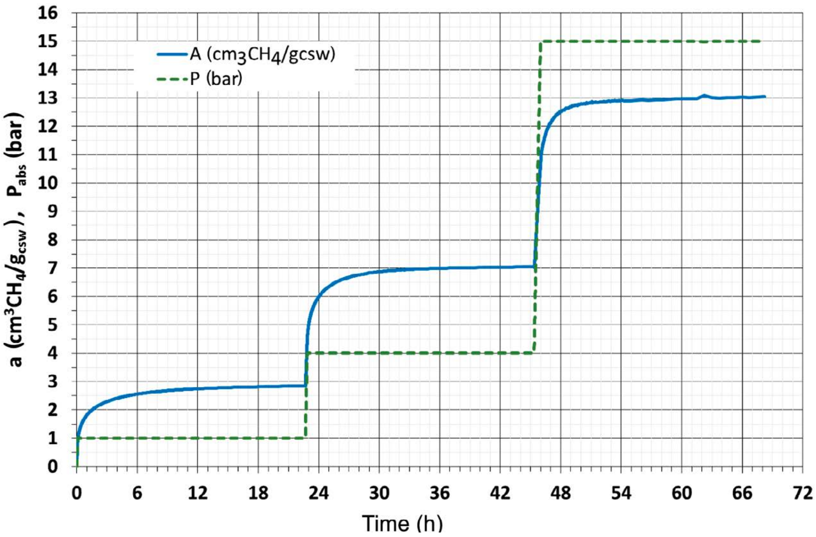

Fig. 5. Kinetics of methane sorption/diffusion on the investigated coal sample, T = 25°C

Rys. 5. Kinetyka sorpcji/dyfuzji metanu na próbce węgla, T = 25°C

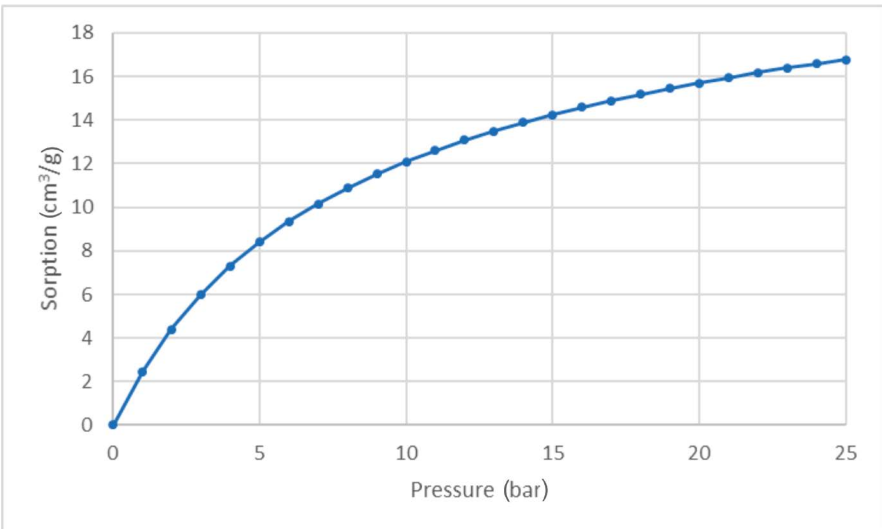

Fig. 6. Isotherm of the sorption process on coal, T = 25°C

Rys. 6. Izoterma sorpcji metanu na próbce węgla, T = 25°C

$$a_m(45°C) = 16.8 \text{ cm}^3/\text{g}$$

Since the *b* coefficient in the Langmuir equation does not change along with temperature, the following formula is available:

$$a = 16.8 \frac{0.163p}{1 + 0.163p}$$

The course of the isotherm of methane sorption on the investigated coal, for the temperature value 45°C, is shown in Fig. 7.

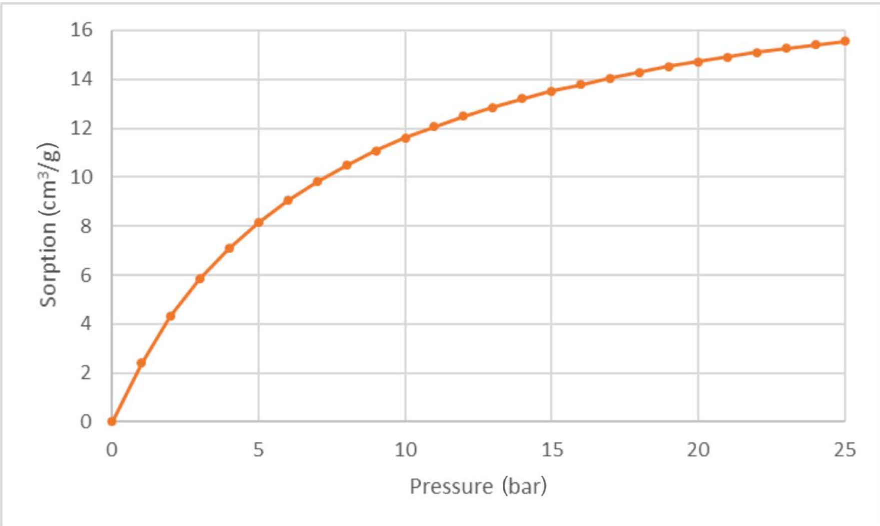

Fig. 7. Isotherm of methane sorption on the investigated coal sample, T = 45°C

Rys. 7. Izoterma sorpcji metanu na próbce węgla, T = 45°C

Knowing the real and apparent density, we can calculate the coal's porosity ε: $\varepsilon = 1 - (r_p/\rho_{He})$. In the investigated case, the coal porosity was 8.6%. The share of the free gas, which is a linear function of pressure, was calculated on the basis of formula (2). The amounts of the free gas and of the sorbed gas in a function of the equilibrium pressure are presented in Fig. 8. The blue curve depicts the total content of methane in coal and can be seen as the methane-bearing capacity of the coal bed. It is worth noticing that its dominant gaseous component is the sorbed gas (the red curve). This remark specifically concerns the investigated range of pressure values, as the sorption curve tends to the asymptotic value as the pressure rises, and the share of the free gas will increase, changing in a linear manner along with the pressure.

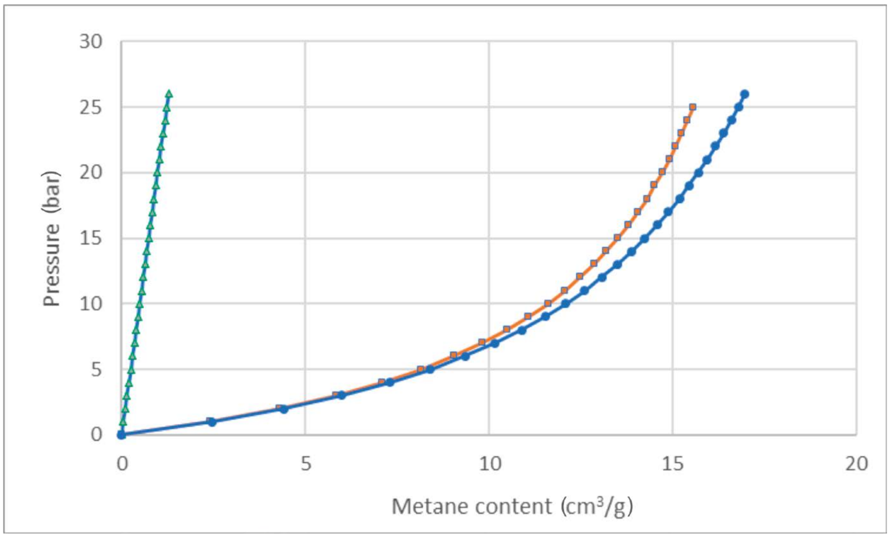

Fig. 8. The content of the free methane, the sorbed methane and their sum in a function of pressure under the temperature value 45°C

Rys. 8. Zawartości metanu wolnego, sorbowanego oraz ich suma w funkcji ciśnienia dla temperatury 45°C

For the methane-bearing capacity of the coal bed of ca. 10 m^3/Mg_{csw}, the coal bed pressure is not particularly high and equals more or less 8 bar. Such a situation is:

- favorable from the perspective of potential gaso-geomechanical threats in the mine,
- unfavorable from the perspective of foregoing demethanization opportunities, as the pressure increase is accompanied by a rise in the value of the diffusion coefficient (Wierzbicki 2013), and the demethanization process is then faster.

3.4. Kinetics of the accumulation and release of gas from coal

Registering the temporal changes of the sorbed methane made it possible to determine the value of the effective diffusion coefficient D_e from formula (3). The value of the effective diffusion coefficient is: $D_e = 2.72 \times 10^{-9}$ cm^2/s. It is worth noticing that the sorption's half-time equals to 1430 s, i.e. almost 25 minutes. This is the time needed for all the grains from the 0.20–0.25 mm grain fraction to accumulate 50% of the total methane content. This time span increases along with the square of the radius. Knowing the value of the diffusion coefficient D_e and the mathematical description of kinetics of methane release from coal by means of the unipore model (3), it is possible to calculate the course of the process of methane release from a coal sample representing any grain fraction. In the work by (Paul and Chatterjee 2011), we will find information that, in the Jharia hard coal basin, cracks are separated from one another by a 2 to 30 cm distance. Figures 9 and 10 show the courses of methane release for grains of replacement diameters equaling 5 and 20 cm, respectively.

For grains representing the 1–2 cm grain fraction, the half-time of methane release is over 2 years. In fact, the duration of methane's partial release from a coal bed may be even greater, as:

- the distance between cracks in a coal bed can be significantly smaller than 1.5 cm (on average),
- the diffusion kinetics may be limited by filtration kinetics in cracks.

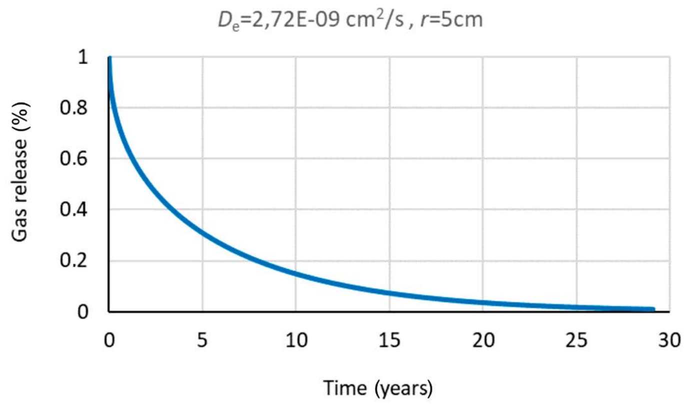

Fig. 9. Kinetics of methane release from a coal sample characterized by a ca. 5 cm diameter (model results)

Rys. 9. Kinetyka uwalniania metanu z próbki węgla o średnicy około 5 cm (wyniki modelowe)

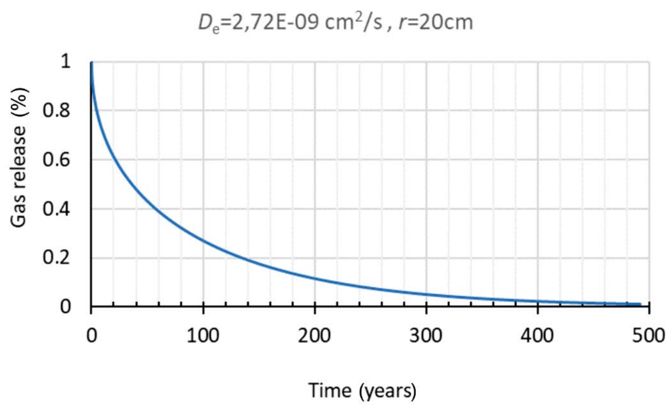

Fig. 10. Kinetics of methane release from a coal sample characterized by a ca. 20 cm diameter (model results)

Rys. 10. Kinetyka uwalniania metanu z próbki węgla o średnicy około 20 cm (wyniki modelowe)

Conclusions

India is facing a serious challenge connected with providing access to electric energy to all its citizens. The task is extremely important, both in light of the state's growing economy and the Indian population, out of which 25% is deprived of electric power, as well as the country's energy security. The main reason behind the lack of energy is the insufficient supply of coal for the Indian power plants. The planned step-up in the coal output may be effectively prevented by the methane threat observed in Indian mines. The process of coal beds' foregoing demethanization may be one possible solution to the problem. The paper presents the results of studies into the processes of methane sorption and diffusion on the coal from a selected Indian mining facility characterized by a high methane-bearing capacity. The investigated coal displays an average degree of coalification; it is also characterized by a high content of ash and multiple mineral intrusions. The low diffusivity of coal gives little chance for effective foregoing demethanization without the coal bed slotting.

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HARD COAL MINING IN INDIA AND THE OPPORTUNITIES FOR APPLICATION OF FOREGOING DEMETHANIZATION IN MOONIDIH COLLIERY

Abstract

The paper discusses the current situation as well as the perspectives for hard coal extraction in India, a global leader both in terms of hard coal output and import volumes. Despite this, over 300 million people lack access to electricity in this country. The main energy resource of India is hard coal and Coal India Limited (CIL) is the world's biggest company dealing with hard coal extraction. CIL has over 450 mines, employs over 400,000 people, and extracts ca. 430 million tons of hard coal from its 471 mining facilities. India is planning the decisive development of hard coal mining to extract 1.5 billion tons in 2020. Hard coal output in India can be limited due to the occurrence of various threats, including the methane threat. The biggest methane threat occurs in the mines in the Jharia basin, located in East India (the Jharkhand province), where coal methane content is up to ca. 18 m^3/Mg. Obtaining methane from coal seams is becoming a necessity. The paper provides guidelines for the classification of particular levels of the methane threat in Indian's mines. The results of methane sorption tests, carried by the use of the microgravimetric method on coal from the Moonidih mine were presented. Sorption capacities and the diffusion coefficient of methane on coal were determined. The next step was to determine the possibility of degassing the seam, using numerical methods based on the value of coal diffusion coefficient based on Crank's diffusion model solution. The aim of this study was the evaluation of coal seam demethanization possibilities. The low diffusivity of coal, combined with a minor network of natural cracks in the seam, seems to preclude foregoing demethanization carried out by means of coal seam drilling, without prior slotting.

Keywords: hard coal, methane, Indian mining, demethanization

GÓRNICTWO WĘGLA KAMIENNEGO W INDIACH I PROBLEM ODMETANOWANIA WYPRZEDZAJĄCEGO NA PRZYKŁADZIE KOPALNI MOONIDIH

Streszczenie

W pracy przedstawiono sytuację aktualną oraz perspektywy wydobycia węgla kamiennego w Indiach. Kraj ten należy do światowych liderów zarówno pod względem produkcji węgla kamiennego, jak i wielkości importu. Mimo to w kraju tym ponad 300 milionów ludzi jest pozbawionych dostępu do energii elektrycznej. Głównym surowcem energetycznym Indii jest węgiel kamienny. Największą na świecie firmą wydobywającą węgiel kamienny jest Coal India Limited (CIL). Posiada ona ponad 450 kopalń, zatrudnia ponad 400 000 ludzi i wydobywa około 430 mln ton węgla. Indie planują zdecydowany rozwój górnictwa węgla kamiennego do poziomu 1,5 mld ton w 2020 r. Problemem podziemnego górnictwa węgla kamiennego w tym kraju staje się zagrożenie metanowe. Największe zagrożenie występuje w kopalniach w Zagłębiu Jharia zlokalizowanym we wschodniej części

Indii. Metanonośność węgla jest bardzo wysoka i wynosi do około 18 m^3/Mg. Koniecznością staje się pozyskiwanie metanu z pokładów węgla. W pracy podano zasady zaliczania do poszczególnych stopni zagrożenia metanowego. Przedstawiono wyniki badań sorpcyjnych przeprowadzonych metodą mikrograwimetryczną na węglu pobranym z kopalń Monnidih. Przedstawiono wyniki analizy technicznej węgla oraz analizy mikroskopowej. Wyznaczono zdolności sorpcyjne metanu na węglu oraz oszacowano kinetykę odmetanowania pokładu, przy wykorzystaniu metod numerycznych, na podstawie znajomości współczynnika dyfuzji węgla na podstawie uniporowego modelu dyfuzji Cranka. Celem badań była ocena możliwości wyprzedzającego odmetanowania pokładów. Niska dyfuzyjność węgla w połączeniu z niewielką siecią spękań naturalnych w pokładzie daje słabe perspektywy odmetanowania wyprzedzającego wykonywanego otworami w pokładzie bez użycia wcześniejszego szczelinowania.

Słowa kluczowe: górnictwo indyjskie, metan, węgiel, odmetanowanie