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JAKUB SIEMEK[1], JAN MACUDA[1], ŁUKASZ ŁUKAŃKO[1*], JACEK HENDEL[1]

THE TECHNOLOGY OF DRILLING WELLS FOR CAPTURING METHANE FROM ABANDONED COAL MINES

The longwall mining system with fall of the roof is still the most common hard coal extraction system in Polish mining. Its utilization for selective coal seams' mining results in the development of post-extraction gobs at different depths. Methane desorption phenomena from the coal seams in the stress release zones and migration of gas towards the area of operations, result in methane accumulating also after completion of coal exploitation. Methane which is not exploited from the gobs can migrate directly to the atmosphere e.g. through overlying layers, faults, workings or directly via an operated ventilation grid of an adjacent coal mine – contributing to the Greenhouse Gas effect. One of the methods to capture methane (Abandoned Maine Methane) from abandoned coal mines is to drill vertical wells through several post-extraction gobs from the surface.

This paper presents the results of drilling operations at the AGH-Wieczorek-1 well, where first time in Poland, down-the-hole-hammer (DTH) with casing-while-drilling (CwD) technology were used to drill through several post-extraction gobs. The AGH-Wieczorek-1 well with 440.0 m MD was successfully drilled without any complications. Finally, three post-extraction gobs and two coal seams were drilled. Additionally, results from drillability tests, which were performed during drilling operations, are presented.

Keywords: Casing-while-drilling, Down-the-hole-hammer, Post-extraction gobs, Methane capturing, Drillability tests

1. Introduction

Methane released during hard coal production may be a valuable source of energy for both heat and electricity production. In some cases, when hard coal is produced by a gassy mine, significant amounts of gases (mainly methane) may be trapped in gobs or in abandoned pathways, tunnels, ventilation entries, or shafts. Gases stored in crushed, fractured zones are often

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[1] AGH UNIVERSITY OF SCIENCE AND TECHNOLOGY, FACULTY OF DRILLING, OIL AND GAS, AL. MICKIEWICZA 30, 30-059, KRAKÓW, POLAND

* Corresponding author: lukanko@agh.edu.pl

explored by vertical wells drilled from the surface, called Gob Gas Ventholes (GGVs). GGVs are mainly created to control methane emission by capturing free gases stored within the overlaying fractured sandstone/mudstone zones and coal seams to prevent its migration to the work environment during hard coal mining (Karacan & Olea, 2013; Karacan, 2015). To allow gas production, GGVs are commonly equipped with exhausters on the wellhead for suction of support gases from the strata to power engine/gas pipes (Karacan & Olea, 2013; (Karacan, 2015). GGVs draw gases from extremely permeable fracture strata zones. According to previous studies (Sinhg & Kendorski,1981; Karacan, 2009), a caved zone, created during coal extraction from coal plays, may be 3 to 6 times thicker than coal seam. However, the fractured zone, wherein the original strata is crushed and released methane are trapped, may reach 30-58 times the coal thickness. (Karacan, 2009) and (Karacan & Goodman, 2011) showed that the permeability of gobs may reach a value 150 Darcies. The average permeability of crushed and relaxation overburden strata (where GGVs with slotted casings are placed) may be valued between 1-10 Darcies (Karacan & Olea, 2013). The porosity of fractured hard coal mining zones depends on rock type and properties, stratigraphy, coal seam mining depth, type, and geomechanical properties of overlaying rocks, etc. (Palchnik, 2002; (Piotrowski & Mazurkiewicz, 2006). The porosity of gobs at the level of the former coal layer is between 17-40% (Piotrowski & Mazurkiewicz, 2006), or may even reach up to 50% (Plewa et al., 2006). It is difficult to estimate the porosity of the overlaying zone, which was under the influence of collapsing gob layers. (Karacan, 2009) used values between 5-10%. It is also clear that porosity and permeability of gobs and the surrounding strata change over time. Each gob (with or without filling) should be characterized with a decreasing permeability and porosity because of subsidence and compaction processes. However, in the area of multilayer hard coal production (ex. In the Upper Silesian Coal Basin, where the mining industry was founded in the 17th century, some mines are currently extracting the 15th or even 20th coal seam in one geological profile), gobs may collapse due to extraction of coal plays which lie below and due to the whipped post-coal layer, which may be re-crushed once more. Achieving very high values of permeability and porosity of gobs and fractured zones, which lie above, means that drilling a borehole through strata covered with several layers of post-extraction caves of former coal seams is almost impossible. Drilling via the use of traditional technology, with drilling mud as a cuttings carrier, generally ends with the loss of mud circulation and can lead to a drilling accident. Because of the high transmissibility and storage capacity of gobs and fractured zones, all drilling mud from the borehole runs out into the first gob. Preventing the loss of drilling mud is difficult or even impossible, so that further, deeper drilling is impossible. In Fig. 1, a 3D visualization of multilayer gobs strata, formed during hard coal production, is presented. Fig. 2 shows a drilling accident caused by loss of drilling mud circulation and its movement out into the 1st gob layer. However, drilling through a few or several strata of unconsolidated layers is possible from a technological point of view but not using classic rotary mud-drilling technology. In Fig. 3, the concept of a successful drilling operation and casing seating is presented. A visualization of AMM production by GGV from two gob layers simultaneously is shown in Fig. 4.

For solving those problems drilling and services companies developed and implemented Casing-while-Drilling (CwD) technology (in some papers called also Casing Drilling CD or Drilling with Casing DwC). In this technique drilling and casing processes are realized simultaneously.

CwD requires special Bottom Hole Assembly (BHA), different, depending on various CwD sub-technology. In general, two CwD types may be listed: retrievable CwD and non-retrievable CwD. With retrievable system, BHA is temporary locked with casing ending by special dedicated link. BHA extends bellow casing ending with a reamer assembly pilot bit. As the name suggests,

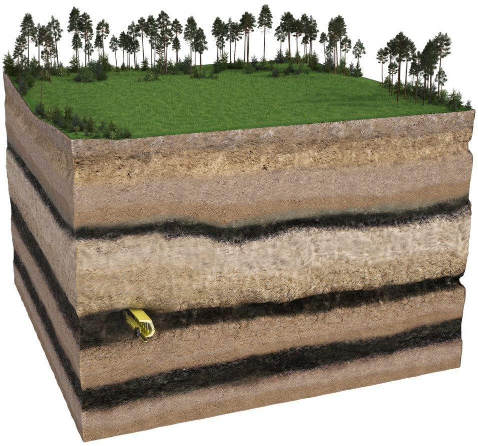

Fig. 1. 3D visualization of multilayer longwall hard coal production using shearer

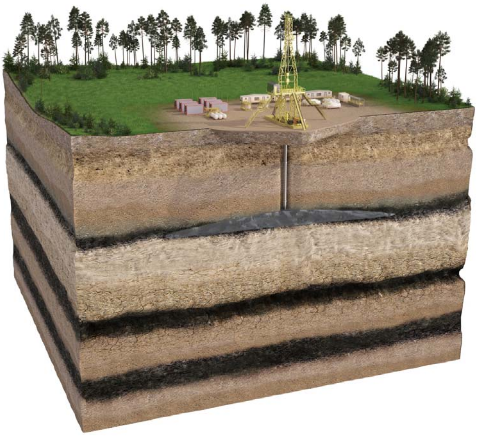

Fig. 2. Drilling mud losing in 1st of gob caused extremely high values of permeability and porosity of post mining extraction caves

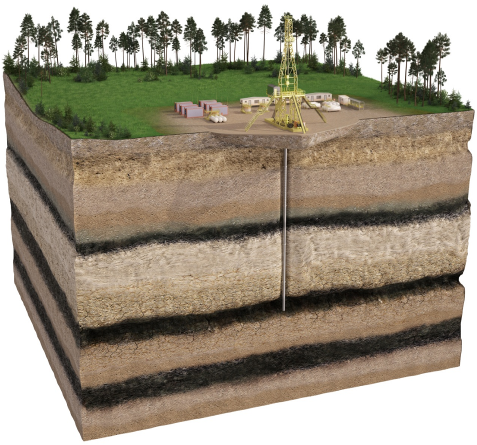

Fig. 3. Successful drilling operation through two or more post extraction layers using proposed in article technology

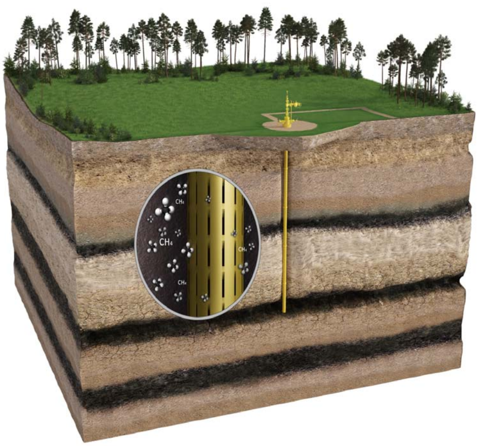

Fig. 4. Visualization of CMM/AMM production by GGV from two gobs layers simultaneously

BHA may be retrieved by a wireline winch for cementing or bit changing. With non-retrieved system BHA is non-restorable. Special dedicated drilling bits are permanently attached to casing ending. After reached total depth, BHA is left on casing ending, cemented and drilled up (similar to float should in conventional technology) with next casing column (if required) (Robinson et al., 2008). CwD technology has lots of advantages e.g. can set casings in trouble zones, proved less running casing problems and less intensity pressure control tripping. CwD minimalized NPT, number of casing columns and sizes need to be used and finally total costs of well (Buntoro, 2008).

As a drilling tool in retrievable CwD system special dedicated, but similar to traditional, Polycrystalline Diamond Compact (PDC) bits can be used. However, during drilling through high porosity/high permeability formation (with high risk of drilling mud loss) or into potential fruitful reservoir formations, air/nitrogen/foam powered hammers may by employed as drilling tool. Hammers may be powered at the hole bottom down-the-hole-hammer or by stroke-generator assembly on the drilling rig on surface (top-hammers). Top-hammers are used during drilling shallow geological/geotechnical wells. Down-the-hole (DTH) hammers may be employed in a high range of depth. Rotary-percussion drilling method with down-the-hole hammer is characterized by very effective mining of rocks with low energy demand. This method can be used with conventional drilling devices using a rotary method with right and reverse circulation of drilling mud. It allows to mining rock at the bottom of the hole with a drill bit with, while using the percussion and rotation of the bit. The slow rotation of the bit is caused by the rotation of the drill pipe driven by the top drive. The downhole hammer is driven by compressed air that is forced from the compressors through the drill pipe. The stream of air flowing out of the downhole hammer also plays the role of an air mud. After cleaning the bottom of the hole from the cuttings are remove to the surface by the annular. The air flow rate must be enough to maintain a flow velocity > 10 m/s in the annular, allowing smooth and uninterrupted elevation of the cuttings to the surface (Atlas Copco, 2015; (Halco, 2016).

2. Result and discussion

2.1. Geology

The AGH-Wieczorek-1 well was located in the central part of the Upper Silesia Coal Basin, in the area of the Wieczorek Coal Mine, near the Roździeński shaft. The discussed area is subdivided into two lithostratigraphic units: Upper Carboniferous (Pennsylvanian) and Quaternary (Kędziora & Jelonek, 2013). The Quaternary formation (0.0-32.0 m) is represented by clays, siltstones, sandstone, and gravels. The Upper Carboniferous (32.0-440.0 m) system is divided into two different lithostratigraphic series: Orzesze Beds (Westphalian B) and Ruda Beds (Westphalian A). Orzesze Beds (32.0-270.0 m) are mainly represented by grey shale, sand shale, siltstones, and sandstones, whereas Ruda Beds (270.0-440.0 m) are represented by shale rock as grey and black shale, coal shale, sand shale, sandstone, and coal. During drilling operations, two coal seams were observed, the first one at a depth of 315.0 to 317.0 m, the second from 367.0 to 368.0 m. The gobs were seen at depths of 332.0-334.0 m, 354.0-357.0 m, and 418.0-420.0 m. Fig. 5 shows geological cross sections from 250.0 to 450.0 m in the study area.

2.2. Construction of AGH-Wieczorek-1 well

Construction of the AGH-Wieczorek-1 well has been designed taking into account geological conditions of the study area. The 18 5/8” conductor casing was set at a depth of 12.0 m MD to stabilize the borehole, due to the fact that the well was located on an anthropogenic embankment. The 13 3/8” surface casing was set at depth of 32.0 m MD. The main role of the casing was to separate the fresh Quaternary water aquifer. The 9 5/8” intermediate casing was set at a depth of 270.0 m MD. The 7” production casing was installed as a liner from 254.0 to 440.0 m MD. The AGH-Wieczorek-1 well construction is presented in Fig. 6.

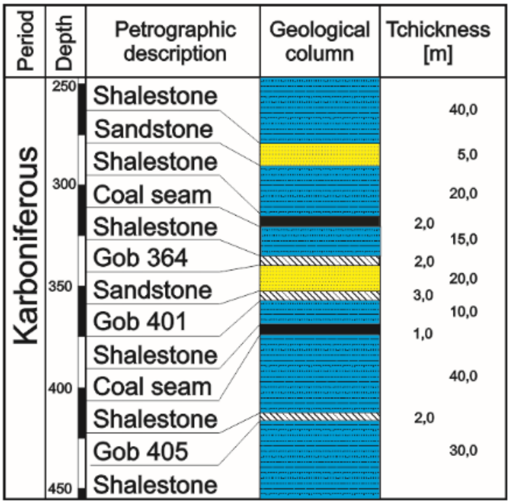

Fig. 5. Geological schematic cross sections in the study area (250.0-450.0 m)

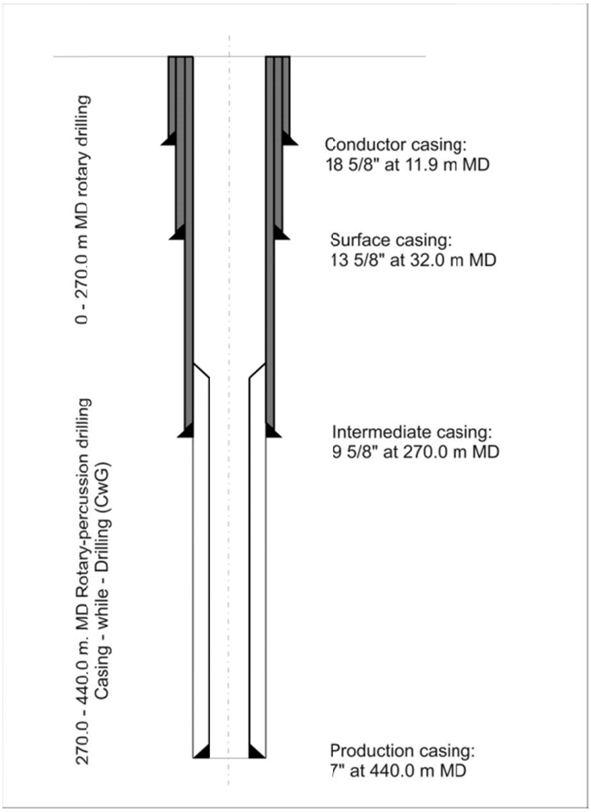

Fig. 6. AGH-Wieczorek-1 well construction

For drilling operations, a drilling unit powered by a 200 HP engine was used, max. depth of drilling was 1500 m and torque was 50 kN. For the interval 0.0-270.0 m, a mud pump powered by a 500 HP engine was used, drilling fluid rate was 35.6 l/s with pressure 92 bar. For the interval 270.0-440.0 m two air compressors were used. The first one was powered by a 700 HP engine, air rate was 38 m^3/min and pressure 30 bar. The second air compressor was powered by a 290 HP engine, air rate was 20 m^3/min and pressure 25 bar. The AGH-Wieczorek-1 well was drilled in 12 days.

As presented in Fig. 6, the AGH-Wieczorek-1 well was drilled with the usage of two different methods. From surface to depth a of 270.0 m, rotary drilling with normal mud circulation was used. During drilling of the Quaternary interval, bentonite mud with biodegradable polymers were used. Mud weights were 1.08-1.12 SG. Viscosity was measured using Marshall funnel and was 57s/1000 ml, pH of drilling mud was 12.

Orzesze Bed formation to 270.0 m was drilled with a 9 5/8" bit with bentonite-polymer mud with weights 1.12-1.22 SG. Viscosity of drilling mud was changed from 45 to 53 s/1000 ml, filtration from 15-20 ml/30min, while pH was 8.4. During drilling operations the rotary drilling speed from interval 32.0 to 79.0 m was 70 rpm, from 79.0 to 270.0 m was 80 rpm. Weight on bit (*WOB*) in the interval 32.0 to 79.0 m was changed from 0.7 to 1.3 t, from 79.0 to 173.0 m was 1.0 t, while from depth of 173.0 to 270.0 m the *WOB* was 1.7 t. During drilling operations, drilling mud losses were observed. From interval 32.0 to 270.0 m, a total amount of 110 m^3 drilling mud was lost. The highest mud loses were observed in interval from 94.0 to 113.0 m-22m^3, 134.0 to 140.0 m-17 m^3, 168.0 to 173.0 m-30 m^3. Intervals in which mud loses were observed, were represented by sandstone. Time for drilling interval from 32.0 to 270.0 m took 7 days.

For drilling through Ruda Beds from 270.0 to 440.0 m, the rotary-percussion drilling method with down-the-hole hammer was used. Additionally, to eliminate the risk of drilling complication the Casing – while – Drilling method was applied. A 3½" drilling pipe, as well as a 7" casing were simultaneously rotated through the top drive. Special BHA was used to connect a down hole hammer with 7" casing. For drilling operations, a 5" down hole hammer was used with a 6" drilling bit. At the end of the 8½" casing, a ring bit set was installed. Weight on bit was 1.5 t while drilling speed was a constant 60 rpm. For removal of cuttings and to drive down the hole hammer, compressed air was used. From a depth of 270.0 to 368.0 m, air rate was 20 m^3/min with pressure change from 25 to 18 bar. In the interval 369.0-407.0 m, air rate was higher – 38 m^3/min with pressure in the range 21-26 bar. The last interval from 407.0 to 440.0 m was drilled with air rate 58 m^3/min and air pressure 24-28 bar. To avoid drilling complications, foam was used at selected intervals during drilling operations. The foam was used during drilling through coal seams and gobs. Time of drilling operations took 5 days.

2.3. Drillability tests

The most important factors affecting the achievement of high penetration rates is the correct selection of the drill bit type and the use of optimal mechanical parameters of drilling such as rotary drilling speed *N* as well as weight on bit *WOB*. In order to determine the optimum drilling parameters during drilling wells using CwD technology, especially in areas without thoroughly identified geological and drilling conditions, drillability tests should be performed. The drillability test should be carried out with the following assumptions (Macuda, 2012):

- bit cycle in macroscopically homogeneous rocks
- bit type correctly selected for the given type of drilled rock

- weight on bit and its rotary speed have constant values
- weight on bit and rotary speed belong to a set of admissible decisions, resulting from the technical characteristic of the rig

Based on the obtained data it is easy to determine the rate of penetration. When parameters of rotary drilling speed or weight on bit are increased, the rate of penetration should also increase proportionally (IADC, 2014). If the increase is proportional it means that optimum mechanical parameters were used. A typical chart of the *ROP* versus *WOB* obtained experimentally with all other drilling variables held constant is shown in Fig. 7.

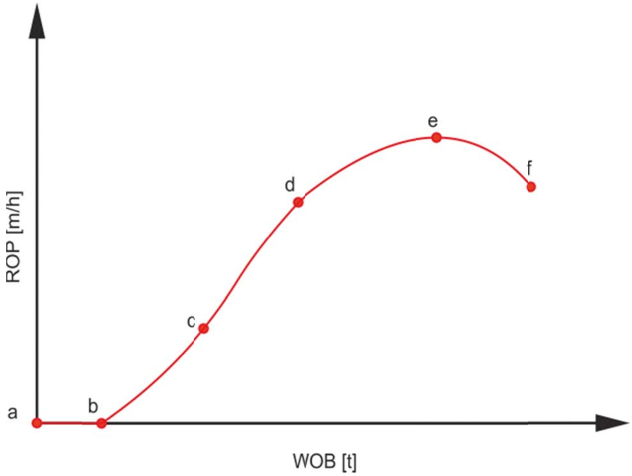

Fig. 7. Typical response of penetration rate to increasing bit weight

No significant penetration rate is obtained until the threshold bit weight is applied (section a-b). Weight on bit is initially applied, but rate of penetration is inefficient due to the very low loads. Once the weight on bit increases, then the value of the rate of penetration also changes (section b-c). As the weight on bit values are increased, a higher increase in *ROP* is observed (section c-d). However, after a certain value of a bit weight, subsequent increase in a bit weight causes only slight improvements in penetration rate (section d-e). In some cases, a decrease in penetration rate is observed at extremely high values of a bit weight (section e-f). This type of behavior is often called bit floundering. The poor response of penetration rate at high values of a bit weight usually is attributed to less efficient bottom hole cleaning at higher rates of cuttings generation or to a complete penetration of the cutting elements of the bit into the well bore bottom (Robinson & Ramsey, 2001). At this weight on bit values, wear on the bit is extremely high (Bourgoyne et al., 1986).

A typical change of penetration rate versus rotary speed obtained with all the other drilling variables held constant is shown in Fig. 8.

Rate of penetration usually increases linearly with an increase in rotary drilling speed (section a-b). After a certain rotary drilling speed value, the increase in *ROP* decelerates as rotation drilling speed is increased (section b-c). After point-c, rotation drilling speed has a very slight

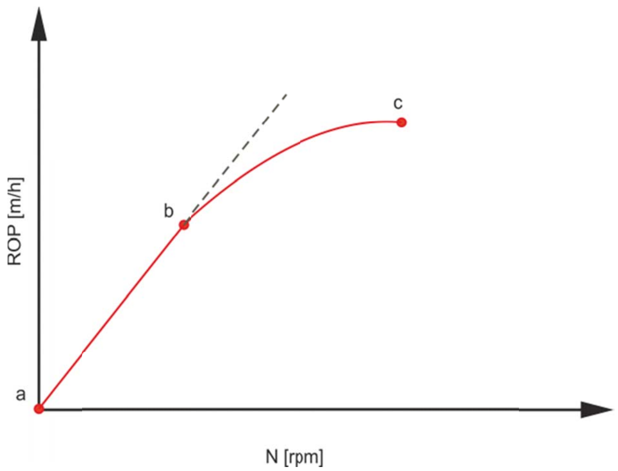

Fig. 8. Typical response of penetration rate to increasing rotary drilling speed

influence on *ROP*. The poor response of penetration rate at high values of rotary drilling speed usually is also attributed to less wellborn stability and enlargement of the wellbore (Bourgoyne et al., 1986).

In order to carry out the drillability tests to assess AGH-Wieczorek-1 well performance, the most popular macroscopically homogeneous rock were identified. For the test four types of rocks were selected:

- Grey shale (A),
- Black-grey shale (B),
- Black shale (C),
- Black shale with coal (D).

During the drillability tests, a 0.5 m rock interval was drilled. Prior to performing the drillability tests, technical characteristics of drilling rig, strength of the drilling pipe, and type of bit used to drill the individual intervals were taken into account. Furthermore taken into consideration were the mechanical parameters of the drilling technology where:

$$WOB \in (WOB_{\min} \div WOB_{\max}) \tag{1}$$

$$N \in (N_{\min} \div N_{\max}) \tag{2}$$

where:

$WOB_{\min}$; $WOB_{\max}$ – smallest and largest value of weight on bit – t,
$N_{\min}$; $N_{\max}$ – smallest and largest value of the rotational drilling speed – rpm.

The drillability test was performed in following mechanical drilling parameters configurations:

- rotary drilling speed const. 30 rpm, weight on bit changed from 0.5 to 2.0 t,
- rotary drilling speed const. 60 rpm, weight on bit changed from 0.5 to 2.0 t,
- weight on bit const. 0.5 t, rotary drilling speed changed from 30 to 60 rpm,
- weight on bit const. 1.5 t, rotary drilling speed changed from 30 to 60 rpm.

The *ROP* for the AGH-Wieczorek-1 well was calculated using equation 1 (Eren & Kok, 2018).

$$ROP = \frac{\Delta Depth}{\Delta Time} \tag{3}$$

The results of the drillability test during drilling of the AGH-Wieczorek1 well are presented in Table 1.

TABLE 1

Result of *ROP* calculation. *N* const., *WOB* $\in$ 0.5÷2.0 t

WOB, [t]	***ROP*, [m/h]**							
	***N* = 30, [rpm]**				***N* = 60, [rpm]**			
	Type of rock							
	A	**B**	**C**	**D**	**A**	**B**	**C**	**D**
0.5	1.8	2.7	2.9	1.2	2.4	3.2	3.3	1.7
0.75	2.7	4.2	4.5	1.8	3.7	5.2	4.7	2.2
1.0	3.5	5.7	6.2	2.3	5.1	7.3	6.2	2.6
1.25	4.3	7.2	7.7	2.6	6.3	9.3	7.9	3.0
1.5	5.1	8.5	8.0	2.7	6.8	11.5	9.7	3.3
1.75	5.0	8.4	7.9	2.8	6.7	11.0	9.6	3.1
2.0	4.6	8.0	7.5	2.5	6.2	10.5	9.2	2.9

Analysis of drillability test results shows that the highest rate of penetration was obtained during drilling of black-gray shale and black shale. Obtained *ROP* results for rotary drilling speed both for *N* = 30 rpm and *N* = 60 rpm are similar. The maximum drilling rate penetration was 8.5 m/h and 11.5 m/h for black – grey shale, and 8.0 m/h and 9.7 m/h for black shale. As shown in Fig. 9 and Fig. 10, in the case of weight on bit change from 0.5 to 1.25 t, the increase of *ROP*

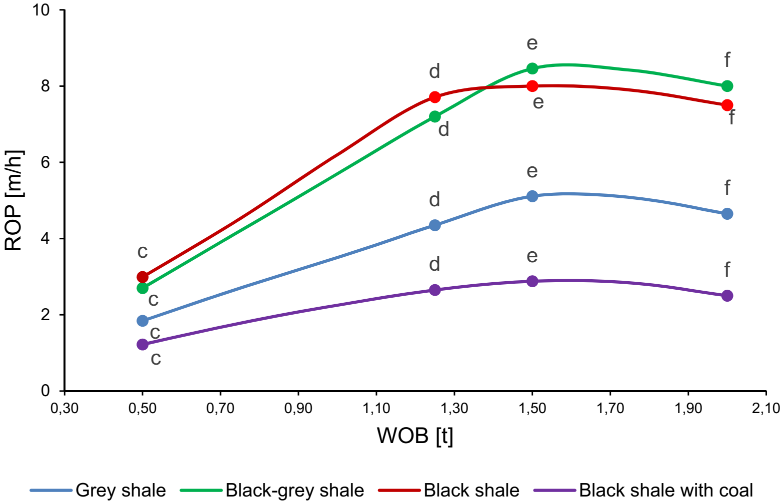

Fig. 9. Result of drillability test. *N* – 30 rpm, *WOB* $\in$ 0.5÷2.0 t

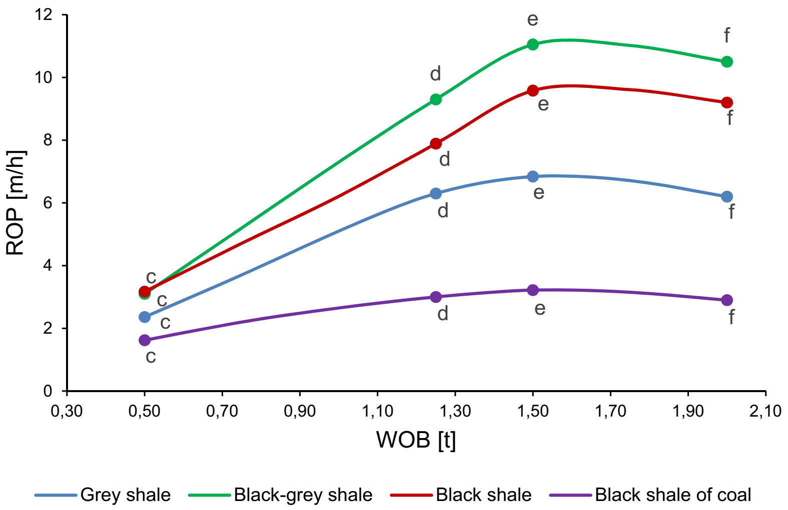

Fig. 10. Result of drillability test. N – 60 rpm, $WOB \in 0.5 \div 2.0$ t

TABLE 2

Result of ROP calculation. WOB const., $N \in 30 \div 60$ rpm

***N*, [rpm]**	***ROP*, [m/h]**							
	***WOB* = 0.5, [t]**				***WOB* = 1.5, [t]**			
	Type of rock							
	A	**B**	**C**	**D**	**A**	**B**	**C**	**D**
30	1.8	2.7	2.9	1.2	5.1	8.5	8	2.7
40	2.2	3.0	3.1	1.5	6.1	10.2	9.2	3.1
50	2.3	3.1	3.2	1.6	6.6	10.8	9.6	3.2
60	2.4	3.2	3.3	1.7	6.8	11.5	9.7	3.3

is very rapid (section c-d), while after achieving $WOB = 1.5$ t, there is a slow decrease of *ROP* (section e-f). In the case of grey shale and grey shale with coal, *ROP* are significantly different from the previous two types of rock. When *WOB* was increasing, the changes of *ROP* were not as rapid as in the previous test (section c-d). Maximum rate of penetration for black shale with coal was 2.7 m/h and 3.3 m/h, while for grey shale was 4.6 m/h and 6.2 m/h. For black shale with coal, differences between min and max value of *ROP* was only 1.3 m/h and 1.2 m/h, depending on rotation drilling speed (section c-e). The decrease in *ROP* (section e-f) was an effect of height of weight on bit and reduced possibility of cuttings removal from the bottom of the hole.

During the second phase of the drillability test, the variable parameter was the rotation drilling speed while weight on bit remained constant. The results of the drillability test are presented in Table 2.

Based on the obtained data, it can be stated that the change in rotation drilling speed had less influence on the increase in *ROP* than the changing of *WOB*. The highest *ROP* increase was observed for each type of rock in section a-b, while in section b-c the *ROP* change was the smallest (Fig. 11 and Fig. 12). Changes in rotation drilling speed had the most significant effect for increase in rate of penetration for black-grey and black shale, and less for grey shale and black shale with coal. For black shale with coal, *ROP* increase was very small and was changed from 0.5 and 0.6 m/h. The highest *ROP* increase was observed for black-grey shale 3.0 m/h when *WOB* was 1.5 t.

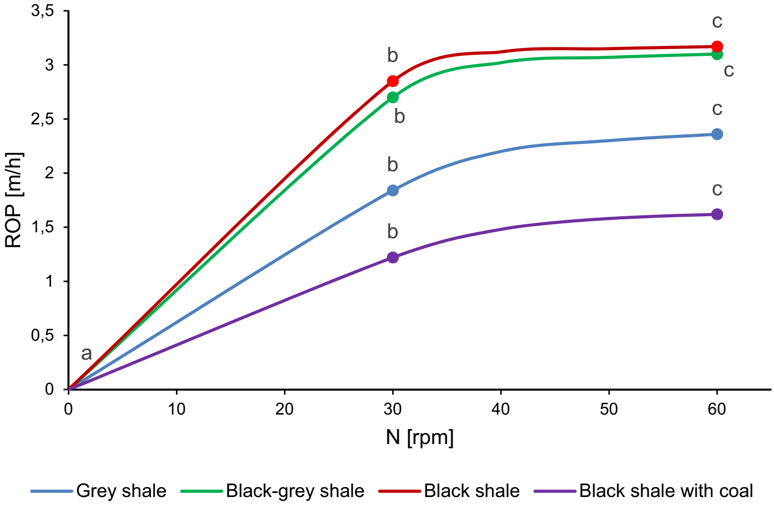

Fig. 11. Result of drillability test. *WOB* – 0.5 t, $N \in 30 \div 60$ rpm

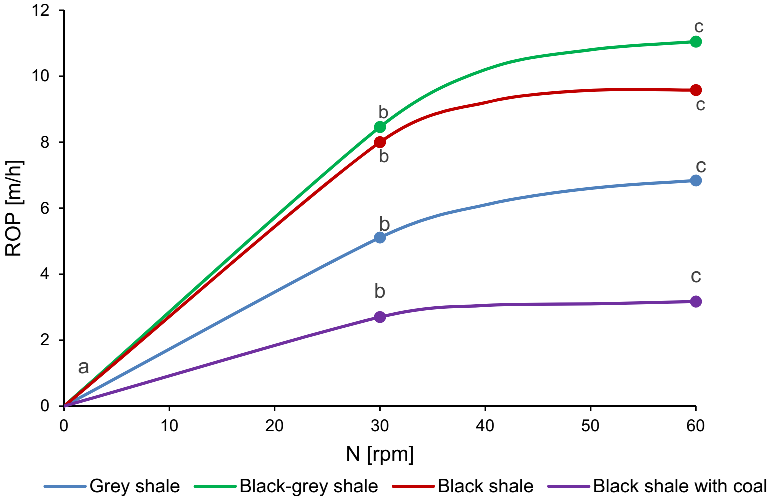

Fig. 12. Result of drillability test. *WOB* – 1.5 t, $N \in 30 \div 60$ rpm

The analysis of drillability tests shows that highest *ROP*s were obtained for rocks with higher mechanical strength for compression such as black-grey shale, black shale than for gray shale and black shale with coal. The obtained data reflect results of laboratory tests of strength parameters of Carboniferous rocks occurring in USCB (Kidybiński, 1982).

3. Conclusion

Methane emission into the atmosphere from abandoned coal mines can be significantly reduced by a well drilled from the surface. Such an approach aside from environmental has also an economic advantage – captured methane can be used to produce electricity energy or heat. Research conducted during a realization of the AGH-Wieczorek-1 well showed that the Casing-while-Drilling (CwD) technology with down hole hammer (DTH) is one of the best methods to capture methane directly from several mining gobs from abandoned coal mines. In order to reduce the risk of drilling complications, foam was used, which additionally improved efficiency of cuttings removal from the bottom of the hole. With increasing drilling depth and number of drilled gobs, the air rate increased from 20 m^3/min to 58 m^3/min.

A very important element of drilling exploitation wells to capture methane from the surface is the selection of optimal mechanical parameters of drilling technology such as weight on bit and rotary drilling speed. From the results of the drillability test during the AGH-Wieczorek-1 well realization, it appears that the optimal values of *WOB* and *N* were 1.5 t and 60 rpm respectively. For these values, *WOB* and *N* obtained rate of penetration were the highest for each type of drilled rocks.

Based on the obtained data, it can be concluded that in the case of drilling wells in areas with unknown geological and drilling conditions, drillability tests should be performed to obtain the highest rate of penetration and thus, reduce the costs of their realization.

Acknowledgments

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