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SUMMARY

A pair of intersecting wells Wesoła PIG 1 and Wesoła PIG 2H were drilled in the central part of the Upper Silesian Coal Basin (USCB) which is a Variscan geological--structural unit composed of Carboniferous molasse deposits within the Moravian-Silesian basin. The basement rocks, beneath the Carboniferous of the USCB, comprise Precambrian, Cambrian and Devonian complexes. The Carboniferous sequence starts with carbonate pre-flysch association, passing upwards into marine clastic sediments of flysch association, followed by molasse coal-bearing strata. The characteristic feature of the Carboniferous coal--bearing succession is its distinct bipartition. The lower part of the coal-bearing sequence is composed of sediments originated in paralic environments, with periodic marine ingressions, and it is distinguished lithostraphically as Paralic Series. The remaining (upper) part of the coal-bearing succession, which consists of sediments deposited in continental environments, prevails in the geologic setting of the central part of the USCB and in the vicinity of the Wesoła PIG 1 and Wesoła PIG 2H wells. It is represented mainly by the two lithostratigraphic units: the Upper Silesian Sandstone Series (USSS) and the Mudstone Series (MS), and, to a lesser extent, by the Cracow Sandstone Series. The overburden of the Carboniferous, in the vicinity of the wells, is not thick and comprises Quaternary, Neogene (Miocene) and Triassic sediments.

All the activities, related to the drilling and testing of the Wesoła PIG 1 and Wesoła PIG 2H wells as well as preparing of the final reports, were carried out within the framework of the research project called "Pre-mine drainage of coal seams with the use of surface wells - the assessment of its implementation in the geological and mining conditions of the Upper Silesian Coal Basin, along with drilling a test well". This project, which fell into the category of responsibilities assigned to the Polish Geological Survey, was funded by The National Fund for Environmental Protection and Water Management. Under the current circumstances in Poland, this project is considered innovative, and the wells, which were drilled, were designated as pilot and parametric. It was a scientific experiment, conducted within the Mysłowice-Wesoła mining area, in which the drilling activities were comprised of:

- Wesoła PIG 1 vertical well drilled to the total depth of 1000 m and to the target seams identified as 501–510;
- Wesoła PIG 2H directional well drilled (from a separate surface location) to the measured total depth of 1918 m, with a horizontal section drilled in the 501–510 coal seams from the point of intersecting the Wesoła PIG 1 vertical well to TD.
- The objectives of this drilling research project were as follows:
- making a detailed interpretation of the Carboniferous coal-bearing lithology column to the depth of 1000 (drilling to the base of USSS and penetrating the 501–510 coal seams);
- determination of methane content, as well as physical, chemical, petrophysical and petrological properties of coal seams based on core samples;
- conducting wireline logging;
- conducting flow tests of gas from the 501–510 coal seams, with the application of hydraulic fracture stimulation.

The aim of the Wesoła PIG 1 vertical borehole, which was cored at intervals, was to gain an understanding of the subsurface geology and methane content distribution of coal seams, as well as to obtain samples for laboratory testing. Subsequently, during the gas flow testing, this borehole became a production well, with downhole pumping equipment installed for recovering of water and gas. Likewise, the aim of the Wesoła PIG 2H directional borehole (drilled without coring), which intersected the vertical well, was to enable in-seam completion of the 501–510 coal seams, as well as to drain methane gas during the testing and hydraulic fracturing operations.

The stratigraphic column of the Wesoła PIG 1 consists of: 0,00–28,00 m Quaternary; 28,00–1000,00 m Carboniferous, including: Moscovian (Westphalian B) to 266,00 m, Bashkirian to 977,10 m (Namurian B–C + Westphalian A) and Serpukhovian (Namurian A) to 1000,00 m. Lithostratigraphically, the Carboniferous sequence comprises: Mudstone Series (28,00–801,86 m, Orzesze Beds s.s., Załęże Beds), Upper Silesian Sandstone Series (801,86–977,10 m, Ruda Beds s.s., Anticlinal Beds), and Paralic Series (977,10–1000,00 m, Poruba Beds).

The stratigraphic column of the Wesoła PIG 2H comprises: 0,00–23,00 m Quaternary; 23,00–51,00 m Neogene (Miocene – Badenian); 51,00–1912,00 m Carboniferous, including: Moscovian (Westphalian B) to 460,00 m, Bashkirian to 1154,00 m (Namurian C + Westphalian A) and Serpukhovian (Namurian A) to 1320,00 m and Bashkirian to 1918,00 m (Namurian B). Lithostratigraphically, the Miocene consists of Skawina formation, while the Carboniferous sequence comprises: Cracow Sandstone Series (51,00-127,00 m Łaziska Beds), Mudstone Series (127,00–911,00 m, Orzesze Beds s.s., Załęże Beds), Upper Silesian Sandstone Series (911,00–1154,00 m Ruda Beds s.s.), Paralic Series (1154,00–1320,00 m Poruba Beds) and Upper Silesian Sandstone Series (1320,00–1918,00 m Anticlinal Beds).

The Miocene sediments occur between the Quaternary cover and the Carboniferous complex, but only in the Wesoła PIG 2H well section. The Miocene is composed of marly clays (claystone) interbedded with medium grain sandstone and one layer of lignite, with well sorted gravel at the base. Lithostratigraphically, the Miocene sediments are represented by the Skawina formation.

The Carboniferous sediments, occurring beneath the Quaternary (Wesoła PIG 1 well) or the Miocene (Wesoła PIG 2H well), are comprised of all the coal-bearing formations, namely: Cracow Sandstone Series (only the Wesoła PIG 2H well), Mudstone Series, Upper Silesian Sandstone Series and Paralic Series. Lithologically, the Carboniferous sequence is composed of sedimentary rocks, solely represented by clastic and phytogenic sediments. In respect of individual lithology occurrences, the Carboniferous sediments are not well differentiated, with the exception of conglomerates which occur only in the Cracow Sandstone Series and Upper Silesian Sandstone Series. Lithological differentiation of the Carboniferous is reflected mainly in relative proportions of occurrences among different lithologies and their types, which is particularly the case for sandstones. Coarser grain sandstones occur predominantly in the Cracow Sandstone Series and Upper Silesian Sandstone Series, whereas they are of secondary importance in the Mudstone Series and almost non-existent in the Paralic Series. These differences are caused by facial and paleogeographic changes, which took place in the depositional environments during the deposition of Carboniferous coal-bearing sediments: starting from diminishing of marine deposition in the coastal environments of plains and deltas, through the period of paralic deposition with recurrent marine ingressions on to the continental areas, where coal-bearing sediments were deposited, and finally, marine influence ceased completely resulting in the development of continental depositional environments of braided and meandering rivers with broad alluvial plains and numerous mires.

The bulk of the coal-bearing Carboniferous strata in the Wesoła PIG 1 and Wesoła PIG 2H wells belong to the Mudstone Series, with a typical feature of cyclicity in the lithology which consists of clastic and phytogenic rocks. These sediments were mainly deposited in meandering river environments with numerous mires and frequent changes of depositional conditions. In the lithology section of both wells, the Upper Silesian Sandstone Series complex is thinner than the overlying Mudstone Series, and is composed of sediments deposited mainly in braided river environments with relatively infrequent mires. The remaining lithostratigraphic formations – Cracow Sandstone Series and Paralic Series – make up only small intervals of both well sections and they are of little importance.

The coal content of the coal-bearing Carboniferous is 8,1% (according to the lithologic interpretation of the Wesoła PIG 1 well). There are 89 coal layers with thickness ranging from 0,05–11,05 m, while their cumulative thickness is 78,78 m. The Upper Silesian Sandstone Series is characterized by the highest coal content of 14,7%, with the two particularly thick coal seams occurring at the base of this formation – the 501 and 510 seams which are 3,47 m and 11,05 m thick respectively, separated by a thin (0,5 m thick) parting. Apart from the two coal seams mentioned above, other four mineable coal seams, with thickness ranging between 1,00 and 2,95 m, occur in this lithostratigraphic formation. The coal content of the Mudstone Series is 6,8%. There are 31 mineable coal seams in this formation, ranging in thickness between 1,00 and 2,10 m. No coal seam was encountered in the Cracow Sandstone Series, although only the lowermost part of this formation was drilled, occurring in the vicinity of the Książęcy fault. Likewise, only the uppermost portion of the Paralic Series was drilled, in which 3 thin coal seams were encountered, ranging in thickness between 0,10 and 0,25 m.

Core recovered from the Wesoła PIG 1 borehole (in the interval of 591,00–1000,00 m) underwent extensive sampling for a wide-ranging CBM testing program with a view to assessing the feasibility of coalbed gas production (using surface wells) and a possible application of hydraulic fracture stimulation. The main objective of coal laboratory testing was to determine coalbed gas content, as well as physical, chemical and petrological properties of coal. No sampling or testing were conducted for stratigraphic investigations because of a well-known and predictable stratigraphic position of this well which is situated in the area of active coal mining.

CBM gas content testing was conducted with the use of two methods – an American, USBM method (desorption test) and a total degassing (quick crushing) method, commonly applied in the Polish coal mining industry. When the USBM desorption process was terminated, the following tests were conducted on the coal samples: residual gas content, gas composition, sorption capacity of coal (sorption isotherm), physical and chemical properties of coal, thermal maturity (vitrinite reflectance) and maceral composition. Desorption tests were conducted on 31 samples from 14 coal seams, starting from the 361 seam through the 510 seam, within the depth interval of 660,55–977,10 m. Sorption isotherm experiments were carried out for five selected coal seams, including the 501 and 510 seams. Methane content testing with the use of a one-phase degassing method was conducted on 44 samples from the same coal seams for which desorption tests were completed.

The results of coalbed gas content determination were as follows: desorbed gas values – from 0,47 to 6,65 m^3/Mg (3,80 m^3/Mg on average), residual gas values – from 1,12 to 3,91 m^3/Mg (2,36 m^3/Mg on average), total gas values – from 2,00 to 9,54 m^3/Mg (6,43 m^3/Mg on average). The largest amount of total gas content is determined for the sample depth interval of 969,84–970,24 m in the 510 coal seam. There is a clear tendency of total gas content to increase with depth. Desorbed gas content as a percentage of total gas content vary between 22% and 72% (55% on average) and is predominant over residual gas percentage, ranging between 23% and 76% (41% on average), and lost gas percentage, ranging between 2% and 6%. Methane is a prevailing component of desorbed gas composition, with its concentrations varying between 94,1 and 99,6%; ethane concentrations are from 0,03 to 0,19%; carbon dioxide from 0,03 to 0,19%; while nitrogen concentrations range from traces (>0,1) to 3,5%. Methane is also a predominant component in residual gas composition, ranging between 90,2 and 98,4%; ethane concentrations are from 0,11 to 0,85%; carbon dioxide from 0,4 to 3,0%; while nitrogen concentrations range from traces (>0,1) to 8,6%. Comparing average composition of desorbed gas and residual gas, it is observed that higher hydrocarbon concentrations are larger in residual gas composition for individual coal seams.

Diffusivity and sorption time were calculated based on desorption curves which express the relationship between evolved gas volume and time of desorption at reservoir temperature. Diffusivity and sorption time values obtained for desorption samples can indicate that the analyzed coal is a microporous system with low permeability. According to the sorption isotherm results, performed on coal samples with equilibrium moisture (as per ASTM standard), the highest sorption capacity of 20,89 m^3/Mg is determined for the 501 coal seam, while the lowest sorption capacity of 18,61 m^3/Mg was measured for the 404/5 coal seam. All desorption coal samples are undersaturated, which means that gas content is lower than sorption capacity at a given pressure. Saturation sorption level for individual coal samples (coal seams) ranges between 24 and 60%, revealing a increasing tendency with depth. Critical desorption pressure, which is defined as the pressure which needs to be reached to initiate desorption of gas from the coal seam, ranges between 0,6 MPa (for the 404/5 coal seam) and 2,5 MPa (for the 510 coal seam).

Methane content of coal, determined using a Polish method of one-phase vacuum degassing, vary from 0,29 to 7,89 m^3 CH_4/Mg csw (csw = pure coal substance), averaging 4,63 m^3CH_4/Mg csw. Substantial differences occur between total gas contents (obtained with a USBM method) and methane contents determined using a one-phase vacuum degassing method. As a rule, total gas content values are considerably higher than methane content values.

Coal quality, or chemical and technological properties of coal, was determined, based on coal analyses performed on the same coal samples which were already desorbed, for 12 coal seams within the depth interval of 660,55–977,10 m. When desorption tests were carried out for more than one sample within a particular coal seam, an average representative sample for chemical and technological properties was prepared and analyzed. The scope of coal analyses was as follows: bulk density, moisture, ash and volatile matter, total sulphur, ash sulfur, combustible sulfur, heat of combustion (determined on 3 different bases: as analyzed; dry; dry, ash, free); as well as elemental composition analysis including: carbon, hydrogen, nitrogen and oxygen. Also, equilibrium moisture was determined for coal samples that were used for sorption isotherm experiments, and Hardgrove index was determined for the 501 and 510 coal seams. Moisture contents of the coal seams vary from 1,43 to 2,86% (2,17% on average), ash content from 2,54 to 17,77% (8,31% on average), volatile matter from 25,52 to 35,70% (30,42% on average), total sulfur from 0,24 to 0,97%. Heat of combustion was determined on 3 different bases ranging from 26 973 to 33 469 kJ/kg (averaging 30 893 kJ/kg) on as analyzed basis, from 27 611 to 34 047 kJ/kg on dry basis, from 33 639 to 35 297 kJ/kg on dry, ash free basis. Elemental analysis showed that carbon contents vary from 66,89 to 83,01% (averaging 75,91%), hydrogen from 3,93 to 4,85% (averaging 4,49%), nitrogen from 0,93 to 1,43% (averaging 1,22%), oxygen from 5,91 to 9,08% (averaging 7,60%). According the ASTM classification of coal by rank, the coal seams under evaluation can be classified as high-volatile B bituminous, high-volatile A bituminous and medium-volatile bituminous.

Vitrinite reflectance measurements and petrological analysis of coal were performed on coal samples which had undergone desorption tests. Vitrinite reflectance values obtained for coal samples vary between 0,80 and 0,96%. Likewise, maceral composition analysis shows that vitrinite macerals prevail for the majority of samples, ranging from 22 to 77%. Inertinite and liptinite contents are within ranges of 12–60% and 4–17% respectively. Inertinite is predominant for coal seams: 405/2, 416, 501 and 510.

The aim of petrophysical tests was to determine coal properties related to methane adsorbed in coal. The testing program encompass the following measurements: material density, particle density and bulk density; total and effective porosity; as well as analysis of micro-fractures. 31 samples from 14 coal seams were collected for petrophysical analyses. Total porosity values are within the range of 0,57 to 16,02% (averaging 8,36%), and open porosity values are from 0,53% to 15,20% (averaging 8,36%). The porosity values of such magnitude are sufficient for treating these coals as a reservoir rock for gas. An important parameter of coal as a reservoir rock for gas is its permeability. Effective permeability values of the analyzed samples fall within the range of <0,008 to 1,45 mD. The average permeability of the 501 and 510 coal seams is approximately 0,09 mD, and thus it is very low in comparison with permeability values of good quality coal reservoirs (e.g. 20 mD). Therefore, high gas flow rates are not expected to occur for the 501 and 510 coal seams. A majority of the coal samples have well developed pore space which, however, is of microporous nature. Values of the threshold pore diameters are less than 0,1 μm, which correspond to cap rock porosities. Thus,

the only way for reservoir fluid to be effectively transported is a system of micro-cleats which is present in the analyzed coal samples. The micro-fracture analysis performed on coal was the basis for making a quantitative characterization of fracture porosity and permeability. It was found that the coal cleat system of the analyzed samples improve flow and storage capacities of the coal reservoir.

A suite of wireline logging was conducted in the Wesoła PIG 1 well, aiming at, among others, lithological interpretation of the Carboniferous section intervals which were not cored, with a special emphasis on coal seams, as well as determination of petrophysical and reservoir properties of penetrated rocks. The following types of logging were conducted: micrulog (normal and lateral resistivity measurements), spectral density log, spectral gamma ray, crossed dipole sonic, extended range micro-imager (XRMI) and caliper. Additionally, cement bond log was run to the depth of 154 m. Furthermore, after the well was intersected by the Wesoła PIG 2H well, special logging tools (comprising: Multifinger Imaging Tool, gamma ray and casing collar locator) were run, within the cased hole interval of 900–998 m, in order to accurately detect the exact spot of intersection. The interpretation of logs run in the Wesoła PIG 1 well was used to determine the hole condition and technical parameters of the well, as well as lithologies along with parameters related to the geometry of strata, joints and fractures. As a result of logging data interpretation, especially density log interpretation, the depth and thickness of coal seams were determined accurately.

A regular logging suite was not conducted in the directional, intersecting well Wesoła PIG 2H, apart from the vertical section of this well, in which caliper and gamma ray logs were run to the depth of 501 m, as well as cement bond log to the depth of 113 m. Whereas, instead of regular logs, continuous logging was conducted during the drilling of directional and horizontal sections with the use of MWD (measured while drilling) and LWD (logging while drilling) systems placed in downhole subs right behind the mud motor. The MWD system was capable of measuring azimuth, inclination, tool face and certain drilling parameters. While LWD system was used for continuous gamma logging which enabled geo-steering so that the well trajectory was kept within the coal seam. The intersection of the vertical well (Wesoła PIG 1) by the directional well (Wesoła PIG 2H) was accomplished with the use of a guidance system called RMRS (Rotating-Magnetic-Ranging-System). The horizontal well path was guided by means of a special detecting device, placed in a sonde run in the vertical well, which detected the magnetic field generated by an emitter placed in a sub behind the bit during the horizontal drilling of the Wesoła PIG 2H well.

Some essential activities undertaken in the Wesoła PIG 1 and Wesoła PIG 2H entail testing of methane gas flow, which was carried out in two phases – before and after hydraulic fracture stimulation. The first phase of testing culminated in achieving a stable pumping regime when the water level was lowered to the depth of ca. 920–930 m and water flow rates were in a range of 1,5–2,0 m^3 per day. The cumulative volume of water recovered during the first testing phase, which lasted 40 days, was 3702 m^3, while the peak gas production rates were at 264,2 m^3. When the first testing phase was finished, the pressure buildup test was carried out. The second phase of tests (after fracture stimulation) was conducted using the same surface and downhole equipment installed at the same depths. General assumptions of the technical plan for the second testing phase has not changed. Gas flow rates obtained during the second phase of testing were similar to those of the first phase, but they were achieved much sooner and with a two-fold increase in water rates. Total volume of gas recovered during the second phase, which lasted 39 days, was 2915,62 m^3 of gas with the daily peak production rates of 224,09 m^3. The incoming water contained a lot of coal particles, which resulted in downhole pump failure and, consequently, termination of the production test.

Samples of water and gas were collected for chemical composition analyses during both phases of production testing. Gas composition was determined based on gas chromatographic analysis in which the following compounds were analyzed: hydrocarbons, N_2, O_2, CO_2, H_2, He. Gas produced during both testing phases was high methane gas with CH4 concentrations in excess of 90% (92,8% on average). Apart from methane, the gas composition included nitrogen (5,4% on average) as well as carbon dioxide – gas samples collected after fracture stimulation had higher concentrations of carbon dioxide (1,9% on average) comparing to samples collected during the first testing phase (0,7% of CO_2 on average). There were also traces of other components, including higher hydrocarbons. The chromatographic analyses of gas from flow tests indicated that there were no significant changes in gas composition with pumping time or pressure fluctuations.

Before the second phase of production testing, hydraulic fracture stimulation of the 510 coal seam was conducted in the horizontal section of the Wesoła PIG 2H well. Guar-based fracturing fluid was used with proppant (quartz sand), amounting to ca. 100–125 m^3 of fluid and ca. 14,6–14,8 tons of sand per fracking phase. Although eight fracking phases were planned, only two fracks were completed at depth intervals of 1891,5–1892,5 and 1833,0–1834,0 m MD. Each frack was designed so that the modelled fracture half-length (in lateral distribution) should not exceed 70 m, and the fracture height (in vertical distribution) should not exceed 15 m. The fracking job was stopped after the second frack because the drill string got stuck in hole.

Translated by Jerzy Hadro