NEW APPROACH TO EVALUATION OF COAL PERMEABILITY IN UNDERGROUND COAL MINES (CBM)

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This paper was prepared for presentation at the International Symposium of the Society of Core Analysts held in Snowmass, Colorado, USA, 21-26 August 2016

ABSTRACT

Laboratory measurements were focused on evaluation of coal permeability at various confining pressure. The investigation shows the distinct relation between coal permeability and overburden pressure which indicate that fracture permeability is a governing factor for methane flow. The petrophysical data (density, porosity, specific surface) measured using the polished sections and thin sections were also analyzed indicating large discrepancy of coal properties. The coal plugs were cut from coal samples collected from walls of underground mine corridors. Our investigations indicated that the coal samples are characterized by the numerous fractures caused by mining operations and stress relief at corridor walls. Such fractures may influence the lab measured permeability of coal. Two hydrodynamic tests were carried out to verify results of laboratory measurements of coal permeability. Such tests are capable to measure the "in situ" permeability in underground conditions. The first test was run in horizontal methane drainage well whereas the second one was run in vertical well which completely penetrated the coal bed. The top of the vertical well was at the overlying mine level. The special equipment constructed in INiG-PIB was used to run the tests (pressure gauge for vertical well and special equipment with two water actuated packers for horizontal well). The data were analyzed using methods invented in INiG-PIB. Results are reproducible and reliable. This paper shows the comparison of laboratory and in situ permeability measurements for coals from one of the Silesian coal mines (Poland).

INTRODUCTION

The methane (CBM) which fills pores and fractures of coal seams can flow to the well in the same way as it does in conventional porous rocks. On the other hand methane is also adsorbed on surfaces at coal grains from where it can be released if the pressure falls below the so called desorption pressure.

Coal is heterogeneous and anisotropic porous rock characterized by two different porosity systems i.e. macropores (cleats) and micropores (matrix). Coal porosity is rather low (some percent) including volume of pores and micro fractures into porosity calculation. Knowledge of permeability, which is the most important factor from the viewpoint of methane production capability, enables evaluation of the potential of methane production from coal. The values of coal permeability are from zero to a few millidarcies, but on average the permeability is rather low.

LABORATORY MEASUREMENTS OF COALS

Coal samples for laboratory measurement were cut from 2 cores (20 meters long each) collected from 2 wells and from coal blocks.

Collected samples were used to analyse the petrophysical features of the studied rocks, such as: density, porosity and permeability. Petrographical studies were performed for sandstones, siltstones and coals. The thin sections and transmitted light method was used. Coals were analysed using the reflected light.

Some of the collected coal blocks were highly fractured/cleated and showed highly varying lithotypes with maximum thickness of bright and dull coal layers less than 3 cm. It was not possible to prepare cylindrical plugs because they broke either at cleats or at weak bright coal layers. Part of coal blocks was suitable for sample preparation and cylindrical plugs were cut in all three directions. In that coal blocks the cleat network was less dense and lithotypes were thicker than for other seams. The 3 porosimetry analyses were performed for each block. Total porosity of the samples was in range 1.32 – 12.7%, porosities in range 3 – 6% were dominating. The analyses showed large diversity of petrophysical data of analyzed rocks (also within the same coal block). The values of specific surface area were generally high (up to 29 m^2/g) and changed in a wide range.

We set a special attention to permeability of coal because it is the most important parameter for methane flow. All measurements were performed using Temco® relative permeability/coreflooding system at 4 confining pressures – 400, 800, 1200 and 1600 psi for plugs cut in parallel and perpendicular direction to bedding. The strong dependence between the measured permeability and the confining pressure indicates that the fractures are the crucial factor for coal permeability (as well as relatively high permeability values). Results of the coal samples measurements were confirmed using the polished and thin sections – calculated permeability values were similar to those obtained with the use of Temco® equipment. Because samples were cut from the walls of mining excavation in our opinion a part of fractures could be the result of mining operations. Also fracture thickness could be the result of coal depressurization.

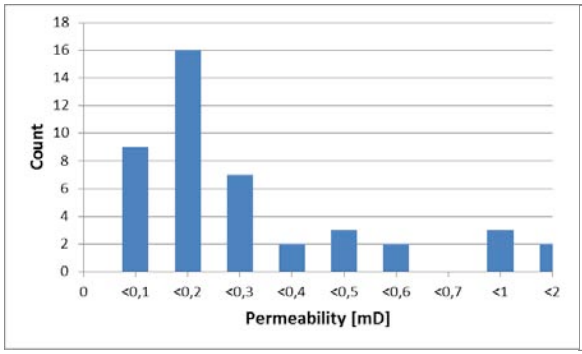

Fig.1. Parellel to bedding (conf.press. 1600 psi)

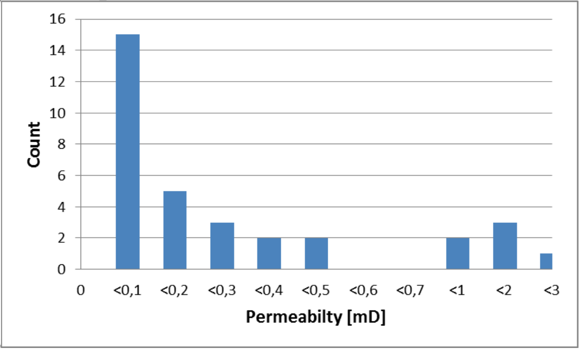

Fig.2. Perpendicular to bedding (conf.press.1600 psi)

INTERPRETATION OF THE WELL TEST DATA

Two hydrodynamic tests were carried out to verify results of laboratory measurements of coal permeability – one in vertical well and the second in horizontal one. Such tests provide information on the “in situ” permeability in underground conditions.

Vertical well

The first test was run in vertical well which completely penetrated the coal bed. The well with depth 37 m, was drilled from the overlying mine level. The 5 inch casing was set and cemented leaving open the coal seam with thickness 6 m. The wooden plug was run to the bottom of the well to isolate the coal bed from particles suspended in water. Next the well was left for pressure stabilization. After some days the water table in a well stabilized some centimeters below the surface (z_0). No outflow of water was observed which means that the reservoir pressure around the well was equal to hydrostatic pressure of water column. Such a low pressure means that some water was drained off the coal to near about mining excavations located a dozen or so meters from well location. Next, the pressure gauge was run to the mid-point of coal bed and some water was blown off the well (z_1) which caused the water table to drop a few meters (z_1) below the stabilized level (see Fig.3).

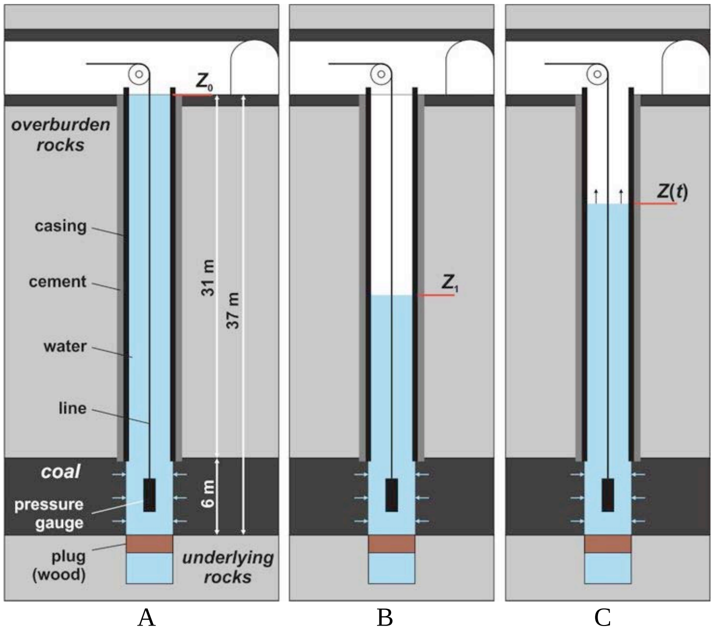

Figure 3: Diagram of the test: A) Hydrostatic pressure balance the reservoir pressure in coal, B) Removal of some fluid volume from the well, C) Monitoring the fluid table behavior

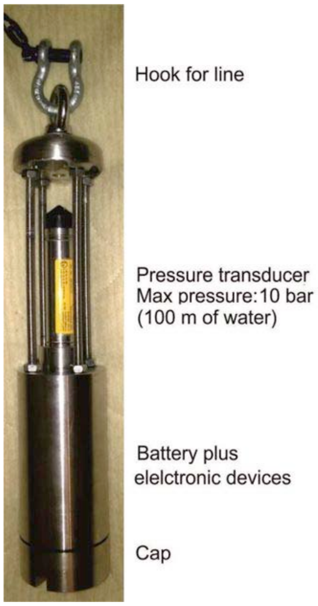

Figure 4: Pressure gauge developed by INiG-PIB

Measurement of water table behavior versus time while the well returned to pressure stabilization was carried out using the INiG-PIB pressure gauge. This equipment (Fig. 4) fulfil the requirements of the restrictive safety regulations for methane coal mine. Time of measurements was around 24 hours. The length of water column above pressure gauge vs. time relation recorded while the well returned to stabilization is shown in Fig. 5 below.

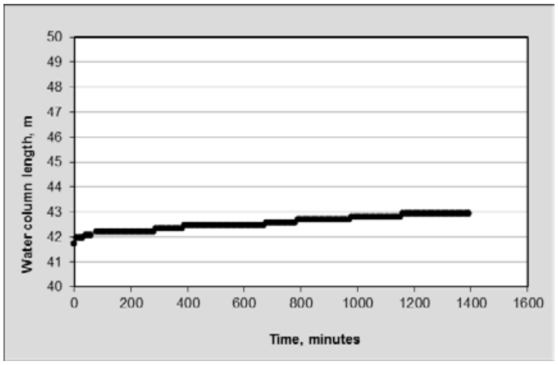

Figure 5: Water column length vs. time curve

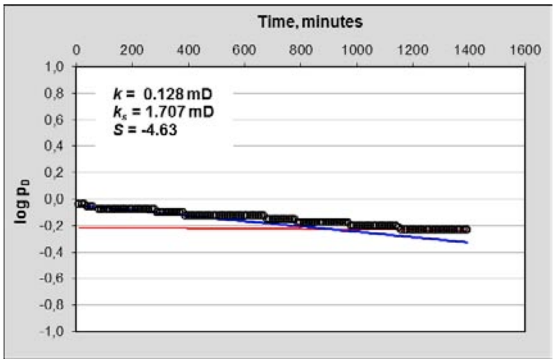

Figure 6: log p_D vs. time curve

The recorded data were interpreted using well known “slug test” method which consists in fitting the curve constructed using the measured data to one of curve among family of theoretical curves (Fig. 7) and INiG-PIB method which theoretical background and interpretation procedure are given in papers [1] and [2].

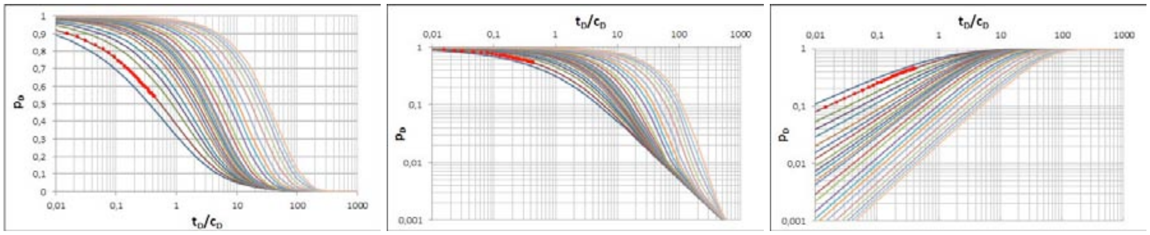

Figure 7. Fitting the whole, initial and final portion of the test curve (red points)

Results of test interpretation using the „slug test” method are given below:

Match of test curve to theoretical curves	**Permeability [mD]**	**Skin effect**
Whole curve	0.1771	-5.24
Initial portion of curve	0.1778	-5.24
Final portion of curve	0.1826	-5.24

According to INiG-PIB method relation between dimensionless pressure p_D and time t during pressure stabilization is as follows:

$$\log\frac{z(t)-z_0}{z_1-z_0} = \log p_D = -5.11{\cdot}10^{-7}\,\frac{Kh\rho t}{r_0 u \overset{**}{u}} - \log\left(1-\frac{S}{\overset{**}{u}}\right) \qquad (1)$$

where $\overset{**}{u}$ is a root of the equation $u = (\ln u - \ln a)/2$ and $a = 0.5(r_0/r_w)^2 h\phi\rho g c$.

In some circumstances it is possible to calculate permeability of the wellbore zone (fracture permeability), permeability of coal matrix, skin effect and depth of permeability impairment/increase. The relation between p_D vs. t is shown in Fig. 6 above. The short time data indicate the fracture permeability (permeability of the wellbore zone) whereas the late time data indicate the permeability of the coal matrix. The following results were obtained: permeability of the wellbore zone (fracture permeability) 1.707 mD, permeability of coal matrix 0.128 mD and skin effect -4.63.

Horizontal well

Figure 8. Test in horizontal well

The second test was run in horizontal drainage well (slightly inclined downward to keep it full of water) drilled in the same coal bed. The data were interpreted using INiG-PIB method presented in [3].

The equipment used to run a test (see Fig. 8) consists of pipe with two water-actuated packers placed at distance *a* one from the other. The segment between packers is perforated to allow water injection into coal matrix using small water pump capable for maintaining constant injection rate. Relation between injection pressure p_{inj} and time t for horizontal drainage well has a following form:

$$p_{inj} = p_0 + 39.81\frac{Q\mu}{aK}\left(\ln t + \ln\frac{K}{\phi\mu c r_0^2} - 8.912 + S\right) \tag{2}$$

which indicate that plot p_{inj} vs. ln t should be linear with slope m:

$$m = 39.81\frac{Q\mu}{aK} \tag{3}$$

permitting calculation of permeability K. If the straight line is extended to $t = 1$ min and corresponding injection pressure $p_{inj\,lin}$ is read out then the skin effect S is given by:

$$S = \left[\frac{p_{inj_{lin}}(t = 1\,\text{min}) - p_0}{m} - \ln\frac{K}{\phi\mu c r_0^2} + 8.912\right] \tag{4}$$

The recorded relation of p_{inj} vs. ln t is shown below in Fig. 9.

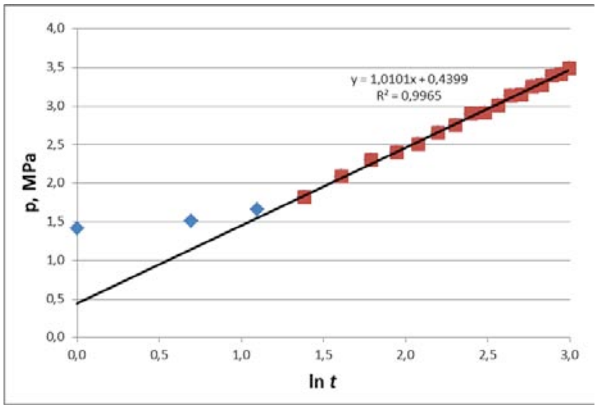

Figure 9. Relation of p_{inj} vs. time

The length of horizontal interval isolated by packers was 10 m and water injection rate was 2 l/min. The interpreted permeability and skin were $k = 0.13$ mD and $S = -4.8$.

CONCLUSION

The laboratory data for 1600 psi confining pressure were used to compare results with flow test data. Such a pressure corresponds to overburden pressure prevailing at the coal bed depth.

Table 1. Comparison of permeabilities

Lab tests (at 1600 psi conf.press.)						Test in vertical well					Test in horizontal well	
Permeability samples measured to bedding						**“slug test”**		**INiG-PIB method**			**INiG-PIB method**	
parallel			**perpendicular**			**Average perm. [mD]**	**Skin effect**	**Permeability [mD]**		**Skin effect**	**permeability [mD]**	**Skin effect**
min	**max**	**average**	**min**	**max**	**average**			**wellbore zone**	**coal matrix**			
0.02	1.34	0.28	0.02	3.90	0.40	0.179	-5.24	1.71	0.128	-4.63	0.13	-4.81

Table 2. Fracture permeability of coal samples

Permeability [mD]	Macro fracture (>0.1 mm)	Micro fracture (<0.1 mm)
Minimum	1.25	1.32
Maximum	2.08	14.73
Average	1.42	4.37

As shown in Table 1 and 2, the results of laboratory measurements and well test data are in a rough agreement which proved correctness of lab measurements in simulated downhole conditions both as the fracture permeability and permeability of the coal matrix are concerned. Comparing the results of laboratory measurements of coal properties with results of well test data seems to be useful procedure when results of any of those methods are in doubt.

NOMENCLATURE

p_{inj} – injection pressure, MPa
p_0 – reservoir pressure, MPa
a – distance between packers, m
Q – injection rate, l/min
c – total compressibility (coal plus media), 1/MPa
h – thickness of coal, m
ϕ – coal porosity
ρ – water density, kg/m^3
μ – water viscosity, mPas
r_0 – inner radius of casing, m
r_w –radius of the well, m

ACKNOWLEDGEMENTS

The research leading to these results was partially founded from Research & Innovation Research Fund for Coal and Steel Development of Improved Methane Drainage Technologies by Stimulating Coal Seams for Major Risks Prevention and Increased Coal Output, Contract No.: RFCR-CT -2014-00004

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