AGH DRILLING, OIL, GAS • Vol. 30 • No. 1 • 2013

http://dx.doi.org/10.7494/drill.2013.30.1.109

**Martin Klempa*, Michal Porzer*, Petr Bujok*,
Ján Pavluš*, Robert Rado****

PETRO-PHYSICAL PROPERTIES OF GEOLOGICAL FORMATION IN THE ASPECT OF POSSIBLE CO_2 SEQUESTRATION

1. INTRODUCTION

Several projects that deal with theoretical and pilot research on CO_2 storage in geological formations are active nowadays. These projects are addressed by national programmes in USA, Canada, Australia and Japan. One of the projects under the supervision of European Union was the RECOPOL project, which evaluated the CO_2 storage in coal seams of Lower-Silesian Basin. The main objective of these projects is to find out whether the CO_2 storage in the geological formations is economically feasible and environmentally safe. In Czech Republic the most perspective formations for the storage of this gas are connected with oil and gas reservoirs.

Potential storage spaces are the depleted and actively produced oil- and gasfields, in which it is possible to enhance oil recovery by 10 to 15% by CO_2 injection in the reservoir. Oilfields are the favourable variant because before they were produced, the hydrocarbons were stored inside them during geological time, and similarly the carbon dioxide can be stored there now. Another advantage they have is a well explored geological environment and therefore an abundance of information on the selection of suitable storage locality, its utilization and long-term monitoring. The capacity of the CO_2 storage space in an oilfield depends on the pore space freed after oil production and the pore space that is filled with water under the oil bearing horizon. Depleted oil- and gasfields represent suitable porous rock structures either for CO_2 sequestration or for underground storage of imported natural gas.

---

* Institute of Geological Engineering, Faculty of Mining and Geology, VSB – Technical University of Ostrava, Ostrava Poruba

** AGH University of Science and Technology, Faculty of Drilling, Oil and Gas

2. STORAGE OF CO_2 IN THE THEORY

It is assumed that horizons used for carbon dioxide sequestration will lie in depths below 800 m. At the temperatures and pressures that correspond to the depths lower than the above mentioned the CO_2 changes its phase behaviour, its density resembles liquids and its state is called supercritical state. This transition into the supercritical state takes place at p,T conditions of 7.38 MPa and 31.1°C.

Carbon dioxide injected in a supercritical state occupies much less space than in gaseous state. In the depth interval between 600–800 m the CO_2 density is increasing with depth. From the depth of 1000 m it reaches its maximum value and it doesn't change with depth further. At standard conditions (temperature 25°C and pressure 0.1 MPa) the density of CO_2 is 1.977 kg/m^3. That means that 1 tonne of CO_2 occupies a volume of 526 m^3. At the temperature and pressure conditions in the depth of 1000 m (35°C, 10 MPa) one tonne of CO_2 occupies a space of 1.5 m^3 (CO_2 density is 650 kg/m^3) [4].

In order for CO_2 to be effectively injected, its density should be in the interval of 600 to 800 kg/m^3 (at p,T conditions of 30°C and 8 MPa).

Mathematical modelling of geochemical sequestration process is needed for developing a notion of how the injected CO_2 will behave in a reservoir. One of such models based on our laboratory experiments was created by professor Labus (Poland). The Geochemist's Workbench 7 (GWB) simulator was used for modelling. Modelling process had two stages. The first stage was aimed at observing the changes in rock environment at the beginning of CO_2 injection. The second stage evaluated the changes caused by CO_2 influence on permeable rocks after the injection [2].

A timespan of 20 thousand years was analysed in the model. During the first three years after the injection ended a continuous increase of porosity takes place in the rock environment. Afterwards this value stabilizes at maximum level without further changes [2].

3. RESEARCH THE ROCK RESERVOIRS IN THE ABILITY ASPECT OF CO_2

For ascertaining the CO_2 storage capability, the knowledge of porosity and permeability values of a natural reservoir is essential. These parameters can be measured with great certainty on the devices that are in possession of the Laboratory of Wells and Hydrocarbon Deposits Stimulation at the Institute of Clean Technologies for Extraction and Utilization of Energy Resources.

3.1. Porosity and permeability of natural reservoirs

Pores can be defined as spaces of different shapes, sizes and origin in soil or between the rock grains that are not filled with solid phase. We differentiate these porosities:

- absolute porosity,
- open porosity,
- effective porosity.

Absolute porosity

It represents a total volume of pores in a rock regardless of their connection with each other.

$$P_c = \frac{V_{pc}}{V_{hc}} \ (\%) \tag{1}$$

where:

V_{pc} – volume of all the pores in a rock;
V_{hc} – bulk volume of rock sample including pores.

In a laboratory, porosity determination is based on the difference between the specific and the bulk density.

Open porosity

It represents a volume of all connected pores (V_{po}) in a rock:

$$P_o = \frac{V_{po}}{V_{hc}} \ (\%) \tag{2}$$

Open porosity value is experimentally determined at rock samples dried at 105$^{\mathrm{o}}$C after the hygroscopic water is released from the rock surface.

For the open porosity coefficient calculation it is necessary to know at least two of the characteristic rock sample volumes i.e. the bulk volume (V_{hc}) and the volume of connected pores (V_{po}) or a grain volume (V_h).

Effective porosity (P_u)

It represents a pore volume (V_{pu}) through which a fluid filtration of a given hydrodynamic system takes place. It is therefore different for different systems and it changes with time:

$$P_u = \frac{V_{pu}}{V_{hc}} \ (\%) \tag{3}$$

Coefficient of open and effective porosity can be dependent on the method of measurement and therefore it is always necessary to mention by what method it was determined.

Automatic porosimeter-permeameter measurement principle

The device's method of work is based on API recommendation (API recommended practice 40, February 1998, pages 5–12/5–18) which uses *Boyle's Law Single Cell Method* for a measurement of a free space. The method uses a reference cell filled with gas, that has a reference volume and pressure, which is afterwards released into the pore volume of a given sample. Sample is placed in a core-holder and is fastened in an elastic sleeve, which induces a confining (lithostatic) pressure. The whole experiment is isothermal.

Core samples porosity measurements show a variance of 0.1 cm^3 for a sample of 50 cm^3 volume, porosity margin is ±0.2% of the real value.

Measured parameters are:

- pore volume V_p (cm^3),
- sample porosity φ (%),
- bulk volume V_b (cm^3),
- grain volume V_g (cm^3),
- grain density Gd (g/cm^3),
- gas permeability K_g (mD),
- slip factor b (psi),
- initial resistance β (ft^{-1}),
- turbulence factor α (μm).

Measurement is based on unsteady filtration methods, where the pore volume is determined according to Boyle's Law and the permeability according to Darcy's Law. Other obtained parameters are dependent on the results of the main parameters measurement.

It is very convenient to determine the above mentioned parameters at expected reservoir pressures. Next it is necessary to determine hysteresis (at an appropriate step – at minimum 6 values) up to the pressure that is 15% higher than the expected reservoir pressure. Last but not least it is desirable to determine an extreme hysteresis (at an appropriate step – at minimum 6 values) for approximately three times the value of expected reservoir pressure.

Permeability is a property of a porous medium and is a measure of its ability to transmit fluids. The reciprocal of permeability represents the viscous resistivity that the porous medium offers to fluid flow when low flow rates prevail. The effective permeability of a porous medium is a measure of its fluid conductivity to a particular phase of a multi-phase fluid system residing within the medium, where the saturation of each phase is specified. Relative permeability is the ratio of the effective permeability of a particular fluid phase to some arbitrary reference permeability.

Measurement principle

Transient pressure technique for gases: Pressure-Falloff, Axial Gas Flow measurements (API, Recommended practice 40, February 98, section 6.4). Transient measurements employ fixed-volume reservoirs for gas. These may located upstream of the sample from which the gas flows into the sample being measured. The pressure falloff apparatus (Fig. 1) employs an upstream gas manifold that is attached to a sample holder capable of applying hydrostatic stresses to a cylindrical plug of diameter D and length L. An upstream gas reservoir of calibrated volume can be connected to the calibrated manifold volume by means of a valve. Multiple reservoir volumes are used to accommodate a wide range of permeabilities. The downstream end of the sample is vented to atmospheric pressure. An accurate pressure transducer is connected to the manifold immediately upstream of the sample holder. The reservoir, manifold and sample are filled with gas. After a few seconds for thermal equilibrium, the outlet valve is opened to initiate the pressure transient. Pressures and times are recorded. This technique has a useful permeability range of 0.1 to 5000 milliDarcys (mD).

3.2. Laboratory measurement of chosen parameters of core samples on Automatic porosimeter-permeameter

To understand the behaviour of rock massif considered for CO_2 storage, real core samples were selected. Their petrographic composition corresponds to potential storage formation. They are fine-grained sandstones with addition of clay. They were drilled out from one larger core perpendicularly to its axis. Parameters of one of the samples are:

- diameter – 38,4 mm,
- length – 68,2 mm,
- initial weight – 156,56 g.

Confining pressure of the first reference measurement was set to be 1000 psi (6.895 MPa). The outcomes of the measurement are presented in table 1 and 2. The core sample, before it was inserted in the automatic porosimeter-permeameter. The objective of a series of subsequent measurements was to determine a hysteresis curves for different confining pressures. The hysteresis curves tell us how different measured parameters are changing when confining pressure is increasing and subsequently decreasing. Another objective was to ascertain how will an internal structure of a tested core look like after repeated rises and drops of confining pressure. To portray the hysteresis curves these pressure steps were chosen: 1000 psi, 1200 psi, 1400 psi, 1600 psi, 1800 psi, 2000 psi, 2100 psi, 2200 psi, 2100 psi, 2000 psi, 1800 psi, 1600 psi, 1400 psi, 1200 psi a 1000 psi. It is a pressure range between 6.895 MPa to 15.168 MPa. These are pressures that can be expected to occur in a formation suitable for CO_2 storage. Because of assumed shape memory of a measured sample a time span between different measurements was at least 24 hours.

Table 1

Measurement outcomes at confining pressure of 1000 psi (6.895 MPa)

Confining pressure	**Pore volume**	**Porosity**	**Bulk volume**	**Grain volume**	**Bulk density**	**Grain density**
Pc (psi)	**Vp (cm^3)**	**φ (%)**	**Vb (cm^3)**	**Vg (cm^3)**	**Bd (g/cm^3)**	**Gd (g/cm^3)**
1000	19.9167	25.2958	78.7226	58.8445	1.9789	2.6620

Table 2

Measurement outcomes at confining pressure of 1000 psi (6.895 MPa)

Confining pressure	**Air (N_2) permeability**
Pc (psi)	**K [air] (mD)**
1000	41.1791

Hysteresis curves determination for chosen measurement parameters

Hysteresis curves were determined based on a measurement of chosen parameters in a pressure range between 6.895 MPa to 15.168 MPa at above mentioned pressure steps. After the first measurement the weight of the core sample was 156.45 g. Weight loss after the first set of measurements was 0.11 g. The measurement outcomes are documented in the following charts for different measured parameters.

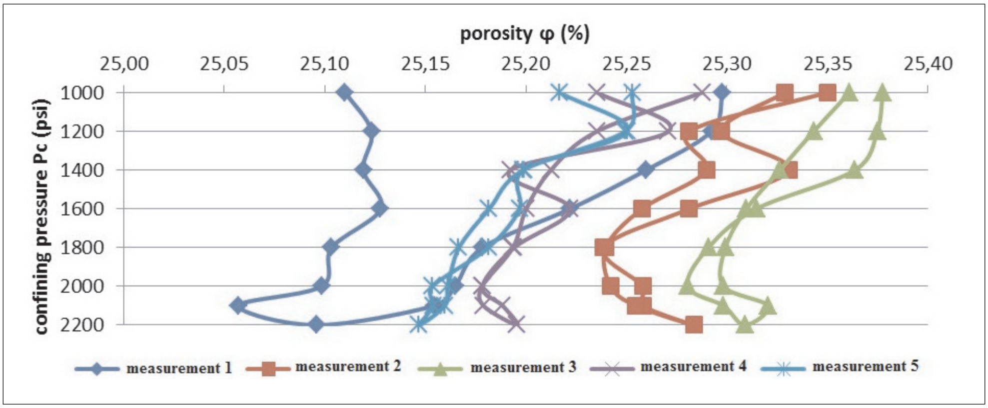

Fig. 1. Hysteresis curves of porosity for different pressure steps

Comparison of the first measurement with other four measurements tells us that the internal structure of the sample had undergone significant changes. In absolute numbers the changes are negligible in the order of one hundredth of a per cent (average value of porosity at 1000 psi is 25.,2880% before the pressure started to rise and 25.2756% after it dropped; at maximum pressure of 2200 psi the porosity was 25.2062%). Nevertheless, the shape of the curves confirms that after several measurements, changes in the internal structure took place, which indicates at least some damage of the internal structure. It can be assumed that during the last two measurements a partial internal porosity consolidation took place – proportionally between effective and close porosity.

Logically, the grain density Gd is higher than the bulk density Bd, due to the low density of fluids filling the pores. In the whole series of measurements (from 1 to 5) the grain density was changing on a second or third decimal position, therefore the change is negligible. An average grain density of the core sample was found to be 2,6620 g/cm^3. An interesting fact is that the grain density Gd curves shape corresponds with the shape of grain volume Vg curve and partially with the porosity curve.

Air permeability (medium – N2) showed itself to be consolidated and, if the measurement no. 3 is not taken into account, it was found to be 40.6139 mD. Measurement no. 3 shows permeability values at least 1 mD higher than the rest of the measurements. It is probably due to the fact that during this measurement the greatest internal structure changes, that caused higher permeability, took place. After a partial consolidation the permeability has settled at primeval values.

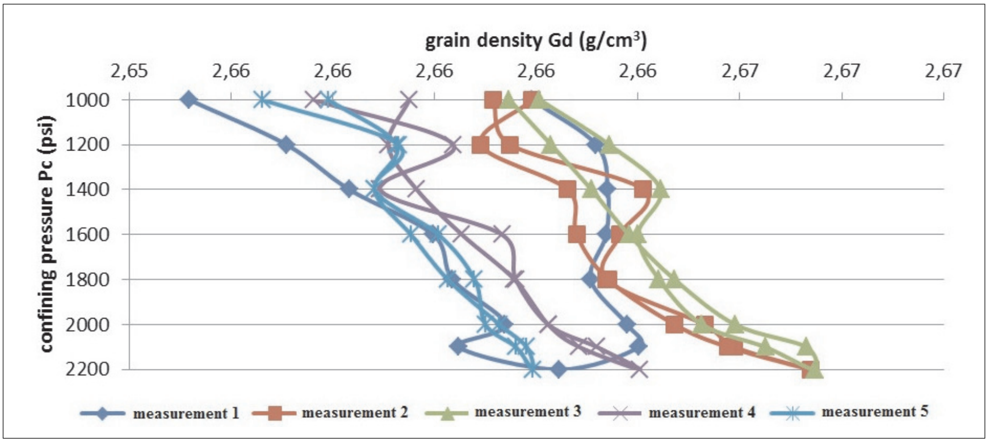

Fig. 2. Hysteresis curves of grain density for different pressure steps

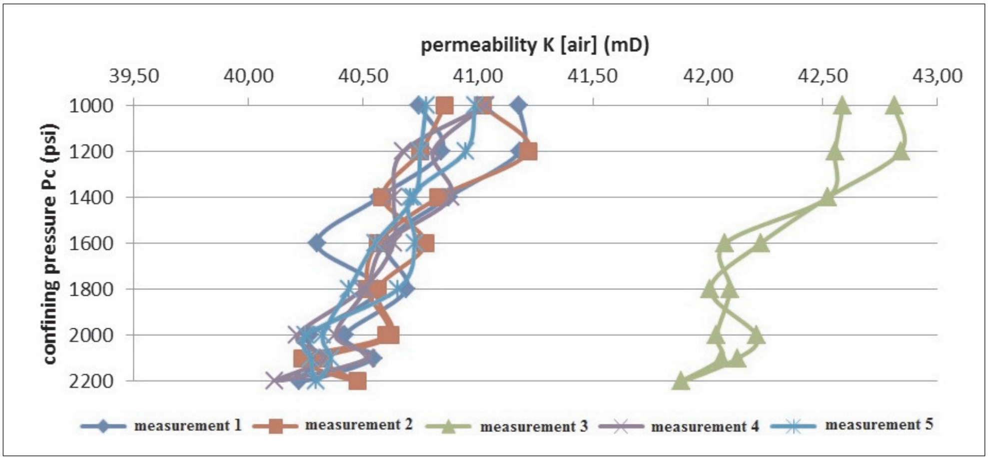

Fig. 3. Hysteresis curves of air (N_2) permeability for different pressure steps

4. CONCLUSIONS

During the laboratory experiment a set of cores from a single borehole was tested. Charts 1 and 3 show the most interesting results. And even though, at first glance, these samples from a similar depth look the same, they had shown not only different petrophysical results, but have also implied possible complications in the internal structure of a reservoir rocks considered for CO_2 storage. For *porosity*, the difference between examined cores was *as much as* 3%, while the difference of *permeability* was more than *40 mD*. At the same time the *grain density* was the same for all the cores (*2.64–2.66 g/cm*^{3}), it varies at the second or third decimal position. Measurements at these cores indicated indirectly that even though the confining pressure was relatively low (6,895 MPa to 15,168 MPa), the internal structure suffered some damage. It is reflected in hysteresis curves (charts 1 to 3). A “bent V” shape of the curves, with a shape memory, was expected. Only the first measurement approximately resembles this shape, four others are much more chaotic. It is likely that after every pressure step, the deformation of porous space took place, in a way that the effective pore space was squeezed so much that it prevented the flow of measuring medium (N_2). The assumption of internal structure deformation is backed by an evidence of visual reconnaissance of the core surface. The cracks, some more than 0,5 mm deep, had appeared on the core’s surface. This phenomenon is known from cyclical operations of underground gas storage sites, where due to the thermal and pressure changes, micro-particles of the rock matrix are crumbled away and form a so called “silt cloud”. The outcome of the measurement confirms the non-homogeneity of the geological environment. Even though the samples are from a single borehole from approximately the same depth, the results vary substantially.

Next part of the research will be focused on ascertaining CO_2 phase permeability at the supercritical state (7.38 MPa and 31.1^{o}C). For this task another laboratory device of the Laboratory of Wells and Hydrocarbon Deposits Stimulation will be used. It is the BRP 350 multiphasic permeameter made by Vinci Technologies (France).

REFERENCES

[1] Bethke C.M.: *Geochemical and biogeochemical reaction modelling*. Cambridge Univ. Press, Cambridge, 2008, 1–543.

[2] Labus K.: *Hydrochemical issues of CO_2 sequestration in the Upper Silesian Coal Basin. Proceedings XXXVI International Association of Hydrogeologists Congress*. 26 October – 1 November 2008, Toyama, 357.

[3] Palndri J.L., Kharaka Y.K.: *A compilation of rate parameters of water-mineral interaction kinetics for application to geochemical modeling*. US Geological Survey. Open File Report 2004–1068, 2004, 1–64.

[4] Xu T., Apps J.A., Pruess K.: *Reactive geochemical transport simulation to study mineral trapping for CO_2 disposal in deep Arenaceous Formations*. J. Geophys. Res., 108: B2, 2003.