AGH DRILLING, OIL, GAS • Vol. 32 • No. 1 • 2015

http://dx.doi.org/10.7494/drill.2015.32.1.33

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ANALYSIS OF RESERVOIR PROPERTIES AND PARAMETERS OF OIL FIELDS SUITABLE FOR THE APPLICATION OF CO_2-EOR METHOD**

1. INTRODUCTION

The MUSE project (carried out jointly by AGH UST and University of Stavanger) is aimed at working out a technology which can be used for simultaneous deposition of carbon dioxide and enhanced production of oil from deposits at the last stage of their production life. Owing to the specific character of the Polish oil fields (mainly their low resources), an idea was put forward to apply the miscible CO_2-EOR method not for single fields but clusters of fields located at a small distance from one another.

The advanced oil production method (CO_2-EOR) where carbon dioxide is injected to oil fields has been used worldwide since the 1970s. Most of the CO_2-EOR method projects are still operational in USA. Recently the number of CO_2-EOR projects has been observed to constantly increase from about 60 in 1975 to about 110 in 2010. Carbon dioxide is injected to the fields to increase oil production in such countries as Canada, Brazil, Trinidad, and single projects in Croatia and Hungary [1].

The reduction of carbon dioxide emission by geological deposition is a younger concept developed in the early 1990s. The authors of the first publications speak of injecting anthropogenic carbon dioxide to geological structures, mainly unused aquifers, oil and gas fields and non-produced coal seams [3, 14, 15, 16, 19].

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** The research leading to these results has received funding from the Polish-Norwegian Research Programme operated by the National Centre for Research and Development under the Norwegian Financial Mechanism 2009–2014 in the frame of Project Contract No Pol-Nor/235294/99/2014

When considering the possibility of lowering CO_2 emissions by its geologic storing underground, the first candidates for such spaces are depleted oil and natural gas fields. These structures are made of shales, where hydrocarbons have accumulated for millions of years, proving their tightness. Moreover, fields which are depleted or at the end of their production life are usually very well recognized for geology and reservoir conditions (frequently they already have their numerical models) and may have infrastructure to be used for injecting carbon dioxide purposes.

The research was also focused on the associated CO_2 storage and enhancement of hydrocarbons production, especially oil [2, 6, 13, 20, 25, 31]. About 20% of oil is produced with primary methods. In secondary methods the oil recovery level oscillates between 45 and 50%, rarely 60%. Tertiary production methods allow for additional production of about 7–20% of oil. When injecting CO_2 in miscible conditions additional 10–20% of oil can be obtained as compared to the primary and secondary methods; in the non-miscible conditions the additional oil production is lower [27].

The selection criteria for oil fields as candidates for the associated CO_2 deposition and tertiary methods of oil production are presented in this paper. The deposit and reservoir parameters of selected oil fields are characterized.

2. SELECTING FIELDS FOR CO_2 DEPOSITION AND USE OF ADVANCED OIL EXTRACTION METHODS

2.1. An overview of selection criteria for oil fields to be used for CO_2-EOR method and geological deposition of CO_2

When selecting oil fields, where the miscible CO_2-EOR method can be applied, five basic parameters are used: depth of deposition, density of oil, reservoir pressure and temperature. Principally, such fields are selected on the basis of the depth of deposition and density of oil. Density of oil and reservoir pressure decide about the miscibility. Oil of higher density than 921.8 kg/m^3 is generally miscible with carbon dioxide. For heavier oils or when the pressure is lower than Minimum Miscibility Pressure (MMP), immiscible movement of oil can take place. The CO_2 injection to oil deposits is limited to fields deeper than 800 m, where after the primary production and secondary methods about 60–70% of primary oil resources are left out. The minimum miscibility pressure, which decides about the applicability of the CO_2-EOR method can be determined. The MMP pressure should be lower than the admissible reservoir pressure. The non-miscibility method can be used in deposits which do not meet the criterion of minimum miscibility pressure. One of the parameters considered as a selection criterion for fields where the CO_2-EOR method can be used is the oil saturation of rocks. It is assumed that the saturation of rocks in most appropriate fields should equal to about 20–30%. The criteria used for selecting oil fields were proposed by numerous authors, e.g. [7, 8, 11, 17, 18, 21, 22, 23, 24, 26, 28, 29].

A different set of criteria is used for selecting geological structures for carbon dioxide deposition grounds. The selection of place for carbon dioxide storage depends on a number of geological, reservoir, technical, environmental and economic factors. This is done on the basis of criteria which can be defined as a system of geological, reservoir and technical parameters to be met by a given geological structure before it is used as a host ground for CO_2. The geological structures are selected for carbon dioxide storages on the basis of geological and reservoir criteria, accounting for the specific properties of carbon dioxide, i.e. magnitude of porous space, depth of deposition of host strata, their thickness, porosity, permeability, mineralization of waters, sufficiently thick overburden of low-permeable rocks. They are used for the preselecting structures which not only have appropriate capacity, but also create conditions for a safe deposition of carbon dioxide. The injected carbon dioxide should be in a supercritical phase. The deposition site should be performed under 800 m in the formation, for the assumed average geothermal level and hydrostatic pressure. The cost of CO_2 storing increases with depth, therefore the storage is assumed to be maximum 3000–3500 m deep. The high thickness and high porosity of reservoir rocks guarantee appropriate storage capacity. The safety of the process is provided by a sufficiently thick and low permeable roof of the overburden rocks. Presently no clear criteria for the selection of carbon dioxide storing places exist, though numerous such attempts have been undertaken [4, 9, 12, 30, 32]. These works contain criteria on the basis of which CO_2 deposition sites can be pre-selected and ranked.

2.2. Oil fields for associated CO_2 deposition and CO_2-EOR method

Onshore oil fields in Poland are localized in three large geologic units, i.e. Carpathians, Carpathian Foredeep and Polish Lowland. The distribution of deposits and resources in these units is uneven. The most abundant and largest oil fields are located in the Polish Lowland, within the Wielkopolska and West Pomeranian provinces (75% of extractable oil). Numerous, frequently depleted oil filed can be encountered in the Małopolska Province (Carpathians) (2% of exploitable resources). Scanty oil deposits can be found in the Carpathian Foredeep (also Małopolska Province) (4% of resources). Only a few oil deposits were discovered in each of the provinces: Lublin and onshore north Pomerania. At the end of 2013 85 oil and condensate fields were documented, 68 of which were managed, 10 unmanaged, and 7 with abandoned production [5].

The analysis of associated deposition of carbon dioxide and CO_2-EOR was performed for 67 oil fields, 63 of which are active now (in the Balance of raw minerals and water of 2014), and 5 are unmanaged. These deposits are located in in the Carpathians (29 fields), Carpathian Foredeep (7 fields) and Polish Lowland (31). Deposits in the Carpathian Foredeep are accumulated in the carbonate rocks (limestones) of Upper Jurassic-Lower Cretaceous time and clastic formations (sandstones, conglomerates) of Cenomanian and Miocene age. The Carpathian oil deposits appear in the flysch sandstones and shales from Krosno,

Istebna, Ciężkowice, Wierzchowiec Menilite and Cergowa beds. The major oil horizon in the Polish Lowland is the Main Dolomite hosting 28 accumulations. These are limestones and dolomites intercalated with anhydrites and clays. Oil deposits in the West Pomerania (4 fields) are deposited in quartzite sandstones of Middle Cambrian age. Presently only one field produces oil from carbonate strata of Devonian time (Lublin Province).

The duration of production of the analyzed fields varies. The oldest ones are localized in the Carpathians, where oil has been produced since the second half of the 19^{th} century (15 fields) and the youngest ones are in the Polish Lowland where 60% of deposits were discovered in the last 20 years.

Owing to the diversified geologic build of host formations they differ in such parameters as:

- surface area (from below 1 km^2 mainly in the Carpathians up to several dozen km^2 in the Polish Lowland),
- depth of deposition (hundreds of meters in the Carpathians to over 3000 m in the Polish Lowland) and the related temperature and reservoir pressure,
- thickness of reservoir rock (from a few meters to tens of meters for stratified deposits in the Carpathians),
- porosity and permeability of reservoir rock,
- oil properties (oils extracted in the Carpathians and Carpathian Foredeep can be classified as medium and heavy – Lubaczów, oils extracted in the Polish Lowland belong to light and medium oils),
- geological resources (the smallest deposits are below 100,000 tons (6 deposits in the Carpathians and 6 in the Polish Lowland), 22 deposits have resources of 100,000 to 1,000,000 tons (12 in the Polish Lowland); the largest geologic resources exceed 1,000,000 tons (14 in the Carpathians, 4 in the Carpathian Foredeep and 11 on the Polish Lowland),
- hydrogen sulfide content in oil (in 37 deposits, out of which 27 on the Polish Lowland).

The average saturation with oil of the analyzed fields is basically high and exceeds 30%; only in two deposits, i.e. Stężyca and Gorlice it is a few to a ten or so percent. The fields also vary in the number of wells performed on them. About 1/3 of the deposits have less than 10 wellbores on them, in that 10 fields have only one well. Generally, 10 to 100 wells were drilled on 8 oil fields, 100 wells on 13 fields.

In a majority of analyzed fields oil is pumped (37 deposits). In 13 fields the oil is pumped and spontaneously produced. Spontaneous production of oil is carried out on 30 deposits.

The deposits are preliminarily selected for the miscible CO_2-EOR method based on the following criteria (Tab. 1): depth of deposition, density of oil, reservoir temperature, saturation with oil.

Table 1

Screening criteria for miscible CO_2-EOR and CO_2 storage in Polish oil deposits

Reservoir Parameter	Miscible CO_2-EOR
Depth [m]	>450
Temperature [K]	301 to 394
Oil Gravity [kg/m^3]	800 to 884
Remaining Oil Fraction in the Reservoir [%]	≥0.30

For further analyses 35 of 68 oil fields were selected: 3 in the Carpathians (Glinnik, Grabownica Wieś, Węglówka), 6 in the Carpathian Foredeep (Brzezówka, Grobla, Jastrząbka Stara, Nosówka, Pławowice, Wierzchosławice), and the remaining 26 in the Polish Lowland.

3. DETERMINATION OF RESERVOIR PARAMETERS RELEVANT FOR THE APPLICATION OF IOR METHODS AND STATISTICAL ANALYSIS OF THEIR VARIABILITY AND MUTUAL CORRELATIONS

The applicability of advance methods for oil production based on the selected geologic data, reservoir parameters and reservoir properties of rocks. Static parameters were analyzed: depth of deposition of the roof of the horizon, average permeability, average porosity, average saturation with oil, initial reservoir pressure and reservoir pressure for 35 oil fields. These fields were preselected as fit for miscible CO_2-EOR method.

3.1. Geologic parameters of selected oil deposits

The basic factor deciding about the possibility of using miscible CO_2-EOR method is the depth of deposition. The average depth of deposition of oil deposits in Poland is 2314 m (Tab. 2). The standard deviation equals to 750 m. This parameter has an average variability. The distribution of deposit depth is asymmetrical on the left. Most of the deposits are found at depths which are higher than average. The kurtosis value proves a weak depth concentration around the average (Fig. 1)

The most shallow are oil deposits in the Carpathians and Carpathian Foredeep, on average at 1539.5 m; at a considerable variation of these values the standard deviation equals to 897 m. The minimum depth of deposition equals to 598 m, the maximum to 3513 m (Tab. 3). Most of the deposits lie lower than at average depths (right-handed asymmetry). The concentration of depth of deposition is observed around the average. The depth of deposition in the Carpathians and Carpathian Foredeep is highly variable.

Table 2

Statistical parameters of reservoir rock properties and reservoir parameters of oil deposits in Poland

Parameters/properties	Sample size	Mean	Median	Minimum	Maximum	Standard deviation	Coefficient of variation	Skewness	Kurtosis
Geological parameters									
Depthu [m]	35	2314.29	2526.70	598.00	3513.00	750.80	32.44	–0.71	–0.23
Average thickness [m]	35	24.90	14.33	2.00	267.00	47.43	190.51	4.48	21.47
Reservoir parameters									
Original reservoir pressure [MPa]	35	34.27	30.66	6.40	67.98	17.11	49.93	0.18	–1.11
Reservoir temperature [K]	35	356.49	357.00	299.20	400.85	25.93	7.27	–0.37	–0.27
Reservoir properties									
Average porosity [%]	35	7.89	6.48	1.27	17.10	4.63	58.70	0.41	–1.00
Average permeability [Md]	35	30.11	5.80	0.10	307.60	67.01	222.52	3.34	11.21
Average oil saturation [%]	35	72.62	70.00	46.00	90.00	9.92	13.66	–0.34	0.66

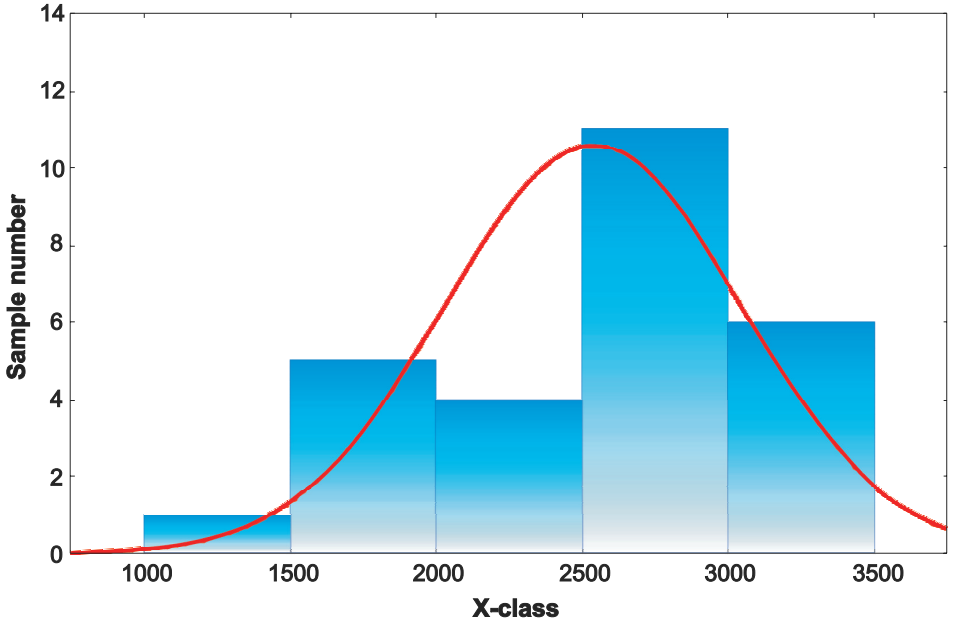

Fig. 1. Distribution of the depth of occurrence of oil fields in Poland

Deposits in the Polish Lowland are deposited on average at 2539.9 m, with the standard deviation of 508 m, the minimum depth of deposition of 1433 and maximum 3559.7 m (Tab. 4). Most of deposits lie at higher depths than the average depth of deposition (left-handed asymmetry). The depth is observed not to concentrate around the average. This parameter has low variability in the Polish Lowland.

The thickness of oil deposits strongly varies, the average for all deposits is about 25 m, and very high standard deviation 47.4 m. This parameter is extremely variable. The distribution of thickness is asymmetrical on the right side (Tab. 2). Most of deposits have lower thickness than the average. The kurtosis value proves the lack of thickness concentration around the average (Fig. 2).

The thickness of deposits in the Carpathians and the Carpathian Foredeep are on average equal to 54 m, and for a considerable variability of these values the standard deviation equals to 89.5 m. The minimum thickness of deposit is 4.2 m and the maximum equals to14.5 m. The distribution of deposit thickness is asymmetrical on the right hand side. Most of the deposits have thickness lower than average. The kurtosis value proves the concentration of thicknesses around the average. This parameter is extremely variable in deposits of the Carpathian and Carpathian Foredeep (Tab. 3).

The deposits in the Polish Lowland have average thickness of 14.9 m, standard deviation 9.2 m, minimum thickness 2 m and maximum thickness equal to 48.5 m. The distribution of thickness of deposits is asymmetrical on the right side. Most of the deposits have lower thickness than the average. The kurtosis value proves the concentration of thickness values around the average. This parameter strongly varies in the Polish Lowland (Tab. 4).

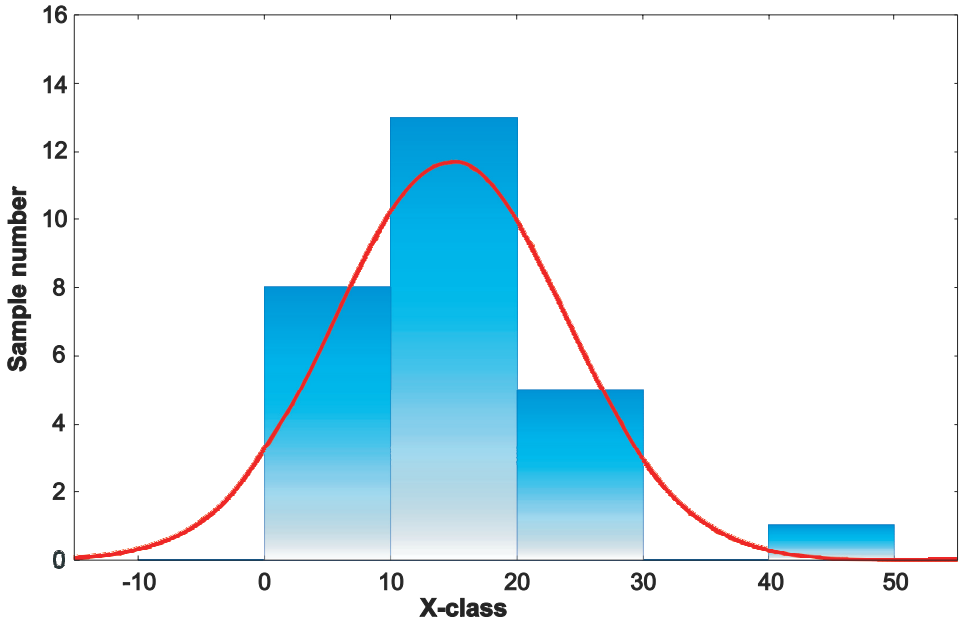

Fig. 2. Distribution of the thickness of oil fields in Poland

3.2. Reservoir parameters of selected oil deposits

Reservoir pressure is a parameter which decides about the applicability of a suitable CO_2 injection method. In the miscible method its value should be higher than the minimum miscibility pressure.

In the Polish oil deposits the initial reservoir pressure was on average 34.3 MPa, at a standard deviation of 17.1 MPa. The maximum measured entry reservoir pressure was 67.9 MPa, and minimum 6.4 MPa. This parameter has a considerable variability. In most deposits the entry reservoir pressure is higher than the average (left asymmetry) (Fig. 3). The values are observed on to concentrate around the average (Tab. 2).

The average initial values of reservoir pressure in oil deposits in the Carpathians and Carpathian Foredeep is 15.8 MPa, at standard deviation of 9.0 MPa. He maximum measured entry pressure is 35.7 MPa, and minimum 6.4 MPa. This parameter is strongly variable. Most of deposits have a pressure lower than the average (right asymmetry). The values tend to concentrate around the average (Tab. 3).

The initial pressure in oil deposits in the Polish Lowland equals to 15.0 to 67.9 MPa, on average 39.7 MPa, at a standard deviation of 14.9 MPa. This parameter has medium variability. The pressure values are under the average (right asymmetry). The values do not concentrate around the average (Tab. 4).

Another very important parameter it temperature as it significantly influences the applicability of the miscible CO_2-EOR method.

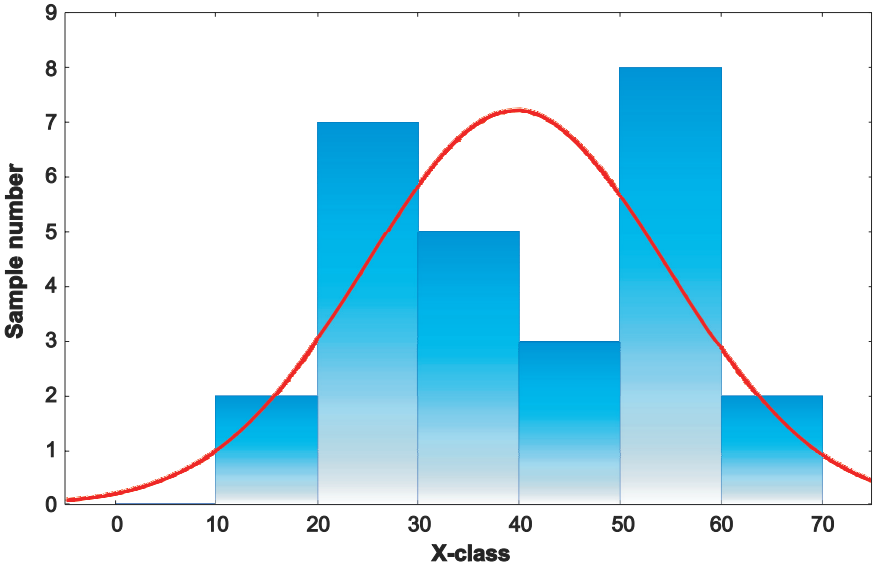

Fig. 3. Distribution of the initial reservoir pressure of oil fields in Poland

Then average temperature in Polish oil fields equals to 356.5 K, at a standard deviation equal to 25.9 K. The maximum and minimum measured temperatures equaled to 400.9 K and 299.2 K, respectively. This parameter has low variability. In most deposits the reservoir pressure has lower values than the average (right asymmetry) (Fig. 4). No temperature concentration around the average is observed, either (Tab. 2).

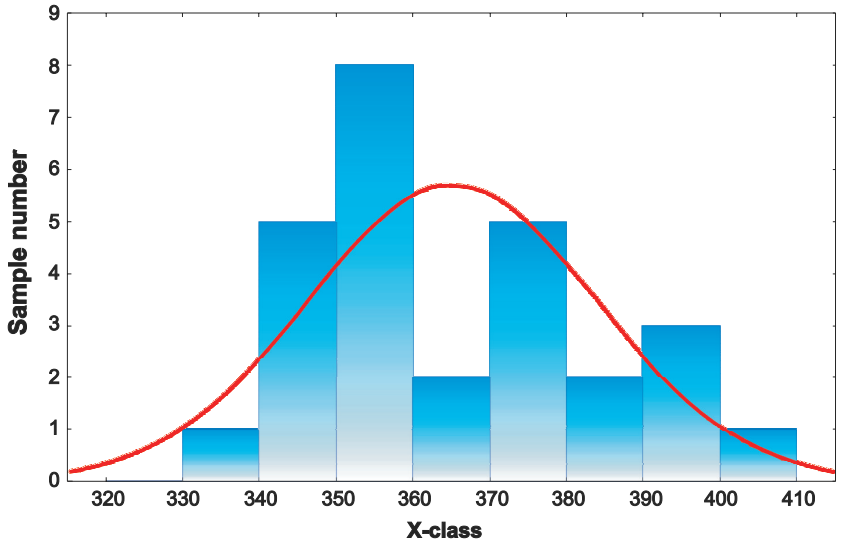

Fig. 4. Thereservoir temperature distribution in oil fields in Poland

Table 3

Statistical parameters of reservoir rock properties and reservoir parameters of oil deposits on the Carpathians and the Carpathian Foredeep

Parameters/properties	Sample size	Mean	Median	Minimum	Maximum	Standard deviation	Coefficient of variation	Skewness	Kurtosis
Geological parameters									
Depth [m]	9	1539.46	1433.00	598.00	3513.00	897.29	58.29	1.37	2.38
Average thickness [m]	9	54.00	14.50	4.20	267.00	89.46	165.67	2.15	4.30
Reservoir parameters									
Original reservoir pressure [MPa]	9	15.78	13.40	6.40	35.70	9.04	57.28	1.43	2.36
Reservoir temperature [K]	9	328.01	325.00	299.20	378.15	24.63	7.51	0.98	0.88
Reservoir properties									
Average porosity [%]	9	8.74	9.30	3.60	14.61	3.50	40.00	0.12	–0.53
Average permeability [Md]	9	77.13	26.45	0.55	307.60	116.40	150.91	1.60	1.02
Average oil saturation [%]	9	69.78	68.00	46.00	86.00	13.41	19.22	–0.52	–0.41

Table 4

Statistical parameters of reservoir rock properties and reservoir parameters of oil deposits on the Polish Lowlands

Parameters/properties	Sample size	Mean	Median	Minimum	Maximum	Standard deviation	Coefficient of variation	Skewness	Kurtosis
Geological parameters									
Depth [m]	27	2539.93	2691.80	1433.00	3159.70	508.52	20.02	–0.67	–0.63
Average thickness [m]	27	14.85	14.33	2.00	48.45	9.19	61.89	1.93	6.08
Reservoir parameters									
Original reservoir pressure [MPa]	27	39.72	33.38	15.00	67.98	14.93	37.57	0.12	–1.33
Reservoir temperature [K]	27	365.10	359.15	332.65	400.85	18.89	5.17	0.35	–0.98
Reservoir properties									
Average porosity [%]	27	7.76	6.00	1.27	17.10	4.97	64.02	0.46	–1.14
Average permeability [Md]	27	14.90	5.75	0.10	101.00	26.51	177.93	2.82	7.50
Average oil saturation [%]	27	73.83	70.00	54.90	90.00	8.43	11.42	0.22	0.44

In oil deposits localized in the Carpathian Foredeep and Carpathians the average temperature is 328.0 K, at standard deviation 24.6 K. The maximum and minimum measured temperatures are 378.2 K and 299.2 K, respectively. This parameter is slightly variable. Most of deposits have lower temperatures than the average (right asymmetry). Temperature values are observed to concentrate around the average value (Tab. 3).

The temperature in oil fields in the Polish Lowland take the values from 332.7 to 400.9 K, on average 359.2 K, at standard deviation 18.9 K. This parameter has low variability. Most of the temperatures are above the average (left asymmetry). No concentration of temperature values around the average is observed (Tab. 4).

The reservoir parameters (porosity, permeability, saturation) of rocks containing oil are frequently accounted for in the evaluation of applicability of advanced production methods.

The porosity of oil deposits in Poland considerably varies, on average 7.9%, at a considerable standard deviation equal to 4.6%. This parameter is highly variable. The distribution of porosity of reservoir rocks is asymmetrical on the right (Tab. 2). The porosity of most deposits is lower than the average. The kurtosis value proves the lack of concentration of porosity values around the average (Fig. 5).

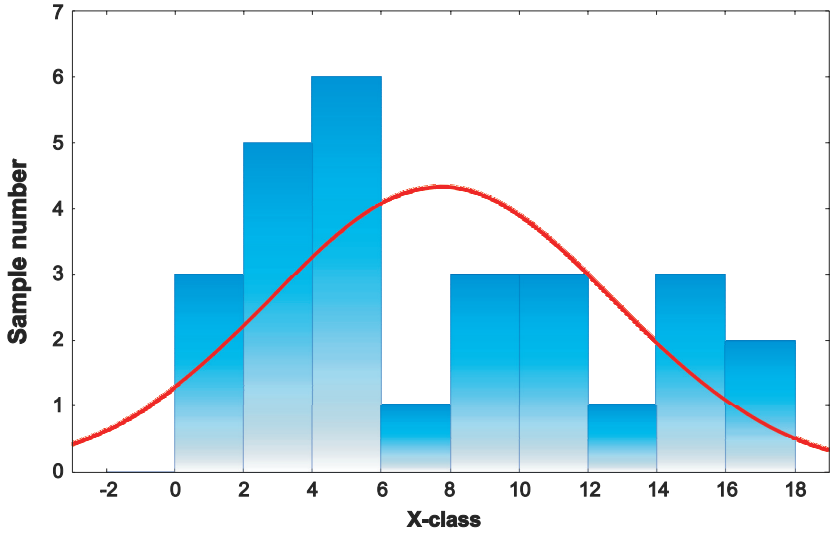

Fig. 5. Distribution of porosity reservoir rocks in oil fields in Poland

The porosity of deposits in the Carpathians and Carpathian Foredeep is on average 8.7%, at a considerable standard deviation of 3.5%. The minimum and the maximum porosity values equal to 3.6% and 9.6%, respectively. The distribution of porosity of deposits is asymmetrical on the right side. The porosity of most deposits is lower than the average. The kurtosis value proves that the porosity values concentrate around the average. This parameter in the deposits of the Carpathians and Carpathian Foredeep has medium variability (Tab. 3).

Deposits in the Polish Lowland have average porosity of 7.8%, standard deviation 5%, minimum porosity 1.3% and maximum porosity 17.1%. The distribution of porosity is asymmetrical on the right side. Most deposits have lower porosity than the average. The kurtosis value proves a concentration of porosity values around the average. This parameter in the deposits of the Polish Lowland is highly variable (Tab. 4).

The average permeability in oil deposits in Poland is 30.1 mD, at a very high standard deviation 67.0 mD. The maximum and minimum permeability of reservoir rocks equals to 307.6 mD and 0.01 mD, respectively. This parameter is extremely variable. In most deposits permeability has lower values than the average (right asymmetry) (Fig. 6). The lack of concentration of permeability values around the average is observed (Tab. 2).

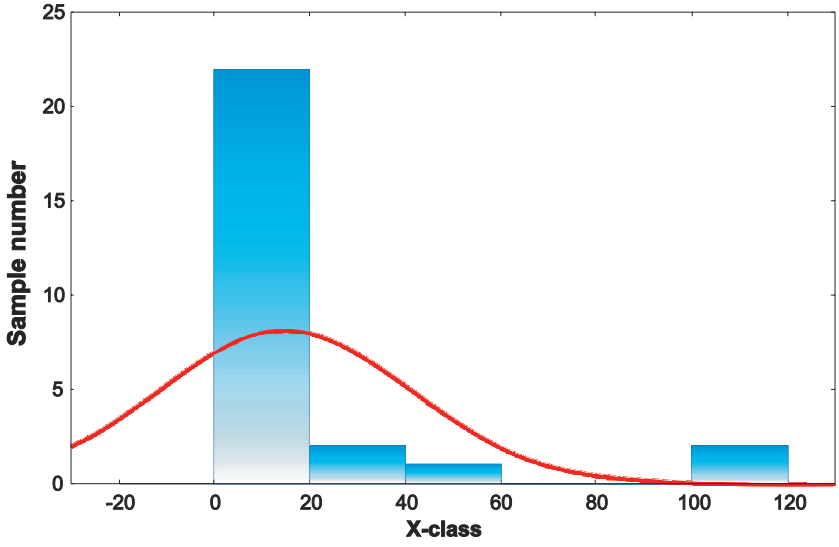

Fig. 6. Distribution of permeability reservoir rocks in oil fields in Poland

In oil deposits in the Carpathians and Carpathian Foredeep the average permeability equals to 77.1 mD, at standard deviation 116.4 mD. Maximum and minimum permeability values equal to 307.6 mD and 0.6 mD, repsectively. This parameter is extremely variable. Most deposits have lower permeability than the average (right asymmetry). Permeability values are observed to concentrate around the average (Tab. 3).

Permeability of Polish oil deposits in the Polish Lowland ranges from 0.1 to 101.0 mD, the average equals to 14.9 mD, at standard deviation of 26.5 mD. This parameter is extremely variable. The permeability of most deposits is lower than the average (right asymmetry). The permeability values tend to concentrate around the average (Tab. 4).

The average saturation of reservoir rocks with oil for all deposits equals to 72.6%, at standard deviation of 9.9%. This parameter has low variability. Saturation of rocks with oil is asymmetrical on the left (Tab. 2). The saturation of most deposits is lower than the average. The kurtosis value proves the concentration of saturation values around the average (Fig. 7).

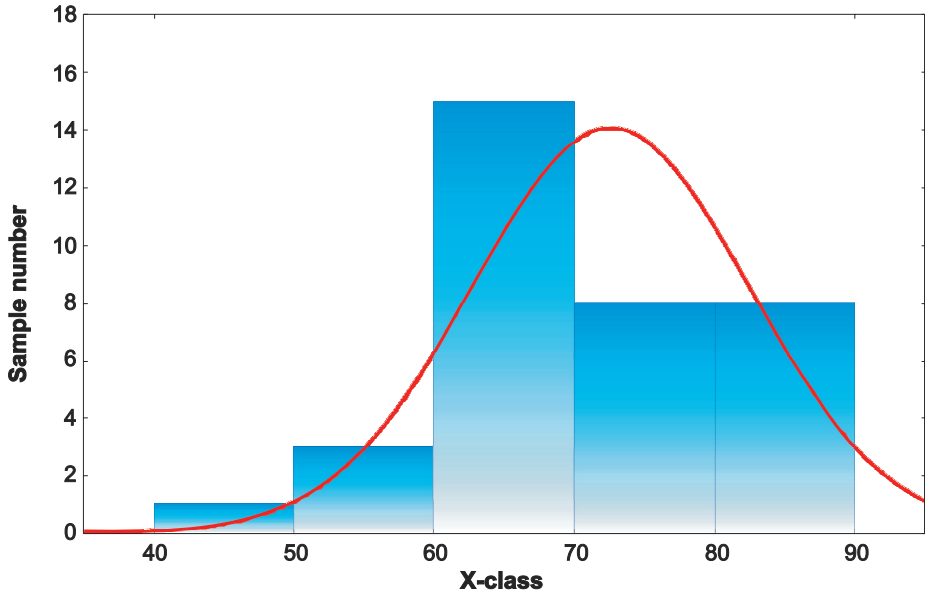

Fig. 7. Distribution of oil saturation of reservoir rocks in oil fields in Poland

Deposits in the Carpathians and Carpathian Foredeep have an average saturation of 69.8%, at standard deviation of 13.4%. Minimum and maximum saturation equals to 46% and 68%, respectively. The distribution of oil saturation is asymmetrical on the left side. The saturation of most deposits is higher than average. Kurtosis values prove the lack of concentration of saturation values around the average. This parameter is little variable for the Carpathian and Carpathian Foredeep area (Tab. 3).

The average oil saturation in the Polish Lowland is of 73.8%, standard deviation 8.4%, minimum and maximum saturation with oil of 54.9% and 90%, respectively. The distribution of satoration of reservoir rocks with oil is asymmetrical on the right, and the saturation in most deposits is higher than the average value. The kurtosis value proves that the saturation values concentrate around the average. In the Polish Lowland this parameter has low variability (Tab. 4).

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