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THE RESULTS OF DOUBLE-CYCLE DRILL STEM TEST DST OF THE MALM CARBONATE ROCKS OF THE CARPATHIAN FOREDEEP**

In the nineties of the twentieth century, intensive work boring for deposits of oil and natural gas in the area of the Carpathian Foredeep, especially in the area between Rzeszów and the Bochnia. The search is carried out among others in the levels of carbonate reservoir rocks separated Malm well logging methods in the profiles of boreholes [5–7]. Designated prospective levels were tested by DST to assess their productivity. DST tests were performed mostly in open hole sections of boreholes and rarely in cased hole – after earlier borehole casing perforations. Probes used American Standard company Halliburton and Baker Inflatable type. During testing of Malm reservoir rocks in approximately 75% was used double-cycle drill stem test DST [3].

Due to renewed interest of the Polish Oil and Gas Company in petroleum prospection of Malm sediments, it is appropriate to use in the petroleum exploration results obtained thus far from industrial research double cycle DST reservoir testing. This provides, among others to modification of drilling technology and to sampling of Malm sediments in the planned boreholes.

1. ANALYSIS OF TECHNOLOGICAL PARAMETERS OF DOUBLE-CYCLE TESTS ON RESERVOIRS WITH DRILL STEM TESTERS

Technological parameters of double-cycle drill stem tests (DST), mainly the initial pressure depression, time of reservoir fluid flow and time of repression can have significant

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influence on the quality of obtained results, therefore their values have been thoroughly analyzed.

There were analysed 25 double-cycle drill stem tests on the Malmian carbonates in the basement of the Carpathian Foredeep in open hole and also in cased hole and perforated parts of the wells (Tab. 1).

In the double-cycle tests the results obtained in the first and in the second cycle can be compared. The times of performing the first and the second cycle were so selected that the radius of the reservoir zone investigated in the second cycle was much bigger than the one in the first cycle. This allows for evaluating changes in reservoir conditions in the closer and further parts of the near-wellbore area, i.e. [1]:

- change of permeability of reservoir rocks in closer and more distant parts of the near-wellbore area,
- change of yield index;
- relieving the given horizon of reservoir rocks from the repression of the column of drilling mud.

The time of testing of an open section of a borehole is determined by the time in which DST can safely stay on the bottom of the hole. Each test time is determined with a special prevention time test, thanks to which DST sticking can be avoided. Accordingly, in the first cycle there was performed a short flow test t_1 = 7–61 min (Tab. 1, column 8) and slightly longer test of the first pressure build-up Δt_1 = 22–62 min (Tab. 1, column 10). The analyzed reservoir rock horizon was relieved from the drilling mud repression in the course of drilling in the formation; the build-up pressure in the analyzed cases was 0.73–4.57 MPa (Tab. 1, column 4), with arithmetic average of 2.71 MPa.

The analysis of industrial data revealed that thanks to the good preparation of the well for DST (workover and washing of the well) the time of the second cycle of the drill stem tester could be safely elongated, without any risk of sticking in the open part of the well. For this reason the flow test in the second cycle stayed within a large interval of t_2 = 14–205 min (Tab. 1, column 9). During the second flow test, attention was focused mainly on obtaining a representative volume of formation fluid in the DST (about 0.5–4 m^3). The time of the second build-up test in the second cycle, Δt_2 = 48–153 min, was selected mainly in view of obtaining the longest radius of the analyzed zone (R_{b2}). The value of the radius was $R_{b2} \approx$ 3–315 m (Tab. 2, column 10), in open parts of the well, and R_{b2} = 10–786 m in cased and perforated intervals.

The specific times of drill stem tests in cased and perforated intervals of wells were much longer, i.e. (Tab. 1): t_1 = 25–209 min; t_2 = 40–1363 min; Δt_1 = 70–110 min; Δt_2 = 93–834 min, respectively.

It should be noted that in the course of drill stem testing of the Malmian reservoir rocks of fracture-pore type, the fractures may close up and the intensity of flow of formation fluid to DST can be limited under the influence of too big repression. The saturation of near-wellbore zone with water and relative water permeability of reservoir rocks may also increase.

Table 1
Technological parameters of double-cycle drill stem tests DST of Malm carbonate rocks

No.	Well No. of test DST	Interval [m] type of sampling open hole (oh) or cased hole (ch)	Static repression of mud [MP]	Technological parameters of test DST						
				The height of the water column [m]; / d_{zw} [mm]	Initial depression [MPa]	The value of depression to repression ratio	Time of tide [min]		Time of bilt up [min]	
							t_1	t_2	Δt_1	Δt_2
1	2	3	4	5	6	7	8	9	10	11
1	Ż-42; 49/97	1483–1492; oh	2.05	215	12.42	6.2	28	83	61	127
2	W-16; 52/97	1868–1904; oh	2.48	412	14.56	5.9	37	89	60	125
3	Ż-42; 53/97	1635–1701; oh	4.59	200	12.83	2.8	30	91	61	153
4	Z-5; 8/96	1178–1230 oh	3.88	110	9.35	2.4	10	14	43	68
5	Z-8 47/96	1280–1299; oh	3.75	300	9.08	2.8	19	51	40	123
6	T-1; 77/96	2692–2710 ch 7"	2.06	417	22.20	10.8	25	625	95	834
7	J-3; 89/96	1494–1525 oh	1.44	300	11.50	8.0	13	53	34	67
8	K-4; 114/96	657–702; oh	0.73	102	5.40	9.0	18	34	62	121
9	B-5; 22/95	1533–1549; n.o.	2.62	475	6.81	2.6	18	72	46	125
10	T-71; 28/95	1824–1853 oh	2.81	500 / 10	13.10	4.7	7	65	22	55
11	B-5; 30/95	1558–1576; oh	2.68	250	12.75	5.5	7	57	31	134
12	T-1; 61/95	2696–2720; oh	3.51	700 / 10	19.51	5.6	15	205	37	79
13	Ł-19; 76/95	1484–1503 oh	1.85	300	11.45	6.2	10	54	27	69
14	Ł-19; 79/95	1516–1533 oh	1.92	310	11.80	6.0	9	92	60	91
15	B-5AK; 97/95	1655–1671 oh	2.87	300 / 8	11.60	4.0	21	196	44	141
16	Z-4; 114/95	1324–1376 oh	2.42	190	10.41	4.3	8	26	29	63
17	Z-7; 147/94	1234–1319 oh	1.58	270 / 10	8.41	5.3	15	35	30	59
18	Z-7 152/94	1250–1264 oh	1.61	350 / 8	8.09	5.0	9	58	30	71
19	Ż-1; 63/93	1491–1540 oh	3.2	450	10.17	3.2	19	39	44	60
20	Z-5k; 81/93	2422–2489; oh	3.88	300	19.88	5.1	18	56	44	48
21	Z-5k; 99/93	2360–2382; ch 7"	3.22	500	14.90	4.6	209	117	110	125
22	Z-5k; 110/93	2238–2248 ch 7"	4.11	360 / 10	20.43	5.0	133	40	70	128
23	W-38; 142/93	2207–2241 oh	2.72	500 / 8	16.63	6.1	61	28	29	75
24	R-2; 153/93	1139–1210 oh	2.88	520 / 10	7.44	2.6	18	83	61	82
25	W-38; 166/93	2305–2314 ch 7"	2.95	635	13.40	4.5	92	1363	88	93

In the analyzed reservoir tests, the initial value of depression exerted on the analyzed gas- and water-bearing horizons was decreased by water cushion 100–700 m high, applied in the tester column in view of the depth of deposition of a given horizon. An increased counterpressure on reservoir was built up at the very beginning of the first flow test. Thanks to the use of thus increased counterpressure, the initial values of depression are lower, i.e. 5.4–19.51 MPa, respectively (Tab. 3, column 6).

During drilling the permeability of reservoir rocks in the near-wellbore zone decreases as a result of colmatation of their porous space with solids from the drilling mud (clayey particles, salt, corrosion, polymers, cuttings). Therefore, to provide good cleaning of rocks in that zone from solids, the selected value of initial depression during the reservoir tests was several times higher than the drilling mud pressure build up during prior drilling operations in the formation. The calculated value of depression to repression ratio vastly ranged from 2.4–10.8 (Tab. 1, column 7).

2. ANALYSIS OF CHANGES IN PERMEABILITY OF MALMIAN CARBONATES IN AREAS ANALYZED WITH DST, ON THE BASIS OF DOUBLE-CYCLE DRILL STEM TESTS

The double-cycle technology of reservoir testing with DST is advantageous as it creates possibility of evaluating changes in the permeability of reservoir rocks on the basis of calculated skin-effect; in this way the character and magnitude of permeability changes of reservoir rocks can be assessed in the analyzed zones. The results of calculations for the first and the second cycle made with the Horner method are listed in Table 2: efficient permeability coefficient for rocks k_1 and k_2; skin-effect S_1 and S_2; radius of area analyzed in the first and in the second cycle R_{b1} and R_{b2}.

The Horner method is based on interpretation of the results of build-up tests in a single--logarithmic coordinates system, accounting for the principle of superposition [2]. The downhole build-up tests on the Malmian formation were interpreted (over 60 min duration) with the log-log method based on the interpretation of the results of pressure build-up tests in a double-logarithmic system, accoutning for the value of the first derivative of bottomhole pressure increases in the function of repressure time increases [4].

The skin-effect index expresses a drop of bottomhole pressure for overcoming hydraulic pressure losses of fluid in the analyzed zone (when the permeability of rocks in that zone is damaged) or decreasing that drop as compared with the original conditions (when the permeability of rocks is improved), caused by, e.g. washing of that zone [8]. If $S = 0$, no permeability changes of rocks in the study area are observed; for $S > 0$, the permeability of the analyzed rocks is damaged (lowered). If $S < 0$, the permeability of rocks improves with respect to their original permeability.

Table 2

The results of double-cycle drill stem test DST of the Upper Jurassic carbonate rocks derived from the interpretation of the recovery curves by Horner

No.	Well No. of test DST	The test interval (open hole oh) [m]	Type of fluid flowing to the DST	The results of double-cycle drill stem test DST						
				$k_1 \cdot 10^{-15}$ [m^2]	S_1 [+, –]	R_{b1} [m]	$k_2 \cdot 10^{-15}$ [m^2]	S_2 [+, –]	R_{b2} [m]	The results of the analysis of the relation S_1 to S_2; k_1 to k_2
1	2	3	4	5	6	7	8	9	10	11
1	Ż-42; 49/97	1483–1492 oh	brine gassed	39.30	+29	134	57	+21	231	Self-cleaning during the test
2	W-16; 52/97	1868–1904 oh	brine gassed	22	+56	83	34.80	+41	165	Self-cleaning during the test
3	Ż-42; 53/97	1635–1701 oh	brine gassed	129	+64	234	122	+50	315	Changes in facies or tectonic
4	Z-5; 8/96	1178–1230 oh	mud and brine gassed	1.20	+3	7	3.85	–2	21	Self-cleaning during the test
5	Z-8 47/96	1280–1299 oh	mud and brine without a trace gas	2.10	+2	22	6.80	–2.6	56	Self-cleaning during the test
6	T-1; 77/96	2692–2710 cased 7"	brine gassed	5.20	–2	48	28	+5	519	Changes in facies or tectonic
7	J-3; 89/96	1494–1525 oh	brine without a trace gas	2.30	+25	11	11.40	+3	71	Self-cleaning during the test
8	K-4; 114/96	657 – 702; oh	brine without a trace gas	3.50	+5	22	1.17	–4.4	122	Changes in facies or tectonic
9	B-5; 22/95	1533–1549 oh	mud. brine and oil gassed	0.75	+12	1.5	1.20	–2	5	Self-cleaning during the test
10	T-71; 28/95	1824–1853 oh	mud and oil gassed	0.20	+25	3	0.44	–2	25	Self-cleaning during the test
11	B-5; 30/95	1558–1576; oh	brine gassed	7	+15	27	50	+35	230	Changes in facies or tectonic
12	T -1; 61/95	2696–2720 oh	brine gassed	8	+25	42	71	+5	20	Self-cleaning during the test
13	Ł-19; 76/95	1484–1503 oh	brine gassed	2.10	+35	12	10	+12	81	Self-cleaning during the test
14	Ł-19; 79/95	1516–1533 oh	brine with traces of gas	0.40	+10	4	0.80	0	23	Self-cleaning during the test
15	B-5AK; 97/95	1655–1671 oh	mud and oil-water emulsion	0.01	+15	0.6	0.02	+1	3	Self-cleaning during the test
16	Z-4; 114/95	1324–1376 oh	mud and brine gassed	145	+73	96	98	+22	160	Changes in facies or tectonic
17	Z-7; 147/94	1234–1319 oh	mud and brine gassed	5	+12	15	13	+5	69	Self-cleaning during the test
18	Z-7; 152/94	1250–1264 oh	mud without a trace gas	0.45	+25	8.5	0.65	+15	15	Self-cleaning during the test
19	Ż-1; 63/93	1491–1540 oh	brine with traces of gas	16	+42	58	28	+7	130	Self-cleaning during the test
20	Z-5k; 81/93	2422–2489 oh	brine gassed	52	+25	110	54	–5	110	Self-cleaning during the test
21	Z-5k; 99/93	2360–2382 cased 7"	mud and brine gassed	22	+56	180	117	+15	567	Self-cleaning during the test
22	Z-5k; 110/93	2238–2248 cased 7"	brine gassed	305	+72	841	205	+11	786	Changes in facies or tectonic

Table 2 cd.

No.	Well No. of test DST	The test interval (open hole oh) [m]	Type of fluid flowing to the DST	The results of double-cycle drill stem test DST						
				$k_1 \cdot 10^{-15}$ [m^2]	S_1 [+, –]	R_{b1} [m]	$k_2 \cdot 10^{-15}$ [m^2]	S_2 [+, –]	R_{b2} [m]	The results of the analysis of the relation S_1 to S_2; k_1 to k_2
23	W-38; 142/93	2207–2241 oh	brine with traces of gas	2	–5	50	1.40	+2	45	Secondary damage
24	R-2; 153/93	1139–1210 oh	brine with traces of gas	0.40	+5	8	0.80	+2	24	Self-cleaning during the test
25	W-38; 166/93	2305–2314 cased 7"	brine gassed	0.15	–1	5	0.10	–2	10	Changes in facies or tectonic
26	Sz-5; 160/94	830–843 oh	brine gassed	35	+10	45	180	+8	250	Self-cleaning during the test
27	Ł-2; 36/93	2652–2752 oh	mud and brine gassed	1.50	–4	14	5	–5	87	Self-cleaning during the test

The following causes of permeability changes in the Malmian reservoir rocks in the zones subjected to drill stem tests can be drawn on the basis of the results of analysis of relation of S_1 to S_2 and effective permeability k_1 to k_2 (Tab. 2):

– spontaneous self-cleaning of reservoir rocks under the influence of pressure depression, based on the relations: $S_1 > S_2$ and $k_1 < k_2$;
– secondary damage of permeability of reservoir rocks in analyzed zones, based on relations: $S_1 < S_2$ and $k_1 > k_2$;
– facial or tectonic changes of horizons of Malmian reservoir rock in the second zone as compared to the first zone, based on relations:
  a) $S_1 > S_2$ and $k_1 > k_2$,
  b) $S_1 < S_2$ and $k_1 < k_2$.

Case 1 covers the most numerous group of results of analyzed tests (19). The observed self-cleaning of the Malmian reservoir rocks of solid particles introduced by the drilling mud in the course of drilling up operations is confirmed by the drilling mud returning to the borehole with the formation fluid in nine analyzed reservoir tests (Tab. 2). The corresponding values of repression of hydrostatic pressure in the course of drilling up of the Malmian reservoir rocks range from 1.4 MPa to 3.88 MPa (Tab. 1), which evidences that the applied drilling mud was too thick and thus more liable to penetrate the near-wellbore zone.

Case 2 was observed only during one test. The secondary damaging of permeability of the Malmian reservoir rocks within the zone of drill stem tests can be a result of colmatation of those rocks the near-wellbore zone with solids (e.g. drilling mud particles, salt) transported by formation fluid flowing towards the well under the influence of pressure depression formed during the test. The initial value of this depression was 13.4 MPa (Tab. 1, line 25).

Case 3, encountered in 7 reservoir drill stem tests, can be caused by the presence of facial or tectonic boundaries in the analyzed Malmian horizons. The influence of those boundaries usually dominates, and the results of self-cleaning of rocks is of secondary importance.

3. FINAL CONCLUSIONS

1) In the 1990s the repression of drilling mud pressure used in boreholes when drilling up the Malmian reservoir rocks was considerable, i.e. on average over 2 MPa. This frequently resulted in penetration of fractured-porous Malmian formation with drilling mud and its return to the borehole during the reservoir tests at about three (or more) times bigger values of pressure depression. This had a negative effect on the reliability of results of drill stem tests.
2) A comparative analysis of interpretation results of repressure plots from the first and the second cycle of a given drill stem test, mainly the skin-effect (S_1 and S_2) and effective permeability of rocks (k_1 and k_2) in the analyzed zones (Tab. 2), creates bases for conclusions on the causes of changes in the permeability of reservoir rocks in the zone of drill stem tests. This gives opportunity to modify the technology of drilling up and testing of the Malmian formation in the planned boreholes.

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