Nafta-Gaz 2023, no. 9, pp. 567–575, DOI: 10.18668/NG.2023.09.01

The modification of filtration properties of porous media using Multizol micellar treatment fluid

Modyfikacja właściwości filtracyjnych ośrodków porowatych z wykorzystaniem micelarnej cieczy zabiegowej Multizol

Marcin Majkrzak[1, 2], Sławomir Falkowicz[1], Winicjusz Stanik[1]

[1] *Oil and Gas Institute – National Research Institute*
[2] *AGH University of Science and Technology, Faculty of Drilling, Oil and Gas*

ABSTRACT: The need for the modification of filtration properties of rock media (most frequently porous rocks) appears frequently, e.g., in hydrocarbon exploitation. Exploitation of crude oil and natural gas is frequently accompanied by an excessive and uncontrolled inflow of reservoir water to the production well, which often results in a significant reduction of hydrocarbon production in the late period of reservoir exploitation. The control of water inflow, through modification treatments of rock filtration properties of the near wellbore zone, is the solution to this problem. The use of dedicated treatment fluids is the basis of such success, which, after the injection and change of original physicochemical properties, create local insulation barriers, enabling the control of the flow of fluids in the geological formation. This paper presents the results of the laboratory assessment of the technological effectiveness of Multizol micellar treatment fluid, which is used for selective blocking of the reservoir water inflow to gas wells. Tests performed, at a preliminary stage, comprised the development of a procedure, the obtaining of samples of the treatment fluid, and the performance of flow tests in test glass tubes, which allow for a swift determination of the technological range of the fluid's capability to form gel and emulsion. Flood tests were the main element of testing, related to the measurement of pressure drops of fluids flowing through the sample under the simulated reservoir conditions. The tests were carried out using two types of media, porous rocks (Szydłowiec sandstone) and sand packs. The determination of the modification degree of filtration properties, both in individual zones and in the entire sample/model, was based on the value of the F_{RR} (*Residual Resistance Factor*) coefficient, being the measure of their permeability reduction. Two types of tests were performed to assess the effect of Multizol treatment fluid on the initial filtration properties of gas and water-bearing zones.

Key words: natural gas exploitation, water inflow, permeability modification, flood tests, microemulsion.

STRESZCZENIE: Potrzeba wykonania zabiegów modyfikacji właściwości filtracyjnych ośrodków skalnych (najczęściej skał porowatych) pojawia się często m.in. w pracach związanych z otworową eksploatacją węglowodorów. Wydobyciu ropy naftowej i gazu ziemnego niejednokrotnie towarzyszy nadmierny i niekontrolowany dopływ wody złożowej do odwiertu produkcyjnego, czego bezpośrednim efektem jest (szczególnie w późnym okresie eksploatacji złoża) znaczne ograniczenie produkcji węglowodorów. Kontrola dopływu wody, poprzez zabiegi modyfikacji właściwości filtracyjnych skał strefy przyodwiertowej, stanowi rozwiązanie tego problemu. Podstawą sukcesu tego typu prac jest wykorzystanie specjalnych cieczy zabiegowych, które po zatłoczeniu i zmianie ich pierwotnych właściwości fizykochemicznych miejscowo wytwarzają bariery izolacyjne, umożliwiając kontrolę przepływu płynów w ośrodku geologicznym. W niejszej publikacji przedstawiono wyniki laboratoryjnej oceny skuteczności technologicznej micelarnej cieczy zabiegowej Multizol, przewidzianej do selektywnego blokowania dopływu wody złożowej do gazowych odwiertów eksploatacyjnych. Przeprowadzone badania, na wstępnym etapie, obejmowały opracowanie procedury i uzyskanie próbek cieczy roboczej oraz realizację tzw. testów płynięcia, które pozwoliły na szybkie określenie technologicznego zakresu zdolności badanej cieczy do tworzenia żelu oraz emulsji. Głównym elementem badań były testy przepływowe, dotyczące pomiaru wielkości spadków ciśnień przepływających przez próbkę płynów, przeprowadzone w symulowanych warunkach złożowych. Badania realizowano z wykorzystaniem dwóch rodzajów ośrodków, rzeczywistych skał porowatych (piaskowiec szydłowiecki) oraz modeli sztucznych warstw/złóż zbudowanych z mieszaniny kulek szklanych i piasku kwarcowego. Określenie stopnia modyfikacji właściwości filtracyjnych, zarówno w poszczególnych strefach, jak i na odcinku całej próbki/modelu, oparto na wartości współczynnika F_{RR} (ang. *residual resistance factor*) stanowiącej miarę zmniejszenia ich przepuszczalności. Symulację zabiegu ograniczania dopływu wody wykonano dla strefy gazowej oraz zawodnionej.

Słowa kluczowe: eksploatacja złóż gazu ziemnego, dopływ wody, modyfikacja przepuszczalności, testy przepływowe, mikroemulsja.

Corresponding author: M. Majkrzak, e-mail: *marcin.majkrzak@inig.pl*

Article contributed to the Editor: 15.05.2023. Approved for publication: 25.08.2023.

Introduction

The term modification treatment of porous rocks filtration properties is used to describe the intentional and conscious reduction of their permeability in a specifically defined zone (Cicha-Szot and Falkowicz, 2010). The reduction of flow possibilities of a given reservoir fluid, most frequently water, as a result of the performed treatment, is a complex issue, which comprises many elements. It is necessary to mention among them primarily the proper selection of the treatment fluid for the reservoir conditions, which requires a laboratory assessment of its technological effectiveness, frequently a multi-stage one (Falkowicz et al., 2012; Sengupta et al., 2012). This paper is the result of the work on the laboratory assessment of the effectiveness of modification treatments of filtration properties of porous rocks by the Multizol micellar treatment fluid, developed at the Oil and Gas Institute – National Research Institute.

A high production of reservoir water in the production wells is an example of serious problems, originating during the production of hydrocarbons, which harms the economics of hydrocarbon exploitation (Alfarge et al., 2017). The value of the water index is the measure of production wells flooding. Proper determination of the cause of high values of the index is the underlying reason for success in treatments to control the water inflow (Chan et al., 1996). Unfortunately, in numerous cases, problems were identified incorrectly because of many, frequently interrelated, factors. We can distinguish among them, e.g., the fact that a properly performed diagnosis requires time and generates additional costs, frequently high, which may lead to the abandonment of this stage of work. In addition, it is still possible to encounter an incorrect opinion, that there is only one method for resolving all water inflow problems, or that all the problems have one source. For example, a frequently complex one, and one more difficult to prevent, inflow by a 3D cone is assumed upfront, while an appropriate analysis of the available data can show the real reason, e.g., flow behind casing or a 2D cone. In addition, certain service companies are convinced that they have one universal solution, working for all cases (Seright et al., 2001; Sydansk and Seright, 2007). These and other elements can negatively affect a reliable assessment of the situation, and only this knowledge allows the right 'repair' program to be implemented, ensuring as the highest possible probability of success of the performed treatment, and it can substantially reduce its costs (Ligthelm, 2001).

A properly performed diagnosis of the reasons for the water inflow to the production well enables the selection of the most appropriate method to prevent the recognized problem. The used 'repair' methods may be divided into two types: mechanical and chemical. In chemical methods, special treatment fluids are injected by the well into the reservoir, to reduce the permeability of the wellbore zone in the water-producing layers. The treatments referred to as selective are most accepted by the operators. In this case, without mechanical insulation of separated layers in the perforation interval, the injected treatment fluids, as a result of a series of physicochemical reactions, should restrict the water inflow to the well, without reducing the hydrocarbon inflow at the same time. Such technologies have been systematically developed since the 1920s (Bruce et al., 1997; Zaitoun et al., 1999). The application of RPM (*Relative Permeability Modification*) techniques has been a popular method for the reduction of water production since the beginning of the 1980s. At first, attempts to perform treatments in oil wells were made, and then they were expanded also to gas wells and underground gas storages in porous rocks. These fluids, most often based on polymers, are injected to a depth of 1 to 2 meters into the formation, and absorb on the pore walls, which causes a significant and selective reduction of water-bearing layers permeability (Zaitoun et al., 1991; Zaitoun et al., 2007). In the 1990s, interesting concepts appeared, using fluids made based on microemulsion in treatments of water production control in gas wells (Sobanova et al., 1993), which, in later years, were developed by Hungarian specialists. The developed technology differs substantially from the RPM techniques, mainly in the assumption of a significantly more radical interference in the reservoir and the creation of gel-insulating barriers in the wellbore zone, with a larger reach and at greater depths. Such barriers, under their assumption, are to effectively restrict the water inflow to the well, to be more durable due to the nature of their formation and do not cause losses in the production of hydrocarbons (Lakatos et al., 2014; Lakatos et al., 2016).

Figure 1 presents a diagram of the formation of a gel insulation barrier in the wellbore zone with the use of micellar treatment fluid manufactured based on microemulsion. In

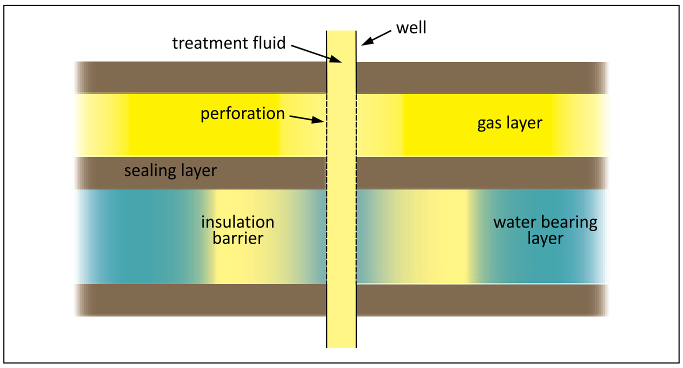


Figure 1. Diagram of gel insulation barrier formation in the wellbore zone of a gas production well, using micellar treatment fluid

Rysunek 1. Schemat wytwarzania żelowej bariery izolacyjnej w strefie przyodwiertowej gazowego odwiertu eksploatacyjnego z wykorzystaniem micelarnej cieczy zabiegowej na bazie mikroemulsji this method, the fluid is injected by the well into the reservoir without using mechanical insulation techniques. This means, in practice, that treatment fluid is injected into the pore space of all perforated layers. The idea of the presented treatment assumes that, as a result of the treatment fluid contact with the reservoir water (at an appropriate proportion) in the wellbore zone of the water-bearing layer, a gel insulation barrier will be formed, reducing the water flow. The discussed technology is based on the phenomenon of microemulsion (treatment fluid) transition from a metastable to stable (gel) state under reservoir conditions and a clear change in the rheological parameters (viscosity increase). Because the inversion of phases cannot occur in low water content, the likelihood of the creation of a barrier in the gas layer is low. On the other hand, the initiation of the gelling process at high contents of reservoir water would result in the lack of possibility to inject the fluid into the water-bearing layer to the technologically expected depth, e.g. from 1.5 to 2–3 meters. Therefore, the treatment fluid, after contact with water, should gel after exceeding a specified threshold of water content. Based on the results of laboratory tests and pilot treatments made in the Algyo reservoir, it was found that it is favorable that the treatment fluid gels (forms a gel) within the range of 20–40% of water content (Lakatos et al., 2016).

The topic of an excessive and uncontrolled inflow of reservoir water to gas production wells, raised in the paper, is a major problem faced by operators worldwide. It frequently causes a drastic reduction in gas production, at a stepwise increase in the costs of works at the same time, which is related mainly to the disposal of the extracted brine. The control (restriction) of water inflow, through modification treatments of filtration properties of the wellbore zone rocks, is one of the methods to resolve this problem. The use of chemical methods for inflow control is the foundation of such treatment success. We refer here to the dedicated treatment fluids which, after the injection to the pore space and change of original physicochemical properties, are capable of local formation of a gel-insulating barrier. The Multizol treatment fluid, developed by Oil and Gas Institute – National Research Institute, is an example of such products. The results of laboratory assessment of its technological effectiveness, presented in the paper, are based on the results of flow tests in test glass tubes and, to a large extent, of flood tests. They comprised preliminary and quick determination of the technological range of Multizol fluid capability to form gel and emulsion and the measurement of intermediate pressure drops of fluids flowing through the sample/model under the simulated reservoir conditions. The flood tests were carried out on the core samples of porous rocks (Szydłowiec sandstone), and sand pack models. The F_{RR} coefficient (*Residual Resistance Factor*), equal to the ratio of permeability before and after the injection of the treatment fluid, was the measure of filtration properties modification. To characterize the wellbore zone fully, the treatment for water inflow reduction was simulated both for the productive (gas) layer and the water-bearing layer.

Methodology

The evaluation of filtration property changes of porous media, with the application of the tested micellar treatment fluid, comprised several actions, from the development of composition and the obtaining of a sample of the fluid, through the performance of frequently complex laboratory assessment of its technological effectiveness. The final element, in the situation of achieving satisfactory results of laboratory tests, should be the implementation of the developed techniques in the form of a full-scale field treatment.

Figure 2 presents the diagram of such work, broken down into individual stages.

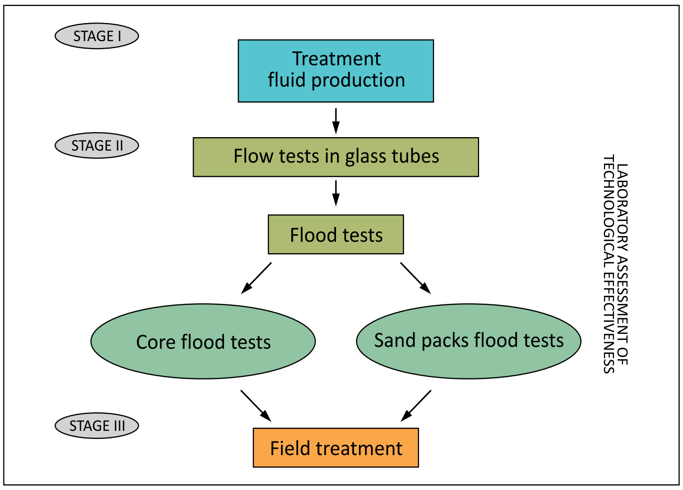


Figure 2. Diagram of the work on the development, assessment, and implementation of the technology for water inflow control

Rysunek 2. Schemat prac opracowania, oceny i wdrożenia technologii kontroli dopływu wody

The development of the laboratory procedure and obtaining samples of fluid intended for treatments was the first stage. An assumption was made that the fluid would be injected into the reservoir without the use of insulation techniques and that its contact (at an appropriate proportion) with the formation water will be the factor initiating the process of gelling. In addition, the developed fluid should have low viscosity and should be safe for the technical personnel and the natural environment.

The laboratory assessment of technological effectiveness required developing and implementing an appropriate testing methodology, in which two main elements should be distinguished, i.e., the flow tests in test glass tubes and the flood tests. The tests comprising the flow tests, allowed for preliminary and quick determination of the technological range of the working fluid capability to form gel and emulsion. Based on this, it was possible to determine whether the tested fluid, due to mixing with brine, would form the gel in the expected range of concentrations. The test performance consisted of mixing (by vigorously shaking) the fluid with brine in test glass tubes at a specified volumetric ratio, from 10% to 30% of brine content, at 5% increments. Test tubes were then placed in a lab rack, which enabled their simultaneous deflection from the vertical, up to achieving a horizontal orientation. After the test tube's deflection (at an angle of approx. 80°), the produced fluid was flowing (or otherwise, if a gel was formed) towards the test tube outlet, and the range of its spreading was a function of the mixture viscosity. The procedure was repeated at specified time intervals (days).

If the results of flow tests were satisfactory, this meant that the fluid in contact with brine formed a gel, the final laboratory verification of its usability for control of water inflow to the wells consisted of so-called flood tests. These were carried out on samples of porous rocks (cores) and sand packs built of a mixture of glass beads and quartz sand. They were aimed at a quantitative evaluation of the fluid effectiveness for the modification of filtration properties of porous media, simulating, if technically possible, the process of control treatment for the water inflow. The flood tests were performed using a test stand by the TEMCO company, which enables measurements of intermediate pressure drops of fluids flowing through the sample under simulated reservoir conditions. In the case of tests on samples of porous rocks, a measurement chamber was the main element of the stand, which enabled the performance of core flood tests on samples 2.54 cm in diameter and a maximum of 15 cm long. Three connections, installed on its side surface, were the key element of the used chamber, enabling the pressure measurements of the fluid injected in specified sample zones. The performance of tests in such a formula enabled a selective assessment of the filtration properties changes in individual parts of the sample, which has translated into the increase in reliability of the obtained results (Dalrymple et al., 2000, Sydansk et al., 2005).

At the same time flood tests were performed on sand packs. This enabled the simulation of the process of barrier formation on a larger scale. In this case, the measurement chamber (Figure 3) was a transparent tube (3), 40 cm long and 2.5 cm in inside diameter, made of poly (methyl methacrylate), in which the building material was placed (4). The tube was closed with aluminum plugs (5), fluids were fed inside it by connectors (1), and further on by stainless steel pipes. To avoid material washout by the flowing fluids through the outlet in the sealing plug, a decision was made to apply a filtration screen (2) on both sides of the model, consisting of a material with a larger grain size. In addition, between the filtration screen and sealing plugs, an aluminum protecting mesh (7) was placed, with a mesh size that made it impossible for the grain material outside the model to move. For a selective assessment of the filtration properties changes in individual parts of the model, three connections (6) were installed, as in the measurement chamber for the core flood tests (Majkrzak, 2017).

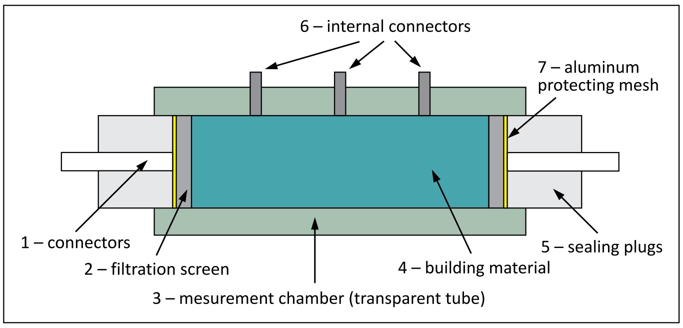


Figure 3. Test stand for conducting tests on the sand pack model

Rysunek 3. Stanowisko badawcze do prowadzenie testów na modelach sztucznych ośrodków porowatych

The construction diagram of the measurement holder, presented in Figure 3 and Figure 4, clearly visualises the method of multi-tap measurements of pressure drops for a selective assessment of the filtration properties of the tested porous media. In this method, within the determined zones (I–IV), based on the reading of the values of pressure drops (ΔPI – ΔPIV) of the fluid flowing through the pore space, it is possible to determine the filtration properties of the medium along its longitudinal axis. The clearly higher, as compared with the rest of the sample, values of the pressure gradient of the flowing fluid are recorded in zones with low values of the filtration coefficient (Dalrymple et al., 2000). It is very important to be aware of the place of possible natural 'restrictions' for the occurrence of fluid flow for the proper interpretation of laboratory results of the assessment of modification treatments of filtration properties, in particular, in the assessment of the reach of originated changes (Majkrzak, 2022).

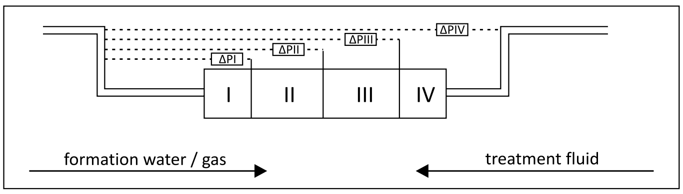


Figure 4. Construction diagram of the multipressure tap flow cell (Dalrymple et al., 2000)

Rysunek 4. Schemat budowy oprawki na próbkę dla wielopunktowego pomiaru spadku ciśnień (Dalrymple et al., 2000)

The determination of the modification degree of filtration properties, both in individual zones and in the entire sample/model section, was based on the value of the F_{RR} (*Residual Resistance Factor*) coefficient, being the measure of their permeability reduction, which was calculated from the following relationship (Shi et al., 2010; Knobloch et al., 2018):

$$F_{RR} = k_0 / k_k \ [-] \quad (1)$$

where:

k_0 – coefficient of permeability measured before the treatment fluid injection,

k_k – coefficient of permeability measured after the treatment fluid injection.

The value of $F_{RR} \geq 20$ shows an effective modification (reduction) of the permeability of water (Han et al., 2015; Seright and Brattekas, 2021). In the considered simulation, variants of the F_{RR} coefficient were determined based on the values of the permeability coefficient:

- effective for gas (K_{eff_g}) – as the simulation of filtration property changes in the gas zone, with a defined irreducible saturation of formation water;
- absolute for brine (K_{abs_w}) – as the simulation of filtration property changes in the water-bearing layer.

Materials

The basic petrophysical parameters of the prepared samples/models were determined within the preliminary characteristic of the tested material. The data for the Szydłowiec sandstone samples (Table 1) show similar (mostly) values of the determined parameters. The CW_2 core is an outlier from the others. The variability of pore volume ranges from 6.95 cm^3 to 14.32 cm^3; the porosity ranges from 9.69% to 21.80% and the absolute permeability for gas from 146 mD to 210 mD. The performed analysis of variability for the basic petrophysical parameters of sand packs (Table 2) shows the possibility of proper and repeatable preparation of models. The value of the determined pore volume ranges from 38.94 cm^3 to 47.09 cm^3, the porosity ranges from 23.33% to 28.64%, and the absolute permeability for gas from 244 mD to 374 mD. The differences existing between individual models should be considered negligible, occurring only due to possible technical errors in the model preparation, and which do not have a direct impact on the results of further tests.

A 5% solution of sodium chloride (NaCl) was used in the tests as the formation water, for which the values of density (1.032 g/cm^3) and dynamic viscosity (0.978 cP) were determined at 25°C.

Table 1. Petrophysical parameters of Szydłowiec sandstone samples
Tabela 1. Parametry petrofizyczne próbek piaskowca szydłowieckiego

Sample No.	Diameter [cm]	Length [cm]	Absolute permeability for gas [mD]	Pore volume [cm^3]	Porosity [%]
CG_1	2.55	12.86	178	14.32	21.80
CG_2	2.57	12.24	146	12.72	20.34
CW_1	2.55	12.84	182	13.61	20.76
CW_2	2.62	12.95	210	6.95	9.96
CW_3	2.57	11.30	203	12.20	20.82

Table 2. Petrophysical parameters of sand packs
Tabela 2. Parametry petrofizyczne modeli sztucznych ośrodków porowatych

Sample No.	Fraction of glass beads [µm] / quartz sand [mm]	Diameter [cm]	Length of sample [cm]	Absolute permeability for gas [mD]	Pore volume [cm^3]	Porosity [%]
MG_1	0–100 / 1–3 (in 2/3 proportion)	2.5	33.50	244	46.97	26.69
MG_2			34.00	339	44.21	25.93
MG_3			33.50	374	40.04	24.34
MW_1			35.00	329	44.28	26.53
MW_2			33.50	285	47.09	28.64
MW_3			34.50	312	46.51	27.46
MW_4			34.00	271	38.94	23.33
MW_5			33.50	302	47.06	28.64

The treatment fluid is characterized by a capability to form the microemulsion in-situ with the reservoir water of Winsor I – Winsor III – Winsor II type, and the gel blocking the water inflow. The formulation of fluid consists of amphiphilic dispersions of surfactants, which show characteristic behavior of molecular self-organization, forming multi-molecular aggregates (micelles) of specified shape, controlled by the critical packing parameter, which characterizes their molecular geometry. The formulation of the micellar fluid (matrix) in a hydrocarbon-oil solvent is a technologically complex process, due to a high possibility of combinations at the formation of the matrix of ionic and non-ionic surfactants with different lyophilicity and hydrophilicity of surfactants, which form with hydrocarbons and oil an isotropic phase of the micellar matrix. The matrix of a micellar fluid should be a thermodynamically stable uniform fluid, which forms Winsor III type microemulsion in the in-situ technology with the reservoir water, and at a specified water concentration should form a gel blocking further water inflow to the well. To achieve a stable Winsor III type microemulsion, in order to obtain ultra-low interfacial tension and the solubilization of the reservoir water and oil, the surfactants soluble in brine and oil should be chosen, taking into account their value of hydrophilic-lyophilic balance (HLB), the salt concentration in water, the type of oil and hydrocarbon solvent, that is the selection of such a structure of the micellar fluid matrix that the difference in the hydrophilic-lyophilic deviation is zero, forming a doubly continuous microemulsion (gel).

Results

Following the adopted methodology, the flood tests were made both for the gas and water-bearing layers. The results of flood tests performed on core samples of Szydłowiec sandstone are presented in Table 3. For CG_1 and CG_2 cores, the values of the F_{RR} coefficient, for each of the zones, are close to one. The F_{RR} value for the whole sample is also low, 1.05 and 1.15, respectively, which suggests the lack of negative impact of the treatment fluid on the gas flow. The results of simulations of water inflow control made for water-bearing layers are entirely different. The F_{RR} coefficient in selected zones reaches values substantially exceeding 20, in zone IV of the CW_1 sample of more than 53, for the CW_2 sample consecutively 110.57 (zone IV) and 40.71 (zone III). The results of tests for the whole samples, CW_1 – 15.54 and CW_2 – 19.69, confirm the modification of filtration properties. For the CW_3 sample, the obtained results are not so unambiguous. Even though the F_{RR} coefficient for zone III is high (13.65), and for zone IV it substantially exceeds 20, then, as a whole, it reaches a low value of 4.95.

The results of flood tests, performed using the sand packs, are presented in Table 4. The values of the F_{RR} coefficient obtained for individual zones, for the MG_1 sample, are almost equal to one. Furthermore, the coefficient determined for the whole sample is low and equals 1.23. The MG_2 sample is characterized by low values of the F_{RR} coefficient in the initial two zones, in the next ones its increase was recorded. This does not translate into the result obtained for the entire sample (F_{RR} = 1.27), which is similar to sample MG_1. The biggest differences occur for the MG_3 sample. The value of the F_{RR} coefficient is close to one only in zone I. In the next zones, it gradually increases up to the value of 3.32 in zone IV. Furthermore, the result obtained for the whole sample is the highest, among models simulating the gas layer, and amounts to 2.12.

The flood tests, simulating the water-bearing layer, were performed on 5 models. The F_{RR} coefficient reaches high values for the MW_4 model, consecutively for zones: I – 3.12, II – 11.43, III – 22.97, and IV – 38.21. It is also high for the whole sample and equals 11.36. Sample MW_3 is characterized by a value of F_{RR} coefficient similar to the MW_4 – 10.11. But its distribution in individual zones is different, from 1.01 in zone I to 28.59 in zone IV. For sample MW_1, the F_{RR} coefficient in consecutive zones ranges from 3.90 to 10.76. For the whole sample, its value reaches 7.90. The injection of treatment fluid to the pore space of MW_2 and MW_5 models has not translated, as in the case of previously described experiments, into achieving the determined F_{RR} coefficient of a value much higher than one. Albeit in both cases, in particular in zone IV of sample MW_2, the F_{RR} values are higher than one, but the coefficient determined for the entire sample is low, 1.69 and 2.31 for samples MW_2 and MW_5, respectively.

Discussion

The analysis of test results, both for tests on porous rocks and sand packs, which simulate gas layers, clearly shows that there was no modification (reduction) of their filtration properties. Achieving an appropriately low, and at the same time consistent with the actual conditions, degree of irreducible saturation for formation water determined the success of the performed simulations. For the CG_1 and CG_2 cores, this level was 11.42% and 9.71%, respectively. In contrast, for three sand packs (MG_1, MG_2, and MG_3), the values of achieved saturation were slightly higher and ranged from 19.12% to 26.89%. It is easy to notice a relationship between the degree of saturation and the value of the F_{RR} coefficient, both for the entire sample and for individual sections. According to that, the higher the value of saturation, the higher the F_{RR} coefficient for the whole sample and the larger range of changes in filtration

Table 3. F_{RR} coefficient for Szydłowiec sandstone samples
Tabela 3. Wartości współczynnika F_{RR} dla próbek piaskowca szydłowieckiego

Sample No.	F_{RR} coefficient [-] in consecutive zones of the sample				Irreducible saturation of formation water, S_{wi} [%]	F_{RR} coefficient [-] for the whole sample
	I	II	III	IV		
CG_1	0.97	0.95	1.12	1.11	11.42	1.05
CG_2	1.15	1.17	1.10	1.19	9.71	1.15
CW_1	1.00	1.04	19.00	53.69	100	15.54
CW_2	9.68	7.03	40.71	110.57	100	19.69
CW_3	0.98	1.84	13.65	32.49	100	4.95

Table 4. F_{RR} coefficient for sand packs
Tabela 4. Wartości współczynnika F_{RR} dla modeli sztucznych ośrodków porowatych

Sample No.	F_{RR} coefficient [-] in consecutive zones of the sample				Irreducible saturation of formation water, S_{wi} [%]	F_{RR} coefficient [-] for the whole sample
	I	II	III	IV		
MG_1	1.01	1.12	1.05	1.09	19.03	1.23
MG_2	1.04	1.21	1.67	2.78	21.12	1.27
MG_3	1.20	1.73	1.98	3.32	26.89	2.12
MW_1	3.90	9.94	5.56	10.76	100	7.90
MW_2	1.92	1.24	2.14	6.04	100	1.69
MW_3	1.01	4.33	7.07	28.59	100	10.11
MW_4	3.12	11.43	22.97	38.21	100	11.36
MW_5	2.03	2.25	2.50	2.59	100	2.31

properties in the determined zones. This is particularly visible for the analysis of the data from tests carried out on sand packs, the differences both in the level of irreducible saturation and in the values of the obtained F_{RR} coefficient for porous rocks, are small. The presented relationship fully coincides with the operation assumptions for treatment fluids based on a microemulsion. It should be emphasized that the determined values of the F_{RR} coefficient, interpreted as a change in the filtration properties of sand packs, are not so high that they could affect the amount of gas flow (inflow to the well). Hence, the performed treatment, with a similar influence of the fluid on the zone, through which the gas inflows to the well, should be considered successfully completed.

The results of tests, performed as simulations of filtration properties changes in the water-bearing layers, generally show their effective modification. Such conclusions are provided primarily by the results of tests on porous rock samples (CW_1 and CW_2), for which the highest values of the F_{RR} coefficient were obtained as well as a significant range of changes in filtration properties in individual zones. For the sand packs, a decrease in their filtration properties after the injection of the treatment fluid was recorded for most models. Models MW_3 and MW_4 should be distinguished here, for which increased values of the F_{RR} coefficient were registered for the entire sample and (in particular in the MW_4 model) for their end and middle zones. F_{RR} values exceeding 20 show the effective reduction of permeability for water. This means that, in the majority of tested samples of rocks and artificial porous models, a gel-insulating barrier was formed due to the contact of the treatment fluid with the reservoir water, which effectively reduced the flow of brine through their pore space. The variability of coefficient values for the other zones shows the diversification of the degree of formed barriers reached. The reason for that can be both the irregular distribution of petrophysical parameters along the longitudinal axis of the sample and the blocking of the flow of fluid to further parts, due to the process of gelling at the beginning stage of the injection.

Recently, as a result of intensive work on the improvement in the technology for selective control of water inflow to a gas well, a workover fluid was obtained, named preliminarily Multizol-35. The results of tests have shown that the new fluid substantially broadens the scope of the results' applicability. The application of Multizol-35 fluid is technologically effective in the wellbore with reservoir waters salinity of up to 15% and a temperature in the perforation zone of up to 80°C.

Conclusions

An uncontrolled inflow of reservoir waters to wells is one of the greatest challenges of the process of hydrocarbon exploitation. It translates into an increase in the costs, which the operators have to incur, and makes the exploitation significantly more difficult. The attempts made to develop universal methods (chemical) for the prevention of excessive production of reservoir water are, as it seems, the only possible path to reduce its negative effects. The microemulsion-based treatment fluid used in the tests can be a response to the existing problems. The laboratory assessment of its technological effectiveness, carried out within flood tests, is considered to be one of the most reliable methods of measurements on porous rock samples, and the addition of tests on sand packs can provide a new package of information helpful in the optimal designing of treatments to control the inflow of reservoir water. The following conclusions may be drawn based on the work carried out:

1. The Multizol micellar treatment fluid, being the object of tests, is an effective tool in the process of controlling the reservoir water inflow to gas wells.
2. The application of the apparatus in flood tests, which enables the measurement of intermediate pressure drops of fluids flowing through the sample/model, significantly increases the reliability of obtained results and broadens the spectrum of obtained data.
3. The determined values of the F_{RR} coefficients for core samples of Szydłowiec sandstone, which simulate the watered layers, show a significant reduction of their filtration properties due to the performed treatment. For the samples, which simulate gas layers, no negative influence of the treatment fluid on their filtration properties was registered.
4. The flood tests carried out using sand packs confirm the results of tests performed using the samples of porous rocks.

This paper was written on the basis of the statutory work entitled: *Wykorzystanie sztucznych ośrodków porowatych w ocenie skuteczności technologii modyfikacji właściwości filtracyjnych skał porowatych*, the work of the INiG – PIB; order number: 0061/SI/2022, archive number: DK-4100-0049/2022 based on the own work: *Poszerzenie zakresu stosowalności selektywnej technologii kontroli produkcji wody w odwiertach gazowych z wykorzystaniem cieczy zabiegowej Multizol*; order number: 1883/SI/2022, archive number: DK-4100-0098/2022.

References

Alfarge D., Wei M., Bai B., 2017. Numerical simulation study of factors affecting relative permeability modification for water-shutoff treatments. *Fuel*, 207: 226–239. DOI: 10.1016/j.fuel.2017.06.041.

Bruce D.A., Littlejohn G.S., Naudts A., 1997. Grouting Materials for Ground Treatment: a Practitioner's Guide, Grouting – Compaction, Remediation, and Testing. Proc. of Sessions Sponsored by the Grouting Committee of the Geo-Institute of the American Society of Civil Engineers, Logan UT, Ed. by C. Vipulanandan, *Geotechnical Special Publication*, 66: 306–334.

Chan K.S., Bond A. J., Keese R. F., Lai Q. J., 1996. Diagnostic Plots Evaluate Gas Shut-Off Gel Treatments at Prudhoe Bay, Alaska. *SPE Annual Technical Conference and Exhibition, Denver, Colorado*. DOI: 10.2118/36614-MS.

Cicha-Szot R., Falkowicz S., 2010. Wpływ modyfikatora na właściwości wiskoelastyczne żeli krzemianowych. *Nafta-Gaz*, 66(12): 1102–1108.

Dalrymple E.D., Eoff L., Reddy B.R., Botermans C.W., Brown D., Brown S., 2000. Studies of a Relative Permeability Modifier Treatment Performed Using Multitap Flow Cells. *Improved Oil-Recovery Symposium, Tulsa, Oklahoma*. DOI: 10.2118/59346-MS.

Falkowicz S., Dubiel S., Cicha-Szot R., 2012. Problemy ograniczania dopływu wody do odwiertów wydobywczych gazowych i ropnych. *Gospodarka Surowcami Mineralnymi*, 28(1): 125–136.

Han S., Zhao C. Ma L. 2015. Determining Residual Resistance Factor of Weak Gel Through Physical and Numerical Simulation. *Advances in Petroleum Exploration and Development*, 9(2): 72–74. DOI: 10.3968/6809.

Knobloch L.O., Hincapie R.E., Födisch H., Ganzer L., 2018. Qualitative and Quantitative Evaluation of Permeability Changes during EOR Polymer Flooding Using Micromodels. *World Journal of Engineering and Technology*, 6(2): 332–349. DOI: 10.4236/wjet.2018.62021.

Lakatos I., Lakatos-Szabo G., Szentes G., Bodi T., Vago T., 2014. Restriction of Water Production in Gas Wells by Induced Phase Inversion: Field Case Studies. *SPE International Symposium and Exhibition on Formation Damage Control, Lafayette, LA, USA*. DOI: 10.2118/168189-MS.

Lakatos I., Lakatos-Szabo G., Szentes G., Bodi T., Vago T., Karaffa Zs., 2016. Multifunctional Stimulation of Gas Wells Operating in Gas Cap over a Depleted Oil Reservoir. *SPE International Conference & Exhibition on Formation Damage Control, Lafayette, USA*. DOI: 10.2118/179013-MS.

Ligthelm D.J., 2001. Water Shut Off in Gas Wells: Is there Scope for a Chemical Treatment? *SPE European Formation Damage Conference, The Hague, Netherlands*. DOI: 10.2118/68978-MS.

Majkrzak M., 2017. Ocena możliwości symulacji przepływu płynów złożowych przez „sztuczne" warstwy/złoża z kulek szklanych. *Nafta-Gaz*, 73(6): 378–386. DOI: 10.18668/NG.2017.06.02.

Majkrzak M., 2022. Ocena selektywnej redukcji właściwości filtracyjnych skał porowatych w zabiegach ograniczania produkcji wody w odwiertach. *Nafta-Gaz*, 78(4): 259–268. DOI: 10.18668/NG.2022.04.02.

Sengupta B., Sharma V.P., Udayabhanu G., 2012. Development and Performance of an Eco-Friendly Cross-Linked Polymer System for Water Shut-Off Technigue. *SPE International Petroleum Technology Conference, Thailand*. DOI: 10.2523/IPTC-14381-MS.

Seright S.R., Brattekas B., 2021. Water shutoff and conformance improvement: an introduction. *Petroleum Science*, 18: 450–478. DOI: 10.1007/s12182-021-00546-1.

Seright S.R., Lane R.H., Sydansk R.D., 2001. A Strategy for Attacking Excess Water Production. *SPE Permian Basin Oil and Gas Recovery Conference, Midland, Texas*. DOI: 10.2118/70067-MS.

Shi L., Ye Z., Y., Zhang Z., Zhou C., Zhu S., Guo Z. 2010. Necessity and feasibility of improving the residual resistance factor of polymer flooding in heavy oil reservoirs. *Petroleum Science*, 7: 251–256. DOI: 10.1007/s12182-010-0029-5.

Sobanova O.B., Fridman G.B., Arefyev Y.N., 1993. Laboratory and Oil Field Testing for Application of Compositions Including Hydrocarbons and Surfactants for Restricting Water Influx into

Producing Wells". *7th European Symposiumon IOR, Moscow, Russia*.

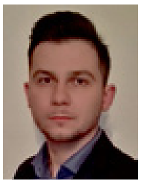
Sydansk R.D., Seright R.S., 2007. When and Where Relative Permeability Modification Water-Shutoff Treatments Can Be Successfully Applied. *Society of Petroleum Engineers Production and Operations*, 22: 236–247. DOI: 10.2118/99371-PA.

Sydansk R.D., Xiong Y., Ai-Dhafeeri A.M., Schrader R.J., Seright R.S., 2005. Characterization of Partially Formed polymer Gel for Application to Fractured Production Wells for Water-Shutoff Purposes. *Society of Petroleum Engineers Production and Facilities*, 20: 240–249. DOI: 10.2118/89401-MS.

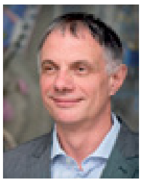
Zaitoun A., Kohler N., Bossie-Codreanu D., Denys K., 1999. Water Shutoff by Relative Permeability Modifiers: Lessons from Several Field Applications. *Annual Technical Conference and Exhibition, Houston, Texas*. DOI: 10.2118/56740-MS.

Zaitoun A., Kohler N., Guerrini Y., 1991. Improved Polyacrylamide Treatments for Water Control in Producing Wells. *Journal of Petroleum Technology*, 43: 862–867. DOI: 10.2118/18501-PA.

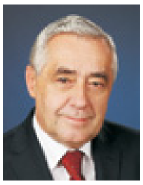
Zaitoun A., Tabary R., Rousseau D., 2007. Using Microgels to Shut Off Water in Gas Storage Well. *International Symposium on Oilfield Chemistry, Houston, Texas*. DOI: 10.2118/106042-MS.



Marcin MAJKRZAK, M.Sc., Eng.
Senior Technical Research Specialist
at theDepartment of Petroleum Engineering
Oil and Gas Institute – National Research Institute
25 A Lubicz St., 31-503 Kraków
E-mail: *marcin.majkrzak@inig.pl*



Sławomir FALKOWICZ, Ph.D., Eng.
Assistant Professor at the Department of Petroleum Engineering
Oil and Gas Institute – National Research Institute
25 A Lubicz St., 31-503 Kraków
E-mail: *slawomir.falkowicz@inig.pl*



Winicjusz STANIK, Ph.D.
Assistant Professor; Head of Department of Experimental and Small-Scale Production and Sales
Oil and Gas Institute – National Research Institute
25 A Lubicz St., 31-503 Kraków
E-mail: *winicjusz.stanik@inig.pl*