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Simulation modeling of physical dispersion phenomenon observed in experimental data

Symulacyjne modelowanie zjawiska dyspersji fizycznej obserwowanej w danych eksperymentalnych

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ABSTRACT: The article concerns a practical solution of the problem connected with modeling of the physical dispersion phenomenon. It is a continuation of the author's previous publications, in which calculations were made on both very simplified simulation models and the model of the real structure. In this article, an attempt was made to model the course of laboratory tests using a previously developed method of controlling the phenomenon of physical dispersion. Laboratory tests selected for modeling were carried out in the Department of Oil and Gas Reservoir Testing, which is located in the Krosno branch of the Oil and Gas Institute – National Research Institute. The said tests were carried out on the so-called long cores and concerned the displacement of oil with water. The method of modeling the course of these type of tests proposed in the article consisted in the use of a hybrid method of minimizing numerical dispersion and the extension of standard saturation equations by an additional element of physical dispersion. The article contains a brief description of the proposed method of controlling the size of the mixing zone of fluids and the results of application thereof. This article is a continuation of the author's previous work and it contains only the most important mathematical formulas. For comparison purposes, the article also presents the results of modeling selected laboratory tests using numerical dispersion. This modeling consisted in modification of the blocks grid size, which resulted in mixing zones of the displacement fluid with the displaced fluid of various sizes. The results of performed simulations presented in the article, in the form of drawings and diagrams, showed the effectiveness of the applied method of limiting numerical dispersion (both for calculations of mobility with multi-point weighing in the direction of inflow, as well as double discretization grid) as well as the effects of using different values of physical dispersion parameters. In the article the results of matching the built simulation models with the results obtained in the laboratory were also presented (in the form of the results of the overall recovery of fluids).

Key words: numerical dispersion, physical dispersion, mixing of fluids, reservoir simulator.

STRESZCZENIE: Artykuł dotyczy praktycznego rozwiązania problemu związanego z modelowaniem zjawiska dyspersji fizycznej. Jest to kontynuacja poprzednich publikacji autora, w których obliczenia zostały wykonane zarówno na bardzo uproszczonych modelach symulacyjnych, jak i na modelu rzeczywistej struktury. W ramach tego artykułu podjęto próbę modelowania przebiegu badań laboratoryjnych przy wykorzystaniu opracowanej wcześniej metody sterowania zjawiskiem dyspersji fizycznej. Wybrane do modelowania badania laboratoryjne zostały przeprowadzone przez Zakład Badania Złóż Ropy i Gazu, zlokalizowany w krośnieńskim oddziale Instytutu Nafty i Gazu – Państwowego Instytutu Badawczego. Badania te zostały wykonane na tzw. długich rdzeniach i dotyczyły wypierania ropy naftowej wodą. Proponowana w ramach artykułu metoda modelowania przebiegu tego typu badań polega na zastosowaniu hybrydowej metody minimalizacji dyspersji numerycznej oraz rozszerzeniu standardowych równań nasyceń o dodatkowy człon dyspersji fizycznej. Artykuł zawiera krótki opis proponowanej metody sterowania wielkością strefy mieszania się płynów wraz z wynikami jej zastosowania. Artykuł ten jest kontynuacją wcześniejszych prac autora, dlatego zamieszczono w nim tylko najistotniejsze wzory matematyczne. Dla celów porównawczych w artykule przedstawiono również wyniki modelowania wybranego badania laboratoryjnego z wykorzystaniem dyspersji numerycznej. Modelowanie to polegało na modyfikacji rozmiarów siatki bloków, w wyniku czego uzyskano różnej wielkości strefy mieszania się płynu wypierającego z płynem wypieranym. Przedstawione w artykule, w postaci rysunków i wykresów, wyniki wykonanych symulacji wykazały efektywność stosowanej metody ograniczenia dyspersji numerycznej (zarówno dla obliczeń mobilności z ważeniem wielopunktowym w kierunku napływu, jak i podwójnej siatki dyskretyzacji) oraz efekty zastosowania różnych wielkości parametrów dyspersji fizycznej. W ramach artykułu (w postaci wyników sumarycznego odbioru płynów) przedstawiono również wyniki dopasowania zbudowanych modeli symulacyjnych do rezultatów uzyskanych w laboratorium.

Słowa kluczowe: dyspersja numeryczna, dyspersja fizyczna, mieszanie się płynów, symulator złożowy.

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Introduction

When injecting fluids into hydrocarbon reservoirs, the phenomenon of physical dispersion (Perkins and Johnston, 1963; Bijeljic and Blunt, 2006) occurs when the injected fluid is mixed with the fluid originally present in the formation. This phenomenon is very important in the underground gas storage practices (Azin et al., 2008; Gołąbek and Szott, 2010; Szott, 2010; Gołąbek et al., 2011a, 2011b;) (especially during the creation of a non-hydrocarbon buffer cushion or injection of high-methane natural gas into formations containing heavily polluted original gas) and in situations where attempts are made to increase the energy of the oil-gas reservoir by injecting gas into the reservoir gas cap. Although physical dispersion has a significant influence on the process of fluid mixing in hydrocarbon formations, it has not been correctly included in the available reservoir simulators (both open code and commercial ones). This paper is a continuation of the previous statutory papers of the Department of Hydrocarbon Reservoir and UGS Simulation (Miłek et al., 2013; Szott and Gołąbek, 2014; Gołąbek and Szott, 2015a, 2015b; Gołąbek and Szott, 2017) within the framework of which a reservoir simulator was built (through the modification of an open code BOAST reservoir simulator (Fanchi et al., 1982) correctly taking into account the phenomenon of mixing of gases. Modifications of the simulator concerned implementation of the hybrid method of minimizing numerical dispersion (mobility with multi-point weighing in the direction of inflow (Tood et al., 1972) + double discretization grid (Audigane and Blunt, 2003) and extension of standard saturation equations with additional term describing physical dispersion and control by specific parameters (Redlich and Kwong, 1949; Soave, 1972; Peaceman, 1977; Kreft and Zuber, 1978; Shrivastava et al., 2005). These changes were tested on simplified simulation models (in which fixed size of blocks, homogeneous reservoir parameters and stationary flow of reservoir fluids were assumed) and the real formation model (selected natural gas reservoir model).

The aim of this paper was to apply the developed method of controlling the phenomenon of mixing of reservoir fluids to the modeling of selected laboratory tests concerning displacement of oil with water performed on long cores from the oil reservoir. The results of laboratory tests carried out in the Department of Oil and Gas Reservoir Testing on cores from production wells were used. Within the framework of the discussed paper, several simulation models, reflecting the course of laboratory tests (with different grid refinement for saturation calculations), were built on which the proposed method of modeling the physical dispersion phenomenon was tested. For comparative purposes, an attempt was also made to model selected laboratory tests by controlling numerical dispersion (size of blocks).

The calculations were carried out using BOAST v. 1.1 reservoir simulator modified in previous work and the Eclipse reservoir simulator by Schlumberger ver. 2014.1 (Eclipse Black Oil and Compositional).

Physical dispersion control method

The method proposed in the previous articles is divided into two stages:

- minimization of numerical dispersion (dilution of simulation results resulting from the calculation method applied – discretization of derivatives by finite differences + "upstream weighing" assuring stability of numerical solutions);
- extension of equations by physical dispersion terms (adding to the simulator the parameters enabling physical dispersion control by setting a constant dispersion value or its linear dependence on flow velocity).

Minimization of numerical dispersion is achieved through an efficient combination of two methods: calculating fluid mobility using multi-point weighing of inflow directions and double discretization grid. The first one had already been partially implemented in the BOAST simulator (Fanchi et al., 1982), and more specifically, it concerns the calculation of the fluids mobility by double-point weighing in the direction of inflow. In order to reduce numerical dispersion more effectively in this hybrid method, the calculation of fluids mobility was extended by three-point weighing.

The addition of physical dispersion control parameters consists in taking them into account in equations for fluids flows from/to adjacent blocks to/from the block with coordinates i, j, k: (the equation below is shown in the gas phase example, but it is also true for the other phases):

$$\bar{Q}_g = \overline{KA_{ci}}\frac{k_{rg,x}}{\mu_g B_g}\frac{P_{i-1}-P_i}{\frac{\Delta x_{i-1}+\Delta x_i}{2}} + \overline{D_{phys,x}A_{ci}}\frac{S_{i-1}-S_i}{B_g\frac{\Delta x_{i-1}+\Delta x_i}{2}}$$

$$+\overline{KA_{cj}}\frac{k_{rg,y}}{\mu_g B_g}\frac{P_{j-1}-P_j}{\frac{\Delta y_{j-1}+\Delta y_j}{2}} + \overline{D_{phys,y}A_{cj}}\frac{S_{j-1}-S_j}{B_g\frac{\Delta y_{j-1}+\Delta y_j}{2}}$$

$$+\overline{KA_{cz}}\frac{k_{rg,z}}{\mu_g B_g}\frac{P_{k-1}-P_k}{\frac{\Delta z_{k-1}+\Delta z_k}{2}} + \overline{D_{phys,z}A_{cz}}\frac{S_{k-1}-S_k}{B_g\frac{\Delta z_{k-1}+\Delta z_k}{2}}$$

where: $\bar{K}$ is the absolute permeability, $\overline{A_{Ci}}$, $\overline{A_{CJ}}$, $\overline{A_{CZ}}$, are the cross-sectional areas between the blocks (between x_{i-1} and x_i, y_{j-1} and y_j, z_{k-1} i z_k), $k_{rg,y}$, $k_{rg,y}$, $k_{rg,z}$, are the relative permeability of the gas displacing in different directions, μ_g, B_g are the viscosity and volumetric coefficient of the displacement gas respectively, Δx_i, Δy_j, Δz_k are the dimensions of the blocks in different directions, $P_{i,j,k}$ are the pressure in the blocks, and $S_{i,j,k}$

is saturation of the displaced gas. In this approach, saturation of the displaced gas is equivalent to its concentration (this assumption is discussed in detail in the appendix to the (Gołąbek and Szott, 2016).

In the case of a one-dimensional model, the above equation is simplified to one term only for the selected direction.

The dispersion can be either constant or may depend on flow velocity, so a dispersion may be assumed in the modified simulator: by setting constant dispersion parameters for each direction or by setting dependence of dispersion on flow velocity, which is linear in nature: $D_{phys,y} = D_y + \alpha\vec{v}_y$ (In this paper the case of immiscible fluids was considered where the molecular diffusion is equal to zero and main phenomenon occurring during fluid displacement is physical dispersion resulting from the complicated flow through the porous media (Gelhar and Collins, 1971; Fanchi, 1983; Reid et al. 1987; Coats et al., 2009; Li, 2010; Vitousek and Fringer, 2011).

Laboratory tests performed on long cores

Laboratory tests, the course of which was used in this paper, were carried out at Department of Oil and Gas Reservoir Testing located in the Krosno Branch of the Oil and Gas Institute. These tests concerned displacement of oil from cores using water as a displacement medium (Warnecki, 2010). Since these tests were commissioned by the industry, no names of the reservoir or the wells from which the cores were extracted for the tests were given in this paper.

Brief description of the tests

The tests used in the paper consisted first of all in the experimental setup drilling cores and determining their petrophysical properties (porosity and permeability). Later, the cores from a selected well were placed in the chamber of PVT core testing apparatus. For each test the cores were arranged in order of increasing/decreasing permeability. In the next stage of the performed tests, the cores were 100% saturated with oil and the initial reservoir pressure was set to about 425 bar. Finally, injecting of water and oil displacement process was performed.

In this paper, the results of three tests of oil displacement with water were used, for which cores parameters presented in Table 1 were selected.

The first of the selected displacement tests lasted about 9.5 hours and during this test about 30 cm^3 of water were injected, the second one lasted about 9.6 hours and about 31 cm^3 of water were injected, while the third test lasted about 17 hours and about 35 cm^3 of water were injected.

The results of oil displacement with water in the first and second tests are very similar. In these tests, the rate of oil recovery amounted to 56.1% and 56.9% respectively, and about 10.2 cm^3 of oil was received. The results are similar because the parameters of the cores used in the tests were similar. The main difference was that in Test no. 1 the cores were arranged by decreasing permeability, whereas in Test no. 2 by increasing permeability.

Table 1. Petrophysical parameters of cores selected for testing
Tabela 1. Parametry petrofizyczne rdzeni w wybranych testach

Core	Test no. 1	Test no. 2	Test no. 3	Test no. 1	Test no. 2	Test no. 3
	Porosity ϕ			Permeability K		
	[–]			[mD]		
1	0.25	0.26	0.27	61	29	398
2	0.24	0.24	0.27	55	36	276
3	0.24	0.25	0.26	43	45	111
4	0.27	0.24	0.18	40	58	31

Core samples were approx. 5 cm long and had a radius of approx. 2.4 cm.

During the displacement, in the third test the oil recovery ratio of 52.8% was achieved and about 9.7 cm^3 of oil was received. This test differs significantly from the two previous ones because the cores involved had different petrophysical properties (much higher permeability values for the first three cores and significantly lower porosity in the last core – Table 1).

Modeling of tests using numerical dispersion

Since the main purpose of this paper is simulation modeling of physical dispersion phenomenon observed in experimental results, apart from the previously developed method, it was decided to undertake an attempt to use numerical dispersion. As it is well known, the numerical dispersion is a kind of calculation error resulting from very complicated numerical solutions used in reservoir simulators. One of the known ways to control numerical dispersion is to change the resolution of the model grid. The numerical dispersion is responsible for the dilution occurring in saturations. The higher the resolution of the model grid, the smaller the smearing of saturations in blocks and vice versa. This smearing is a measure of mixing of fluids in the model, therefore it is possible to use numerical dispersion to model the phenomenon of mixing of fluids.

All the models used to describe the tests described in the previous chapter were built in a similar way, i.e. a model consisting of 4 blocks representing core samples prepared for the tests was built first, and then the grid was refined depending on the results obtained. Petrophysical parameters of these cores were assigned to blocks and 100% oil saturation thereof was assumed. In the model, the pore volume of the blocks was also

scaled because the cores used in the tests were cylinders and in the model they were approximated with cubes. Properties of reservoir fluids, i.e. density, viscosity and volume factors were assumed to be such as in the case of fluids found in the structure from which the cores were taken. On the other hand, the relative permeability curves were assumed to be linear, while the real values of the so-called endpoints were assumed.

The course of all tests on oil displacement with water looked similar, i.e. constant mean pressure in the cores was assumed at the level of reservoir pressure. Water was injected at a constant rate to one side and fluids were collected from the other side with the rate resulting from the maintenance of the reservoir pressure.

Model of Test no. 3

Test no. 3 was selected for the presentation of modeling results because the core samples involved in it show much greater spread of petrophysical properties. The results of modeling the test in questions are presented in Figures 1–4. The first one of the above mentioned figures shows the distribution of oil saturation in models with different degrees of grid refinement for the selected time. The next figure (Fig. 2) shows oil saturation in the model blocks as a function of the model length. In the case of this test, the width of the zone of water and oil mixing in three models does not exceed the length of the model, and in the model with 200-fold grid refinement it amounted to about 10 cm.

The last two figures (Fig. 3, 4) showing the recovery of fluids from the model show that this test was best reflected by a model with 100-fold grid refinement. Further increase in the model grid refinement gave the opposite effect than expected and instead of reducing, it significantly increased oil recovery from the model. It turns out that with the assumed transport properties, volumetric coefficients and 200-fold grid refinement, the model recovered the least amount of water and, while maintaining the specified pressure conditions, it recovered more oil.

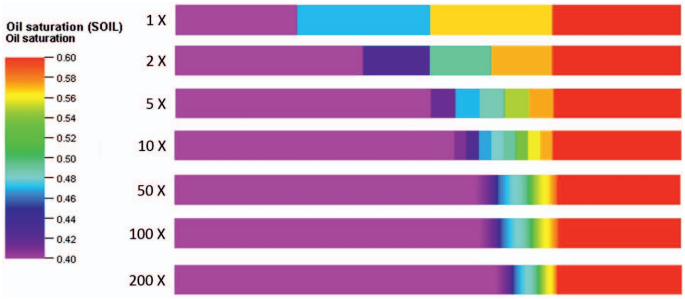

Fig. 1. Test no. 3 – oil saturation in the model blocks (at half time of the test duration)

Rys. 1. Test nr 3 – nasycenie ropą w blokach modelu (w połowie czasu trwania testu)

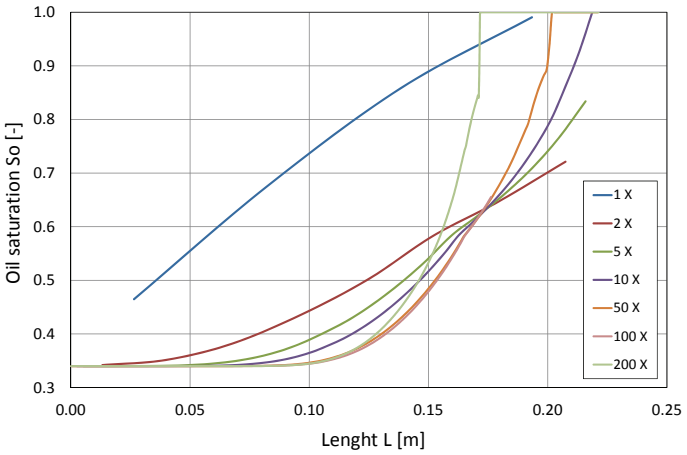

Fig. 2. Test no. 3 – oil saturation vs position in the model (at half time of the test duration)

Rys. 2. Test nr 3 – nasycenie ropą vs pozycja w modelu (w połowie czasu trwania testu)

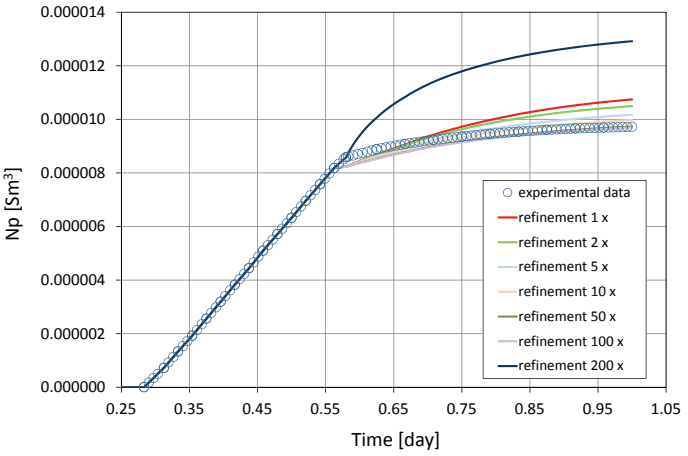

Fig. 3. Test no. 3 – total oil production. Models results vs measurement data

Rys. 3. Test nr 3 – sumaryczny odbiór ropy. Wyniki modelowania vs dane eksperymentalne

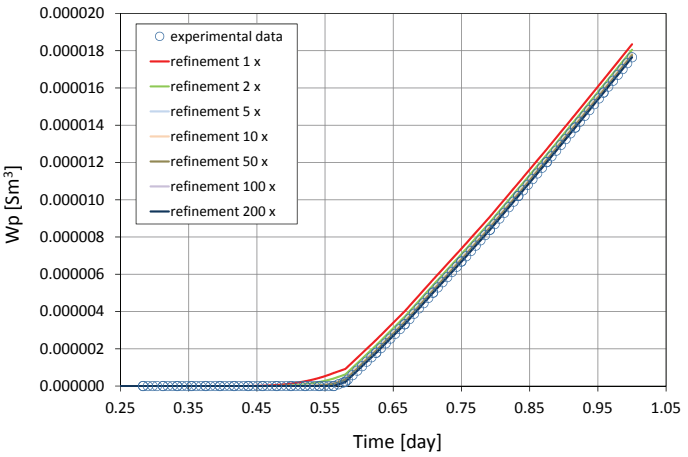

Fig. 4. Test no. 3 – water production. Models results vs measurement data

Rys. 4. Test nr. 3 – sumaryczny odbiór wody. Wyniki modelowania vs dane eksperymentalne

Modeling of tests by physical dispersion control

Modeling of the phenomenon of fluids mixing according to the previously presented physical dispersion control method consists in minimizing numerical dispersion and selecting appropriate values of physical dispersion parameters.

Minimization of numerical dispersion

The results of numerical dispersion reduction by changing the method of calculation of fluid mobility are presented in Figure 5 in the form of water saturation distributions in the model blocks. The effect of applying the modified calculations was shown for a model with 100-fold grid refinement. A clear reduction in smearing of saturation distribution (from the numeric dispersion) can be seen in the case of double-point weighing. The use of three-point weighing results in a lower improvement compared to two-point weighing, but it is still significant. As can be seen in the figure in question, after using three-point weighing to calculate the mobility of fluids, the width of their mixing zone decreased twice.

Since the proposed method of minimizing numerical dispersion is a combination of two methods: mobility with multi-point weighing in the direction of inflow with a double discretization grid, further results of limiting numerical dispersion were shown with the use of three-point weighing when calculating fluids mobility. The results of the grid refinement for saturation calculations are shown in Figure 6 in the form of water saturation distributions for the selected moment of time. Each subsequent increase in the model grid refinement for saturation calculations significantly reduces numerical dispersion (smearing of the front between the injected water and the displaced oil). The best result of the reduction of numerical dispersion (for this model) was found to be the use of a thousand-fold grid refinement for saturation calculations. Since the difference between five hundred-fold and a thousand-fold refinement is not large, further concentration increase will be ineffective.

Fluids mixing zone control

Using a modified reservoir simulator, after optimal minimization of numerical dispersion, control of the fluid mixing phenomenon can be started by setting physical dispersion parameters. Physical dispersions in the chosen direction can be set by parameters D_0 and α, by means of which the linear dependence of dispersion on flow velocity is determined. In the case of laboratory testing models constant parameter D was used because the flow velocity during the modeled tests is constant ($D_0 = 0$, $v = const$, $D = \alpha v = const$). Figure 7 presents saturation with water in the model blocks depending on the value of the D parameter.

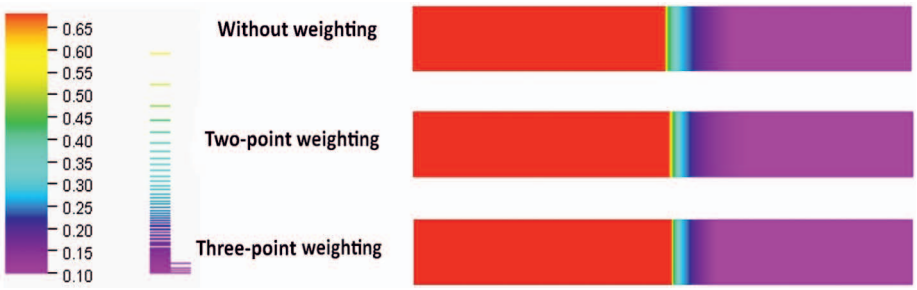

Fig. 5. Numerical dispersion limitation. The effect of changing the method of mobility calculation. Water saturation in the model blocks

Rys. 5. Ograniczenie dyspersji numerycznej. Efekt zmiany obliczeń mobilności płynów. Nasycenie wodą w blokach modelu.

Fig. 6. Numerical dispersion limitation. The effect of using a double discretization grid with triple weighing during fluid mobility calculations. Water saturation in the model blocks

Rys. 6. Minimalizacja dyspersji numerycznej. Efekt zastosowania podwójnej siatki dyskretyzacji w połączeniu z trzypunktowym ważeniem dla obliczeń mobilności płynów. Nasycenie wodą w blokach modelu.

Fig. 7. The effect of taking into account physical dispersion. Water saturation in the model blocks

Rys. 7. Efekt uwzględnienia dyspersji fizycznej. Nasycenie wodą w blokach modelu

The figures below (Fig. 8, 9) present the results of the application of the physical dispersion control method for modeling the course of the selected test of oil displacement of with water performed on long cores. These figures show total recovery of oil and water from the model volume, depending on the physical dispersion value. The course of Test no. 3 is best reflected by the models with D = 0.1 and 0.2 m^2/d where the width of the mixing zone of fluids does not exceed several centimeters.

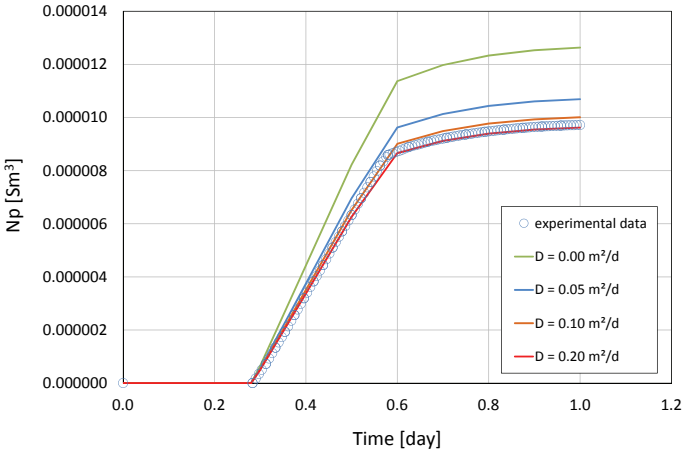

Fig. 8. Test no. 3 Total oil production

Rys. 8. Test nr 3. Sumaryczny odbiór ropy

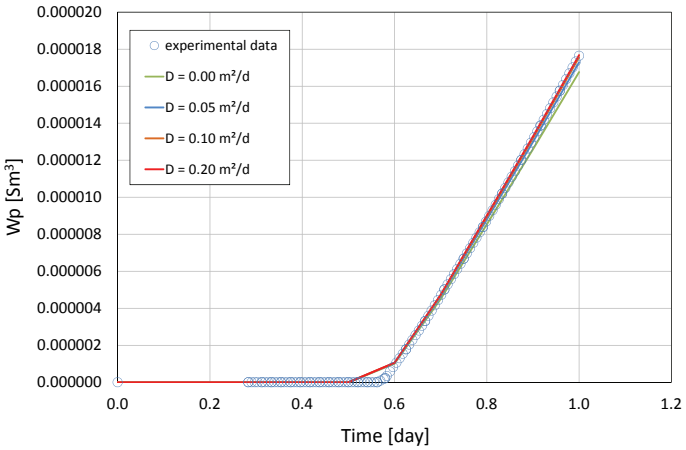

Fig. 9. Test no. 3 Total water production

Rys. 9. Test nr 3. Sumaryczny odbiór wody

The results of modeling using the previously developed method of physical dispersion control are better than those obtained using numerical dispersion because they better reflect the course of the test over time. The average error obtained of results corresponding to experimental data in best simulation case with numerical dispersion control and proposed method were 2.1% and 1.2% respectively. Modeling the mixing of fluids with a "trick" using the control of the numerical dispersion is not elegant and not entirely effective. In the proposed method, the calculations are much faster because they are divided into two independent discretization grids. In the case of modeling by changing the grid resolution, all calculations are performed on the same grid and high grid refinement can cause problems with pressure distribution calculations.

Summary and conclusions

Issues concerning numerical modeling of the physical dispersion phenomenon occurring during oil displacement with water during laboratory tests performed on long cores were discussed in this paper. Since no options allowing for proper modeling of the process of fluids mixing have been made available in standard, commercial reservoir simulators (Eclipse or CMG), this paper uses the method (implemented in BOAST simulator) proposed in earlier papers, which consists in the following:

- minimizing numerical dispersion by multi-point weighing in the calculation of fluids mobility and using a double discretization grid (coarse grid for pressures calculations and refined grid for saturation calculations);
- setting physical dispersion parameters (depending on the direction and velocity of flow) added to the simulator by adding a dispersion module to the equation of fluids flow between blocks.

As part of this paper, several models reflecting the course of laboratory tests was also modeled, differing in resolution of the grid for saturation calculations, on the basis of which the implemented method of modeling the fluids mixing phenomenon was tested. Apart from the physical dispersion control method, the course of laboratory tests was modeled using numerical dispersion.

Conclusions

1. Minimizing the numerical dispersion that occurs during simulation calculations, can be achieved by changing the method of calculating fluids mobility and the refinement of the model grid for saturation calculations in the IMPES calculation scheme.
2. Using a modified numerical scheme, the physical dispersion phenomenon can be correctly modeled taking into account its complex nature.
3. The proposed method of physical dispersion control can be used to model the course of laboratory tests.
4. Modeling using the previously developed method of physical dispersion control better reflect the course of the test over time.
5. Average error obtained of results corresponding to experimental data in the best simulation case with numerical

dispersion control is higher than in the best simulation case with method of physical dispersion control.

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Literature

Audigane P., Blunt M.J., 2003. Dual mesh method in upscaling. *Society of Petroleum Engineers*. DOI: 10.2118/79681-MS.

Azin R., Nasiri A., Entezari A.J., Montazeri G.H., 2008. Investigation of Underground Gas Storage in a Partially Depleted Gas Reservoir. *Society of Petroleum Engineers*. DOI: 10.2118/113588-MS.

Bijeljic B., Blunt M.J., 2006. A Physically-Based Description of Dispersion in Porous Media. *Society of Petroleum Engineers*. DOI: 10.2118/102869-MS.

Coats K.H., Whitson C.H., Thomas L.K., 2009: Modeling Conformance as Dispersion. *Society of Petroleum Engineers*. DOI: 10.2118/90390-PA.

Eclipse Black Oil and Compositional, v 2010.1 firmy GeoQuest Schlumberger.

Fanchi J.R., 1983. Multidimensional Numerical Dispersion. *Society of Petroleum Engineers*. DOI: 10.2118/9018-PA.

Fanchi J.R., Harpole K.J., Bujnowski S.W., 1982. BOAST: a three-dimensional, three-phase black oil applied simulation tool (Version 1.1). Volume 1: Technical Description and FORTRAN Code. Keplinger and Associate, Inc., Tulsa, Oklahoma and the BDM Corporation, Bartlesville, Oklahoma.

Gelhar L.W, Collins M.A., 1971. General analysis of longitudinal dispersion in nonuniform flow. *Water Resour. Res*., 7(6): 1511–1521. DOI: 10.1029/WR007i006p01511.

Gołąbek A., Miłek K., Szott W., 2011a. Symulacyjne modelowanie procesu konwersji złoża na PMG i regularnej jego pracy, z udziałem CO_2 jako gazu buforowego. Część I – Konstrukcja i weryfikacja modelu, symulacja procesu wytwarzania buforu magazynu. *Nafta-Gaz*, 3: 153–162.

Gołąbek A., Miłek K., Szott W., 2011b. Symulacyjne modelowanie procesu konwersji złoża na PMG i regularnej jego pracy, z udziałem CO_2 jako gazu buforowego. Część II – Symulacyjne prognozy pracy magazynu. *Nafta-Gaz*, 4: 240–248.

Gołąbek A., Szott W., 2010. Symulacyjne modelowanie procesu konwersji złoża PMG i regularnej jego pracy z udziałem CO_2 jako gazu buforowego. Praca statutowa INiG – PIB, nr zlecenia 51/KZ, nr archiwalny DK-4100-51/10.

Gołąbek A., Szott W., 2015a. Modyfikacje symulatora złożowego dla potrzeb modelowania zjawisk mieszania się gazów. *Nafta-Gaz*, 3: 177–184.

Gołąbek A., Szott W., 2015b. Trójwymiarowy symulator złożowy umożliwiający modelowanie mieszania się gazów. Praca statutowa INiG – PIB, nr zlecenia 40/KZ, nr archiwalny DK-4100-40/15.

Gołąbek A., Szott W., 2016: Numeryczne modelowanie zjawiska dyspersji fizycznej – modyfikacja pełnowymiarowego symulatora złożowego. *Nafta-Gaz*, 7: 528–533, DOI: 10.18668/NG.2016.07.05.

Gołąbek A., Szott W., 2017. Numeryczne Modelowania zjawiska dyspersji fizycznej –model rzeczywistej struktury. *Nafta-Gaz*, 2: 75–80. DOI: 10.18668/NG.2017.02.01.

Kreft A., Zuber A., 1978. On the Physical Meaning of the Dispersion Equation and its Solutions for Different Initial and Bonduary Conditions. *Chemical Engineering Science*, 33: 1471–1480. DOI: 10.1016/0009-2509(78)85196-3.

Li D., 2010. Comparative Simulation Study of water Flood. *Technology Interface Journal*, 10(3): 158–167. DOI:10.2118/88459-MS.

Miłek K., Szott W., Gołąbek A., 2013. Symulacyjne badanie procesów wypierania metanu rozpuszczonego w wodach złożowych poprzez zatłaczanie gazów kwaśnych w ramach ich sekwestracji. *Nafta-Gaz*, 2: 112–121.

Peaceman D.W., 1977. Fundamentals of numerical reservoir simulation. Elsevier Scientific Publishing Company.

Perkins T.K., Johnston O.C., 1963. A review of Diffusion and Dispersion in Porous Media. *Society of Petroleum Engineers*. DOI: 10.2118/480-PA.

Redlich O., Kwong J.N.S., 1949. On the Thermodynamics of Solutions. V. An Equation of state. *Fugacities of Gaseous Solutions. Chem. Rev*., 44: 223-244. DOI: 10.1021/cr60137a013.

Reid R.C., Prausnitz J.M., Polling B.E., 1987. The Properties of Gases and Liquids. McGraw-Hill, New York, USA.

Shrivastava V.K., Nghiem L.X., Okazawa T., 2005. Modeling Physical in Miscible Displacement – Part 1: Theory and the Proposed Numerical Scheme. *Journal of Canadian Petroleum Technology*, 44(5): 25–33. DOI: 10.2118/05-05-01.

Soave G., 1972. Equilibrium Constants from a modified Redlich-Kwong equation of state. *Chemical Engineering Science*, 27: 1197–1203. DOI: 10.1016/0009-2509(72)80096-4.

Szott W., 2010. Zastosowanie symulacji komputerowych do modelowania pracy podziemnych magazynów gazu w Polsce. *Nafta-Gaz*, 5: 339–344.

Szott W., Gołąbek A., 2014. Symulacyjne modelowanie procesów mieszania się gazów w warunkach złożowych. *Nafta-Gaz*, 3: 151–161.

Tood M.R., O'Dell P.M., Hirsaki G.J., 1972. Methods for Increased Accuracy in Numerical Reservoir Simulators. *Society of Petroleum Engineers*. DOI: 10.2118/3516-PA.

Vitousek S., Fringer O., 2011. Physical vs. numerical dispersion in nonhydrostatic ocean modeling. *Ocean Modelling*, 40: 72–86. DOI: 10.1016/j.ocemod.2011.07.002.

Warnecki M., 2010. Ocena skuteczności procesu wypierania ropy z długich rdzeni wiertniczych dolomitu głównego. *Prace Naukowe Instytutu Nafty i Gazu*, 170: 255–260.

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