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## A STUDY OF WATER CONING CONTROL IN OIL WELL BY INJECTED BARRIER AND DOWNHOLE WATER SINK TECHNOLOGY

**Summary.** A numerical simulation of heavy oil recovery process developed in this work to investigate the time dependent development and dynamic shape of the water-oil interface around the well producing from a bottom-water-drive homogenous reservoir. The objectives of this study: developing a numerical model demonstrating water coning; placement of a drainage completion under the barrier, and perform a parametric study of a combined gel barrier placement with water drainage; ascertainment of the ability of a horizontal gel barrier to prevent water breakthrough; investigation of the performance of the gel barrier shut off technology associated with the Downhole Water Sink (DWS) technology; investigation the impermeable manmade barrier shut off and DWS methods' impact on the breakthrough time, and the critical rate; investigation of the effect of barrier radial size; demonstration of barrier-drainage system efficiency etc.

## STUDIUM OGRANICZANIA STOŻKÓW ZAWODNIENIOWYCH W OTWORACH NAFTOWYCH PRZY ZASTOSOWANIU BARIERY INIEKCYJNEJ I TECHNOLOGII ODWADNIANIA DNA OTWORU

**Streszczenie.** Przedstawiono numeryczny model procesu pozyskiwania ropy z jednorodnego złoża z wodą denną. Pozwala on prześledzić zmiany i rozwój granicy woda-ropa wokół otworu eksploatacyjnego. Uzyskane rezultaty potwierdzają przydatność modelu do analizy wpływu zastosowania bariery iniekcyjnej i technologii odwadniania dna otworu (DWS) na ograniczenie tendencji do tworzenia się stożków nawodnieniowych.

## 1. Introduction

To describe thermal treatment of pools, the temperature model of two-phase filtration [2] based on the Muskat-Leverett isothermic model (the MLT model) was used. The model takes heat effects into account via the known dependences on the viscosity, and capillary properties of the two-phase liquid (water-oil) components. System of equations describing the process also includes the contribution of gravity forces. Author was the first to consider 3D cylindrical thermal two-phase filtration model taking into account all terms of the existing mathematical model including barrier-drainage system investigation. Dimensionless parameters were derived from the governing equations in view of physical characteristics of flow. The author also proposes a new formula for approximation of Leverett J-function which is convenient to use in numerical experiments from his point of view. The main advantages of this formula are related to the facts that it able to quite precisely approximate any monotonically decreasing smooth function by selection constants, and also unlike some formulas its derivative is not equal to infinity at zero. Observed was the effect of well completions on water coning in four different reservoir settings. The first was a case of conventional completion and was studied as a base case. In the second case was set dual completion with water drainage. The third scenario was an impermeable barrier injected around the well bore. In the fourth case was considered complex effect of dual completion with water drainage and impermeable barrier.

## 2. Research and Practice

Siddiqi and Wojtanowicz used a scaled physical model and numerical simulator to determine the effect of artificial barrier and downhole water sink technology on water coning performance [2]. This work was taken as a source of results for comparison.

### 2.1. Mathematical Model

The MLT model [3] of the two-phase immiscible fluids' (water and oil) flow through a porous medium is much more complex than Darcy's model. Continuity equations and generalized Darcy's model for each fluid component can be written in the form:

$$\frac{\partial}{\partial t}(m_0 \rho_i s_i) + \operatorname{div}(\rho_i \vec{v}_i) = 0, \quad \vec{v}_i = -K_0 \frac{\bar{k}_i}{\mu_i} (\nabla p_i + \rho_i \vec{g}), \quad i = 1, 2 \quad (1)$$

Hence (indexes  $i = 1, 2, 3$  correspond respectively water, oil and porous medium below):

$$m \frac{\partial s}{\partial t} = \operatorname{div}[a_1 \nabla s + \vec{f}_1 + a_2 \nabla \theta], \quad \operatorname{div}(K \nabla p + \vec{f}_2 + a_3 \nabla \theta) = 0, \quad (2)$$

$$-\vec{v} = K \nabla p + \vec{f}_2 + a_3 \nabla \theta, \quad \frac{\partial \theta}{\partial t} = \operatorname{div}[\lambda(x, s, \theta) \nabla \theta - \vec{v} \theta] \quad (3)$$

$$m = m_0 (1 - s_1^0 - s_2^0), \quad (4)$$

$m_0$  - porosity,  $s_i^0$ ,  $i = 1, 2$ , residual water and oil saturations respectively;

$$s = \frac{s_1 - s_1^0}{1 - s_1^0 - s_2^0} \in [0, 1], \quad (5)$$

$s_i$  - saturation,  $i = 1, 2$ ;  $s_1 + s_2 = 1$ ;  $0 < s_i^0 \leq s_i \leq 1 - s_j^0 < 1$ ,  $i \neq j$ ;  $t$  - time;

$$a_i = -K_0 \frac{k_1 k_2}{k} \frac{\partial p_c}{\partial s} \quad (6)$$

$K_0$  - symmetrical flow tensor of an anisotropic porous medium. In the case of anisotropic porous medium  $K_0$  can be expressed via  $k_h$  - horizontal permeability and  $k_v$  - vertical permeability components of symmetrical flow tensor.

$k_i = \frac{\bar{k}_i}{\mu_i}$  - relative permeabilities;  $0 \leq \bar{k}_i \leq 1$ ;  $\bar{k}_i(s_i^0) = 0$ ;  $\bar{k}_i(s) > 0$ ,  $s \in (0, 1)$ ;

$\bar{k}_i(0) = \bar{k}_i(1) = 0$ .  $\mu_i$  - dynamic viscosity coefficient ( $\mu_i = \text{const}$ );

$$\mu_2 = \mu_{2\max} + (\mu_{2\min} - \mu_{2\max}) \frac{\theta - \theta_{\min}}{\theta_{\max} - \theta_{\min}} \quad (7)$$

$\theta$  - temperature;  $k = k_1 + k_2$ ;  $p_2 - p_1 = p_c(x, s, \theta) \geq 0$ ;  $p_c(x, s, \theta) = \bar{p}_c(x, \theta) J(s)$ ;

$$p_c = \sigma \cos \vartheta \left( \frac{m_0}{K_0} \right)^{1/2} = \gamma(\theta) \left( \frac{m_0}{K_0} \right)^{1/2} \quad (8)$$

$\theta$ , where  $\sigma$  - interfacial tension coefficient,  $\vartheta$  - wetting angle,  $|K_0|$  - determinant of matrix  $\{k_{i,j}\}$ ;  $J(s)$  - Leverett function.

$$\vec{f}_1 = K_1 \left( \nabla p + \int \nabla \frac{\partial p_c}{\partial s} \frac{k_2}{k} ds \right), \quad (9)$$

$$K_i = K_0(x) k_i(s) = K_0(x) \frac{\bar{k}_i(s)}{\mu_i}, \quad (10)$$

$$p = p_1 - \int_s^1 \frac{\partial p_c}{\partial s} \frac{k_2}{k} ds + \rho_1 gh \quad (11)$$

$\rho_i$  - density, (both fluids are assumed to be incompressible, i.e.  $\rho_i = const$ ),  $g$  - acceleration of gravity,  $h$  - height.

$$a_2 = K_1 \int_s^1 \frac{\partial}{\partial \theta} \left( \frac{\partial p_c}{\partial s} \frac{k_2}{k} \right) ds, \quad (12)$$

$$K = K_0 k = K_0 (k_1 + k_2), \quad (13)$$

$$\vec{f}_2 = K \int_s^1 \nabla \frac{\partial p_c}{\partial s} \frac{k_2}{k} ds + K_2 (\nabla p_c + (\rho_2 - \rho_1) \vec{g}) \quad (14)$$

$$a_3 = K \int_s^1 \frac{\partial}{\partial \theta} \left( \frac{\partial p_c}{\partial s} \frac{k_2}{k} \right) ds + K_2 \nabla \theta, \quad \vec{v} = \vec{v}_1 + \vec{v}_2, \quad (15)$$

$div \vec{v} = 0$ ;  $\vec{v}_i$  - velocity;

$$\lambda(s, \theta) = \sum_{i=1}^3 \frac{\alpha_i \lambda_i}{\rho_i c_{pi}}, \quad (16)$$

$\alpha_1 = m_0 s_1$ ,  $\alpha_2 = m_0 (1 - s_1)$ ,  $\alpha_3 = 1 - m_0$ ;  $\lambda_i$  - thermal conductivity ( $i=1,2,3$ , respectively water, oil and core);  $c_{pi}$  - heat capacity coefficient of  $i$ -phase at constant pressure.

## 2.2. Model Description and 3D Simulation Results

For the proposed Leverett function formula:

$$J(s) = \frac{1}{b + (a-b) \cdot s^\alpha} - c \cdot s^\beta, \quad (17)$$

were taken following constants:  $a = 5$ ;  $b = 0.2$ ;  $c = 0.2$ ;  $\alpha = 1$ ;  $\beta = 500$ .

Table 1

Description of the Cases  
analyzed in this study

Cases considered	Description
Case 1	W/o barrier and w/o drainage
Case 2	W/o barrier and with drainage
Case 3	With barrier and w/o drainage
Case 4	With barrier and with drainage

Table 2

Reservoir geometry, rock and fluid properties considered for the all 4 cases

Property	Denotation (Unit)	Value
Reservoir Radius	R (m)	40
Total Thickness of the Reservoir	H (m)	20
Initial Water Zone Thickness	H <sub>w</sub> (m)	10
Initial Oil Zone Thickness	H <sub>o</sub> (m)	10
Well Penetration Thickness	H <sub>p</sub> (m)	4.5
Water Viscosity	$\mu_1$ (cp)	0.5
Oil Viscosity at $\theta_{\min}$	$\mu_{2\max}$ (cp)	5
Oil Viscosity at $\theta_{\max}$	$\mu_{2\min}$ (cp)	1
Maximum Surface Tension at $\theta_{\min}$	$\sigma$ kg/s <sup>2</sup>	0.03
Minimum Surface Tension at $\theta_{\max}$	$\sigma$ kg/s <sup>2</sup>	0.015
Horizontal Permeability	$k_h$ (darcies)	2
Vertical Permeability	$k_v$ (darcies)	0.6
Relative Permeabilities	(1 - water, 2 - oil)	$k_1 = s^2$ , $k_2 = (1 - s)^2$
Porosity	$m_0$ (fraction)	0.25
Irreducible (Residual) Water Saturation	$s_1^0$ (fraction)	0.2
Residual Oil Saturation	$s_2^0$ (fraction)	0.2
Total (Liquid) Production Rate in the Oil Zone	$q_1$ (b/d)	1000
Water Production Rate in the Water (Drainage) Zone	$q_2$ (b/d)	3000
Water Density	$\rho_1$ (kg/m <sup>3</sup> )	1000
Oil Density	$\rho_2$ (kg/m <sup>3</sup> )	730
Rock Density	$\rho_3$ (kg/m <sup>3</sup> )	4216
Thermal Conductivity of Water	$\lambda_1$ (W/(m · K))	0.644
Thermal Conductivity of Oil	$\lambda_2$ (W/(m · K))	0.08
Thermal Conductivity of Core	$\lambda_3$ (W/(m · K))	2.4
Specific Heat Capacity Coefficient of Water at Constant Pressure	$c_{p1}$ (J/(kg · K))	4071
Specific Heat Capacity Coefficient of Oil	$c_{p2}$ (J/(kg · K))	2100
Specific Heat Capacity Coefficient of Core	$c_{p3}$ (J/(kg · K))	920
Initial Reservoir Pressure (Modified Pressure)	$p$ (Pa)	$25 \cdot 10^6$
Initial Water Zone Temperature	$\theta$ (K)	350
Initial Oil Zone Temperature	$\theta$ (K)	330

Figures 1 and 2 show the results of 3D reservoir simulation:

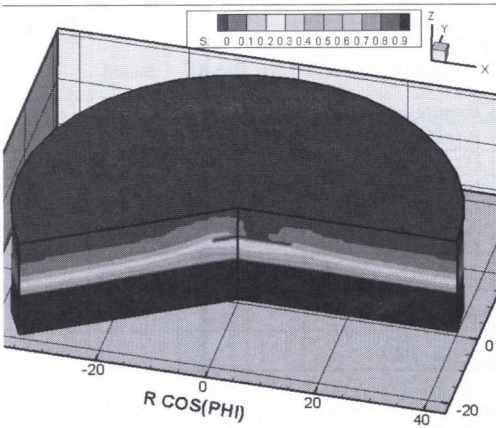


Fig. 1. Water saturation distribution at  $t = 85$  h  
 Rys. 1. Rozkład nasycenia wodą;  $t = 85$  h

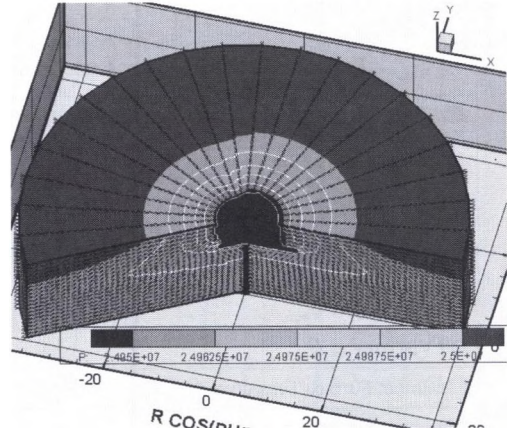


Fig. 2. Pressure and velocity distribution at  $t = 90$  h  
 Rys. 2. Rozkład ciśnienia i prędkości;  $t = 90$  h

### 3. Conclusion

The comparison of results from this work and the work carried out by Siddiqi and Wojtanowicz [2] suggest that a novel model can be used to study the effect of an impermeable barrier and downhole water sink technology on the coning phenomenon. The results could help in selecting methods for specific reservoir conditions (see figures 3-6).

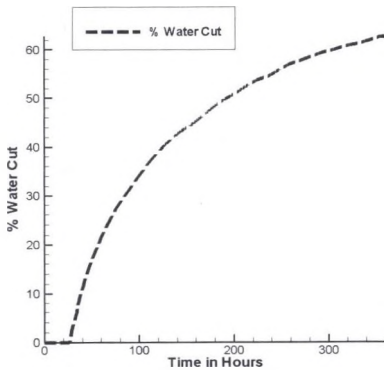


Fig. 3. Case 1  
 Rys. 3. Przypadek 1

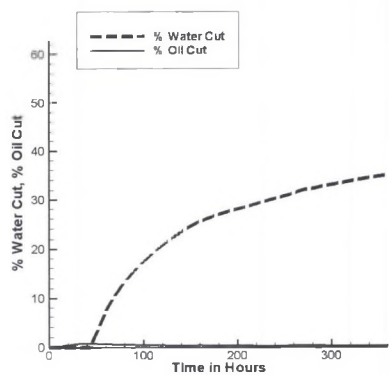


Fig. 4. Case 2  
 Rys. 4. Przypadek 2



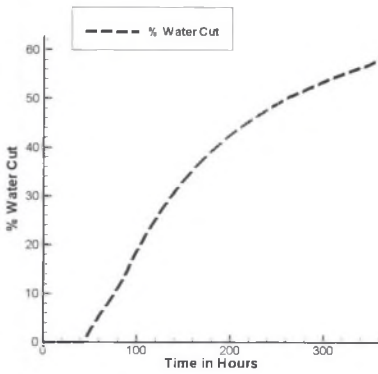


Fig. 5. Case 3

Rys. 5. Przypadek 3

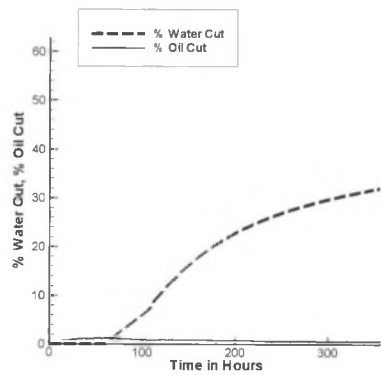


Fig. 6. Case 4

Rys.6. Przypadek 4

### Case 1 vs. Case 3 (Conventional well vs. Barrier shut off technology)

The study revealed that placing a man-made impermeable barrier around the well bore would delay the water breakthrough and, thus, can be useful in increasing the period of water free oil. Study also showed that breakthrough time was directly proportional to the radius of gel barrier. The results from this model showed that although placement of such a layer delays the breakthrough of water, it does not stop water-coning process. In case of high oil production rate, the water simply goes around the barrier's top and breaks to the well's completion. After the water breakthrough, the reservoir system behaves in the same way as if there was no barrier, i.e. the final water-cut value in the barrier case is the same as in the no barrier case.

### Case 1 vs. Case 2 (Conventional well vs. DWS Technology)

The study revealed that in the homogenous reservoir, using dual completion, it was possible to decrease water-cut in the oil production by draining water from the bottom completion and producing oil from the top completion. This study also confirms the fact that has been established by earlier studies: dual completion can stop water coning but for doing that the water production rate from the drainage has to be much higher than the oil production rate.

### Case 2 vs. Case 4 (DWS Technology vs. Barrier shut off + DWS Technology)

It was observed that DWS technique has not high efficiency in controlling water coning in the presence of an impermeable barrier around the well bore as the barrier stops the pressure communication between the sink and the production completion. Hence the results obtained from the novel 3D model agree with the physical model (the experimental data) as well as with results of numerical simulator.

## BIBLIOGRAPHY

1. Bocharov O.B., Telegin I.G.: Numerical modeling of thermo-capillary countercurrent impregnation, *Thermo physics and aeromechanics*, 2005, volume 12, № 3.
2. Siddiqi, S. S. and Wojtanowicz, A. K.: A Study of Water Coning Control in Oil Wells by Injected or Natural Flow Barriers Using Scaled Physical Model and Numerical Simulator, SPE 77415, presented at the SPE Annual Technical Conference and Exhibition held in San Antonio, Texas, 29 September–2 October 2002.
3. Zhumagulov B.T., Monakhov V.N.: *The Fluid Dynamics of Oil Production*: Translated & ed. by AgipK CO. – Milan: Interservice, 2003, p. 307.
4. Hernandez Juan C.: *Oil Bypassing by Water Invasion to Wells: Mechanisms and Remediation*, PhD Dissertation, August 2007.

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