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Determination of Starting Pressure Gradient of Oil and Water in Low-Permeability Reservoirs Using Genetic Algorithm

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Abstract. We consider a method for the determination of the starting pressure gradients of oil and water in two-phase flow in low-permeability reservoirs. Moreover, we obtain the relative permeability curves of oil and water according to water saturation for the interpretation of oil-water two-phase flow.

In the case of two-phase Darcy flow in reservoirs, in order to obtain the relative permeability curves of oil and water according to water saturation, the JBN (Johnson, Bossler and Naumann) method is improved universally which is based on the analysis of data of two-phase unsteady displacement. The method may be improved in the case of low velocity non-Darcy flow in the low-permeability reservoirs, too. Therefore, in the context, we present a new method by which we can determine the starting pressure gradient of oil and water in two-phase non-Darcy flow in the low-permeability reservoirs. Based on these starting pressure gradients, we obtain relative permeability curves of oil and water according to water saturation by the process of data from two-phase unsteady displacement experiment using the Genetic Algorithm. In order to do for this, when oil and water flow simultaneously, the water content function in the condition of oil-water two-phase flow is obtained from the equations of motion of oil and water, and the equation of determining relative permeabilities using experimental data is presented. Based on this, the starting pressure gradients of oil and water are determined using search method of the Genetic Algorithm with powerful self-adaptability, and the curve of the relative permeability is plotted.

The method can be improved effectively to determine the starting pressure gradients and relative permeabilities of oil and water in two-phase seepage in the low-permeability reservoirs and to study the numerical simulation and the reservoir engineering in these reservoirs.

Keywords. Low-permeability reservoir, Low velocity non-Darcy flow, Oil-water two-phase flow, Starting pressure gradient, Relative permeability

1. Introduction

At the present lots of attentions are turned to the development of low and ultra-low permeability reservoirs and the researches that reclaim the flow theory, and its application areas in these reservoirs have been getting wider [1], [2], [3], [4]. Xie et al.

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[5] established the seepage model of the multi-stage fractured horizontal well considering stress sensitivity and the starting pressure gradient in order to evaluate its productivity, and Li and Zhang [6] presented the production calculation model in consideration of variable starting pressure gradient in the ultra-low permeability reservoir. Ye et al. [7] presented the fractal model for calculation of the starting pressure gradient considering the fractal dimension of the tight oil reservoir, and Su et al. [8] built the analytical model for the permeability of oil and water in the low-permeability reservoir based on the fractal theory for porous media. Ke et al. [9] studied the effect of the starting pressure gradient on the remaining oil distribution in the heavy-oil reservoirs, and Tian et al. [10] addressed the different factors that affect the starting pressure gradient in the tight sandstone gas reservoirs with high water saturation. Wang et al. [11] provided the multi-scale insights on the starting pressure gradient in the low-permeability porous media. As known, the flow of fluids in these reservoirs disobeys to the traditional Darcy's law. In the non-Darcy flow theory in the low-permeability reservoirs one of essential problems is the existence of a starting pressure gradient [12], [2], [13]. Usually, the starting pressure gradient in the case of single-phase flow is determined by the experimental measurement and also estimated by the interpretation of well testing data. In the case of oil-water two-phase flow in low-permeability reservoirs a starting (or a minimal starting) pressure gradient of two-phase flow are described [14], [15], [16], [17], [3], [18]. However, in multiphase flow a method of determining starting pressure gradients of phases has not been suggested obviously yet. The problem for determining the starting pressure gradient and the relative permeability of oil and water in two-phase flow in the low-permeability reservoirs are surely needed for the study of reservoir engineering such as oil displacement by water. In fact, there is no guarantee by which the respective starting pressure gradients of oil and water in the single-phase flow are being remained without a change of the starting pressure gradient in the simultaneous flow of two phases, and this assumption is impossible. On the other hand, in two-phase flow the total or minimal starting pressure gradient of two-phase is estimated in the experiment and, however, the concrete meaning of this starting pressure gradient and its application are not obvious.

In this connection, we have studied a method by which we can determine the starting pressure gradient and relative permeabilities of oil and water in oil-water two-phase non-Darcy flow in the low-permeability reservoirs by processing data from two-phase unsteady displacement using the Genetic Algorithm.

2. Methodology

2.1. Determination of the relative permeability of oil and water by two-phase unsteady displacement

The equation of motion when oil and water flow simultaneously with the low velocity non-Darcy law in the low-permeability reservoir are as follows.

$$v_o = vf_o = -\frac{kk_{ro}}{\mu_o}\left(\frac{\partial p_o}{\partial x} + \lambda_o + \rho_o \sin\theta\right), \tag{1}$$

$$v_w = vf_w = -\frac{kk_{rw}}{\mu_w}\left(\frac{\partial p_w}{\partial x} + \lambda_w + \rho_w \sin\theta\right), \tag{2}$$

where $v=v_o+v_w$-total flow rate, m/s
v_o, v_w-flow rate of oil and water, respectively, m/s
f_o, f_w-content function of oil and water, respectively
p_o, p_w-pressure in oil and water phase, respectively, Pa
μ_o, μ_w-viscosity of oil and water, respectively, Pa·s
k-absolute permeability of reservoir, m^2
k_{ro}, k_{rw}-relative permeability of oil and water, respectively
λ_o, λ_w-starting pressure gradient of oil and water, respectively, Pa/m
ρ_o, ρ_w-density of oil and water, respectively, kg/m^3
g-acceleration of gravity, m/s^2
θ-formation slope, rad

From Eqs. 1 and 2, the water content function (Buckley-Leverett) $f_w(s)$ in the condition of oil-water two-phase flow is obtained as follows.

$$f_w(s) = \frac{1 + \frac{1}{v}\frac{kk_{ro}}{\mu_o}\left(\frac{\partial p_C}{\partial x} + \lambda_o - \lambda_w - g\Delta\rho\sin\theta\right)}{1 + \frac{k_{ro}\mu_w}{k_{rw}\mu_o}}, \tag{3}$$

Where $p_c=p_o-p_w$- capillary pressure, Pa
s-water saturation
$\Delta\rho=\rho_w-\rho_o$, kg/m^3

When oil and water are filtrated simultaneously with Darcy's law in the reservoir, the JBN method is improved universally for determination of the relative permeability of phases according to water saturation. This method is based on the interpretation of data from two-phase unsteady displacement experiment.

We can solve the problem for determining relative permeabilities of phases based on the unsteady displacement, too. In our case, oil and water are filtrated with non-Darcy law in the low-permeability reservoirs.

Then $\theta=0$, and in disregard of the capillary pressure, the Eqs. 1, 2 and 3 is rewritten as follows.

$$v_o = -\frac{kk_{ro}}{\mu_o}\left(\frac{\partial p}{\partial x} + \lambda_o\right), \tag{4}$$

$$v_w = -\frac{kk_{rw}}{\mu_w}\left(\frac{\partial p}{\partial x} + \lambda_w\right), \tag{5}$$

$$f_w(s)=\frac{1+\frac{1}{v}\frac{kk_{ro}}{\mu_o}(\lambda_o-\lambda_w)}{1+\frac{k_{ro}\mu_w}{k_{rw}\mu_o}}, \tag{6}$$

According to the Buckley-Leverett theory of the oil displacement by water, the formulas of determining the relative permeability of oil and water based on the experimental data may be obtained as follows.

$$k_{ro}(s_{we})=f_o(s_{we})d\left[\frac{1}{V(t)}\right]\Big/d\left[\frac{1}{I_o(t)V(t)}\right], \tag{7}$$

$$k_{rw}(s_{we})=\frac{\mu_w}{\mu_o}f_w(s_{we})d\left[\frac{1}{V(t)}\right]\Big/d\left[\frac{1}{I_w(t)V(t)}\right], \tag{8}$$

$$I_o(t)=\frac{v(t)/[\Delta p(t)-\lambda_o L]}{v_i/(\Delta p_i-\lambda_o L)}, \tag{9}$$

$$I_w(t)=\frac{v(t)/[\Delta p(t)-\lambda_w L]}{v_i/(\Delta p_i-\lambda_w L)}, \tag{10}$$

where s_{we} -water saturation in the output side

$V(t)$-dimensionless cumulative volume of injected water, m^3

$$V(t)=\frac{1}{\phi AL}\int_0^t q_{wi}(t)dt=\frac{1}{f'_w(s_{we})}, \tag{11}$$

ϕ-porosity

A, L-cross section (m^2) and length (m) of the core sample, respectively

$q_{wi}(t)$-water injection rate at moment t, m^3/s

v_i-total flow rate at initial moment, m/s

Δp_i-pressure difference between both ends of the sample at initial moment, Pa

On the other hand, the water saturation in the output side may be decided from the following formula.

$$s_{we}(t)=s_i+\frac{Q_o(t)}{\phi AL}-f_o(s_{we})v(t), \tag{12}$$

where s_i-initial water saturation of the sample

$Q_o(t)$-cumulative oil recovery in the output side at the moment t, m^3

$$Q_o(t) = \int_0^t q_o(t)dt$$

Therefore, if λ_o and λ_w are known, in the case of oil-water two-phase flow in the low-permeability reservoirs the relative permeability of oil and water may be determined with the data of two-phase unsteady displacement.

2.2. Determination of starting pressure gradient of oil and water using Genetic Algorithm.

At the previous section we have presupposed that the starting pressure gradients of phases λ_o and λ_w have been known. Therefore, only when λ_o and λ_w are determined correctly, the value of the relative permeability of oil and water according to water saturation may be obtained reliably.

As we said, the starting pressure gradient of phases in multiphase flow in the low-permeability reservoirs is resulted from not only characteristics of porous medium and fluid but also complex interactions such as physical, chemical and hydrodynamic interactions. Then, it is natural that these gradients in the single-phase flow and in two-phase flow are differentiated each other.

Therefore, for the determination of the starting pressure gradient and the relative permeability according to water saturation of oil and water in two-phase flow from data of two-phase unsteady displacement we have used the Genetic Algorithm based search method with powerful self-adaptability.

There, we have drawn up the adaptability by using the water content function $f_w(s_{we})$ in the output that reflects the flow characteristics of oil and water.

$$fitness = 1 - \frac{1}{n}\sum_{i=1}^{n}\left[f_{wa}(s_{wei}) - f_{wt}(s_{wei})\right]^2 , \tag{13}$$

where $f_{wa}(s_{wei})$, $f_{wt}(s_{wei})$-actual and calculated value of the water content function at i^{th} measure point, respectively

s_{wei}-water saturation in the output at i^{th} measure point (moment t_i)

The actual value of the water content function is obtained from experiment result as follows.

$$f_{wa}(s_{wei}) = \frac{Q_w(t_i)}{q_o(t_i) + q_w(t_i)} , \tag{14}$$

where $q_o(t_i)$, $q_w(t_i)$-flow rate of oil and water in the output at moment t_i, respectively, m^3/s

The theoretical value of the water content function is calculated from Eq. 6 as follows.

$$f_{wt}(s_{wei}) = \frac{1 + \frac{1}{v(t_i)} \frac{k_{ro}}{\mu_o}(\lambda_o - \lambda_w)}{1 + \frac{k_{ro}}{k_{rw}} \frac{\mu_w}{\mu_o}}, \tag{15}$$

The optimal search parameters using the Genetic Algorithm are the starting pressure gradients of oil and water λ_o, λ_w. We must compose the search space of λ_o and λ_w, and in every generation calculate $k_{ro}(s_{wei})$, $k_{rw}(s_{wei})$ from Eqs. 7, 8, and $f_{wa}(s_{wei})$, $f_{wt}(s_{wei})$ from Eqs. 14, 15, and estimate the adaptability, and go on with the search through the Genetic operation.

After λ_o and λ_w are optimally found, with these we must finally calculate the value of relative permeability of oil and water to water saturation and plot the relative permeability curve.

Based on this consideration, we have developed the program in Windows XP, which determines the starting pressure gradient of oil and water, and plots the relative permeability curve in two-phase non-Darcy flow in the low-permeability reservoirs from data of two-phase unsteady displacement.

3. Result and discussion

Low-permeability core samples at two different permeability levels were taken from a reservoir in the Korea West Sea oilfield. With them in laboratory, the two-phase unsteady displacement has been processed and its results have been analyzed. Initial materials of samples are shown in table 1.

Table 1. Materials of samples

sample	Length L,cm	Diameter D,cm	Porosity ϕ ,%	Initial water saturation s_i, %	Viscosity, mPa·s		Air permeability k, 10^{-3}m^2
					oil, μ_o	water, μ_w	
1	6.2	2.72	12.1	0.32	9.84	0.98	4.12
2	6.1	2.20	9.3	0.36	6.26	0.96	0.97

The starting pressure gradients of oil and water that have been determined from data of two-phase unsteady displacement are shown in table 2 with the starting pressure gradients of phases in the single flow.

Table 2. Starting pressure gradients of oil and water

sample	λ_o, kPa/m		λ_w, kPa/m	
	Two phase	Single phase	Two phase	Single phase
1	16.75	2.98	8.03	0.97
2	17.78	4.67	10.12	1.26

As shown in table 2, the starting pressure gradients of oil and water in two-phase flow and single-phase flow are different. The starting pressure gradients of water and oil in case of the two-phase flow are a lot bigger than those in the case of single-phase flow. This shows that when we use the starting pressure gradients of water and oil in the case of two-phase flow, the investigation of oil-water two-phase flow can be improved effectively in the low-permeability reservoirs.

4. Conclusion

The process of data from two-phase unsteady displacement using Genetic Algorithm may determine the starting pressure gradients of oil and water in two-phase non-Darcy flow in the low-permeability reservoirs. Therefore, based on these starting pressure gradients, we can obtain reliably the relative permeability curve for oil and water according to water saturation.

In order to interpret of oil-water two-phase flow, we have considered the method for the determination of the starting pressure gradients of oil and water in two-phase flow in low-permeability reservoirs and obtained the relative permeability curves of oil and water according to water saturation. We present the new method by which we can determine the starting pressure gradient of oil and water in two-phase non-Darcy flow in the low-permeability reservoirs. Based on these starting pressure gradients, we obtain relative permeability curves of oil and water according to water saturation by the process of data from two-phase unsteady displacement experiment using the Genetic Algorithm.

In order to do for this, when oil and water flow simultaneously, the water content function in the condition of oil-water two-phase flow is obtained from the equations of motion of oil and water, and the equation of determining relative permeabilities using experimental data is presented. Based on this, search method of the Genetic Algorithm with powerful self-adaptability is used, where the adaptability is obtained from the actual and calculated water content and the search space of λ_o and λ_w is constructed. λ_o and λ_w are optimally found, the value of relative permeability of oil and water to water saturation is calculated and the relative permeability curve is plotted. We compare the starting pressure gradients in the two-phase flow to that in the single-phase flow using core samples from the Korea West Sea oilfield.

The starting pressure gradients of phases in multiphase flow are unequal to these in single-phase flow and usually the former is lots bigger than the latter.

The method presented in this paper may improve effectively the investigation of oil-water two-phase flow in the low-permeability reservoirs.

References

[1] Huang YZ. Percolation mechanism in low-permeability reservoirs [M]. Beijing: Petroleum Industry Press, 1998, pp.14～65. (in Chinese)

[2] Cheng Z, et al. Oil water two phases and well test analysis of low-permeability reservoir progress. Well testing, vol. 20, No. 2, 2011, pp. 1-5. (in Chinese)

[3] Cheng Z, et al. New progress of non-Darcy well testing analysis for two-phase oil and water and its outlook. Well testing vol. 21, No. 3, 2012, pp. 8-12, 16. (in Chinese)

[4] Song F, Song X, Wang Y, Sun Y. Single- and two-phase flow model in low-permeability reservoir. Petroleum vol. 5, No. 2, 2019, pp. 183-190.

[5] Xie Y, He Y, Hu Y, Jiang Y. Study on productivity Prediction of Multi-Stage Fractured Horizontal Well in Low-Permeability Reservoir Based on Finite Element Method. Transport in Porous Media vol. 141, 2022, pp. 629-648.

[6] Li CL, Zhang Y. Production calculation model considering variable start-up pressure gradient in ultra-low permeability reservoirs. IOP Conference Series: Earth and Environment Science, vol. 354, 2019, 2019

International Conference on New Energy and Future Energy System 21-24 July 2019, Macao, China Citation C L Li and Y Zhang 2019 IOP Conf. Ser.: Earth Environ. Sci. 354 012127.

[7] Ye W, Wang X, Cao C, Yu W. A Fractal model for threshold pressure gradient of tight oil reservoirs. Journal of Petroleum Science and Engineering vol. 179, 2019, pp. 427-431.

[8] Su H, Zhang S, Sun Y, Wang X, Yu B, Wang Y, Yang M, Meng W, Yi H, Yu J, Sun Z. Comprehensive Model for Oil-Water Relative Permeabilities in Low-Permeability Reservoirs by Fractal Theory. Fractals vol. 28 No. 3, 2020, 2050055.

[9] Ke W, Liu Y, Zhao X, Yu G, Wang J. Study on the Effect of Threshold Pressure Gradient on Remaining Oil Distribution in Heavy Oil Reservoir. ACS Omega 2022, 7, 5, pp. 3949-3962.

[10] Tian W, Li A, Ren X, Josephine Y. The threshold pressure gradient effect in the tight sandstone gas reservoirs with high water saturation. Fuel 226, 2018, pp. 221-229.

[11] Wang H, Wang J, Wang X. A. Chan, Mult-scale insight on the threshold pressure gradient in low-permeability porous media. Symmetry 12(3), 2020.

[12] Lu CY, et al. An experimental study on starting pressure gradient of fluids flow in low-permeability sandstone porous media. Petroleum exploration and development vol. 29, No. 2, 2002, 86-89. (in Chinese)

[13] Alvaro Prado, et al. Modification of Darcy's law for the threshold pressure gradient. Journal of Petroleum Science and Engineering vol. 22, No. 4: 1999, pp. 237-240.

[14] Li JD, et al. Study on water-oil percolation law of low-permeability reservoir in Dajing oilfield. Journal of oil and gas technology vol. 30 No. 1, 2008, pp. 285-288. (in Chinese)

[15] Xu JH, et al. A new method and application calculating start-up pressure gradient in low permeable reservoirs. Journal of southwest Petroleum University, 2007, 29(4): 64-66. (in Chinese)

[16] Yao YD, et al. Oil-water two-phase fluid flow in low-permeability reservoir. Journal of the University of Petroleum, China. vol. 29 No.2, 2005, pp. 52-56. (in Chinese)

[17] Su FQ, et al. An experimental study on minimal starting pressure gradient of oil and water two phases in low-permeability sandstone reservoir-taking block Shishen 100 in Shinan oilfield as an example. PGRE vol. 11, No. 4, 2004, pp. 44-48. (in Chinese)

[18] Li ZX, et al. The new calculated method and the application of starting pressure gradient in low-permeability reservoirs. Petroleum exploration and development vol. 30, No 3, 2004, pp. 109-111. (in Chinese)