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The Influence of Dynamic Capillary Pressure on the Seepage of Ultra-Low Permeability Reservoir

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Abstract: Capillary pressure has a great influence on the percolation of oil-water two-phase. We find that the seepage resistance of oil-water two-phase in ultra-low permeability reservoir is complex and the capillary pressure presents dynamic variation features through water flooding experiment. In this paper, first, we study the variation features of seepage resistance by mercury injection experiment. Second, we establish a percolation numerical model of oil-water two-phase which considers the dynamic capillary pressure in ultra-low permeability reservoir. Finally, we analyze the sensitive factors of dynamic capillary pressure and the effects of dynamic capillary pressure on oil-water two-phase seepage.

The results show that the capillary pressure and the dynamic effect of capillary pressure are obvious in ultra-low permeability reservoir. When the coefficient τ of dynamic capillary pressure or the injection rate is larger, the dynamic capillary pressure will be bigger. The existence of dynamic capillary pressure hinders the fltting speed of waterflood front and reduces the oil production. The dynamic capillary pressure makes the moisture content rise faster for water wetting ultra-low permeability reservoirs while it reduces the rising velocity of moisture content for oil wetting ultra-low permeability reservoirs. This study is of great benefit to finding out the percolation law of ultra-low permeability reservoir and the subsequent work of development.

Keywords: Dynamic capillary pressure, oil-water two-phase, seepage, ultra-low permeability.

INTRODUCTION

Capillary pressure influence on the percolation of oil-water two-phase greatly. Generally, only static capillary pressure (oil-water interface reaches to balance state) is considered and the dynamic capillary pressure is ignored (oil-water interface fails to reaches to the equilibrium state) in high permeability reservoirs. While the dynamic capillary pressure has a great effect on the seepage of oil-water two-phase in ultra-low permeability reservoir for the pores and throats are very fine and the flow speed is very low. Hence, it is necessary to study the dynamic capillary pressure of ultra-low permeability reservoir.

The dynamic capillary pressure refers to the capillary pressure relates to the variation rate of the wetting phase saturation when the oil-water interface fails to reach to the state of equilibrium. A lot of studies found that the relationship between capillary pressure and saturation is not unique and the dynamic effect of capillary pressure exists in the unbalanced state while it does not exist in the equilibrium state [1-4]. The dynamic capillary pressure in unsteady state is larger than that in the equilibrium state or steady state during the process of unsteady experiment. While others only studied the capillary pressure when the oil-water interface reaches to the equilibrium state and thought that the capillary pressure is a function of wetting phase saturation [5, 6]. Topp *et al*. (1967) found that the dynamic effect of capillary pressure (see Fig. **1**) and the capillary pressure is bigger than the static capillary pressure under the same saturation when the displacement speed is larger [4].

Stauffer (1978) studied the dynamic effect of capillary pressure by displacement experiment. He revealed that the relationship between capillary pressure and saturation is not unique and the transient capillary pressure is greater than quasi static capillary pressure [7]. He also established empirical equations between capillary pressure and saturation (see Eqs. 1 and 2) [8]. Hassanizadeh *et al*. (1993) confirmed that the equations proposed by Stauffer are correct [9]. The equations are given as:

$$p_c^d - p_c^e(S_w) = -\tau_s \frac{\partial S_w}{\partial t} \tag{1}$$

$$\tau_s = \frac{\alpha_s \mu_w \phi}{K\lambda}\left(\frac{P_e}{\rho_w g}\right)^2 \tag{2}$$

where, α–constant, which is equal to 0.1; φ–porosity, fraction; μ_w–viscosity of the wetting phase, $mPa\cdot s$; P_e, λ–factors of the relationship between capillary pressure and saturation in the Brook-Corey model; K–absolute permeability of the wetting phase, $10^{-3}\mu m^2$; ρ_w–density of the wetting phase, kg/m^3; g–gravity acceleration, m/s^2. Wildenschild *et al*. (2001) found that the dynamic effect of capillary pressure is obvious in sandstones and the capillary

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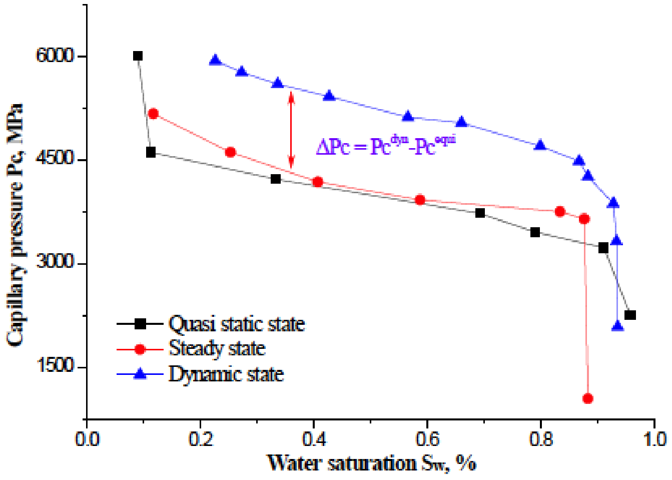

Fig. (1). The dynamic effect of the capillary pressure.

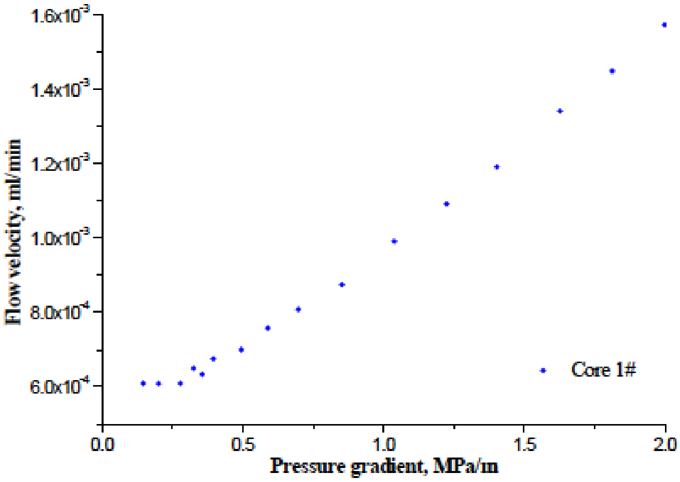

Fig. (2). The seepage flow curve of water displacing oil (1#).

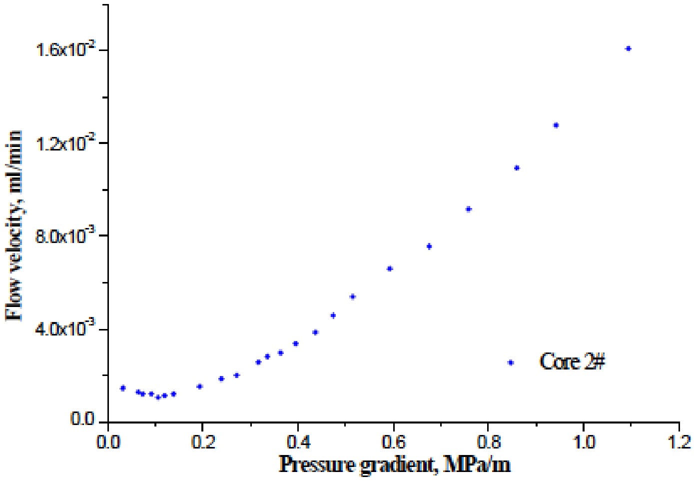

Fig. (3). The seepage flow curve of water displacing oil (2#).

pressure will be larger at faster displacement speed. While there is no dynamic effect of capillary pressure in fine grained sandstones [10].

Previous studies show that there is a lack of study about dynamic capillary pressure in ultra-low permeability reservoir. Hence, it is necessary to analyze the dynamic capillary pressure through experiments and the influence on the oil-water two-phase flow since the dynamic capillary pressure is obvious in ultra-low permeability reservoir.

In this paper, we aim at studying the influence of dynamic capillary pressure on the seepage of oil-water two-phase in ultra-low permeability reservoir. First, we study the

Table 1. Parameters of cores in the water flooding experiment.

Sample	Length (*cm*)	Diameter (*cm*)	Air based Permeability ($10^{-3}\mu m^2$)	Porosity (%)	Dry Weight (*g*)	Wet Weight (*g*)	Saturated Volume (*mL*)	Saturation (%)
1#	16.85	9.90	0.14	10.8	3205.4	3294.1	111.15	79.39
2#	19.65	9.85	0.73	11.7	3525.7	3649.6	155.36	88.73

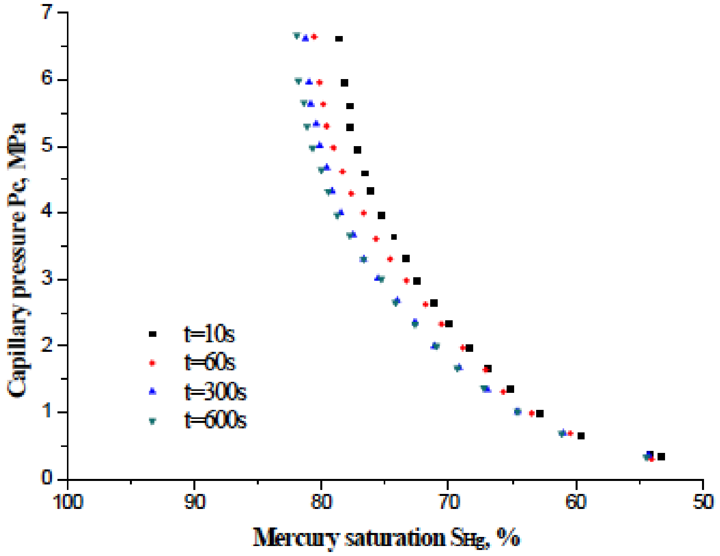

Fig. (4). The capillary pressure curves of different mercury injection rate.

variation features of seepage resistance by mercury injection experiment. Second, we establish a percolation model of oil-water two-phase which considers the dynamic capillary pressure in ultra-low permeability reservoir. Finally, the dynamic capillary pressure sensitive factors and the effects of dynamic capillary pressure on oil-water two-phase flow are analyzed.

1. CAPILLARY PRESSURE IN THE SEEPAGE OF OIL-WATER TWO-PHASE

In this section, we focus on the capillary pressure phenomenon of oil-water two-phase flow in ultra-low permeability reservoir through water flooding experiment and mercury injection experiment.

1.1. The Water Displacing Oil Experiment

1.1.1. Experimental Method

The seepage resistance is very big for the existence of oil-water interface. In order to analyze the capillary pressure effect, we measure the flow rate under different conditions of differential pressure. The ultra-low permeability cores from Changqing oilfield in Ordos basin are used in the experiment. The experimental fluid is standard brine and kerosene. We conduct the water flooding experiment by setting different injection velocity, and then we measure the pressure every certain time before and after the core end during the displacement process with cores of different magnitude permeability. The displacement process is repeated many times. The seepage of single phase is in accord with Darcy's law while the seepage of oil-water two-phase is not, there must be additional seepage resistance which is caused by the capillary pressure.

1.1.2. Experimental Results and Analysis

The seepage curves of water displacing oil (see Figs. **2** and **3**) indicate that the relationship between pressure gradient and flow rate of two-phase is not linear which proves the existence of additional seepage resistance. By Eq. 1, we can see that the force may not be resistance and can be driving force when the wetting phase displacing nonwetting phase and the variation rate of saturation is not very big. The capillary pressure performs as driving force when the pressure gradient is small. We conduct mercury injection experiment for further research.

1.2. The Conventional Mercury Injection Experiment

We analyze the capillary pressure curves under different injection rate by conventional mercury injection experiment with cores of similar physical properties. During the mercury injection experiment, we measure the volume of mercury enter into the core and the pressure value when each pressure point reach to a steady state by exerting a pressure under constant pressure differential conditions. For the mercury is non-wetting phase, we can get the capillary pressure and the volume of mercury when the pressure is balanced by pressing the mercury into the core sample under high pressure, then the relationship between the capillary pressure and the mercury saturation of the core sample can be obtained. On Fig. (**4**), We can see that the faster the mercury injection rate, the greater the capillary pressure will be. The capillary pressure differs not quite when the mercury

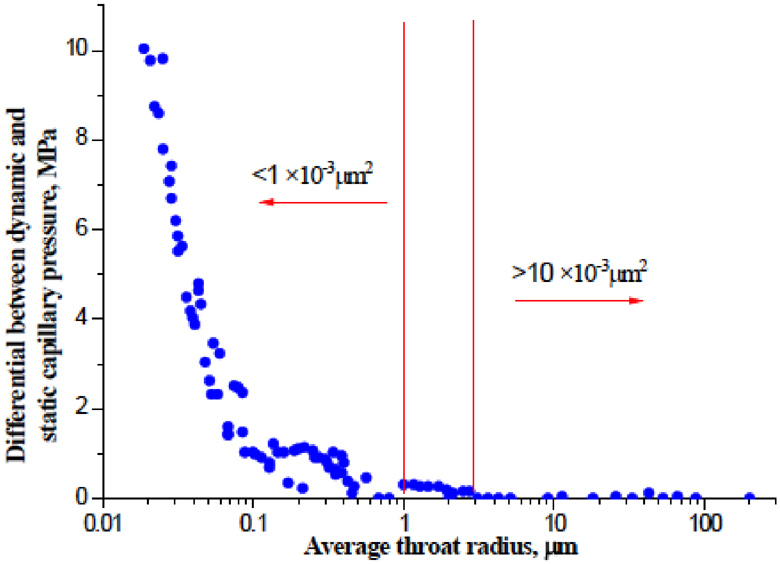

Fig. (5). The dynamic effect of capillary pressure in cores of different permeability.

injection time is 300*s* and 600*s* which indicates that the capillary pressure at the mercury injection time of 300*s* can be approximated for static capillary pressure.

We summarize the relationship between the throats radius and the differentials of dynamic and static capillary pressure based on a number of measurements of cores (see Fig. **5**) and can see that the dynamic capillary pressure increases along with the reduction of permeability. The dynamic capillary pressure can be neglected when the permeability is more than $10\times10^{-3}\mu m^2$ while it cannot be neglected when the permeability is less than $1\times10^{-3}\mu m^2$ (ultra-low permeability reservoir).

2. THE MATHEMATICAL MODEL INCLUDING DYNAMIC CAPILLARY PRESSURE

By previous study, we can see that the dynamic effect of capillary pressure increases the seepage resistance and increases along with the increase of coefficient τ and the variation rate of water saturation. The dynamic capillary pressure depends on porosity, P_e, and the absolute permeability of wetting phase which is determined by the microscopic pore structure of cores. The tighter the reservoir is, the more obvious the dynamic capillary pressure will be. So the dynamic capillary pressure needs to be considered when we establish a percolation model of oil-water two-phase in ultra-low permeability reservoir.

2.1. The Model Establishment of Two-phase Seepage

We assume that (1) the seepage of fluid is isothermal; (2) there is only oil-water two-phase in the media, the seepage of each phase is in accord with Darcy's law; (3) the media is homogeneous and indeformable; (4) the fluid is incompressible; (5) the influence of capillary pressure is considered while the influence of gravity is ignored and the capillary pressure is variational. Then we can establish a percolation model of oil-water two-phase which considers the dynamic capillary pressure in ultra-low permeability reservoir.

The dynamic capillary pressure is given as:

$$p_o - p_w = p_c^d = p_c^e - \tau\frac{\partial S_w}{\partial t} \tag{3}$$

Where, P_c^e is the static capillary pressure and τ is a constant which can be calculated.

The basic differential equation of oil-water two-phase can be given as, for the oil phase,

$$\frac{\partial}{\partial x}\left(\frac{KK_{ro}}{\mu_o}\frac{\partial p_o}{\partial x}\right) = \phi\frac{\partial S_o}{\partial t} \tag{4}$$

for the water phase:

$$\frac{\partial}{\partial x}\left(\frac{KK_{rw}}{\mu_w}\frac{\partial p_w}{\partial x}\right) = \phi\frac{\partial S_w}{\partial t} \tag{5}$$

Thus substituting Eq. 4 into Eq. 5 and then combining with Eq. 3 lead to the equation:

$$\frac{\partial}{\partial x}\left(\frac{KK_{ro}}{\mu_o}\frac{\partial\left(p_w + p_c^e - \tau\partial S_w/\partial t\right)}{\partial x}\right) + \frac{\partial}{\partial x}\left(\frac{KK_{rw}}{\mu_w}\frac{\partial p_w}{\partial x}\right) = 0 \tag{6}$$

Eq. 6 is the two-phase Seepage model for ultra-low permeability reservoir considering the dynamic capillary pressure.

2.2. The Numerical Solution of the Model

Next, we get the numerical solution with IMPES method.

Initial conditions;

$$S_w = S_{wi}\ ;\ P_w = P_{wi}\ ;\ P_o = P_{oi} \tag{7}$$

Boundary condition:

the entrance saturation,

$$S_w(x=0) = 1 - S_{or} \tag{8}$$

the inlet flow rate is a constant at the outside boundary,

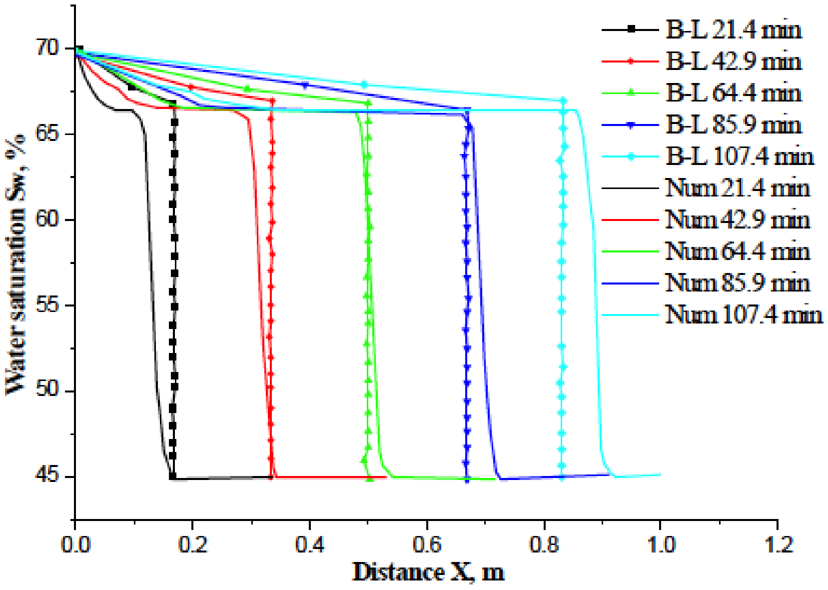

Fig. (6). The water saturation distributions were derived by B-L method and numerical calculation.

$$q = A\left(\frac{KK_{rw}}{\mu_w}\right)_{1-S_{or}} \frac{\partial P_w}{\partial x} \tag{9}$$

the outlet pressure is a constant at the inner boundary,

$$\left.\frac{\partial P_o}{\partial t}\right|_{x=L} = 0 \tag{10}$$

To Eq. 6, by using the finite difference method and assuming that,

$$T_o = \frac{KK_{ro}}{\mu_o}\frac{1}{(\Delta x)^2}\ ;\ T_w = \frac{KK_{rw}}{\mu_w}\frac{1}{(\Delta x)^2}\ , \tag{11}$$

we can get,

$$\begin{aligned}&\left[(T_o)_{i-1/2}^{n+1} + (T_w)_{i-1/2}^{n+1}\right](p_w)_{i-1}^{n+1}\\ &-\left[(T_o)_{i+1/2}^{n+1} + (T_w)_{i+1/2}^{n+1} + (T_o)_{i-1/2}^{n+1} + (T_w)_{i-1/2}^{n+1}\right](p_w)_i^{n+1}\\ &+\left[(T_o)_{i+1/2}^{n+1} + (T_w)_{i+1/2}^{n+1}\right](p_w)_{i+1}^{n+1}\\ &= -(T_o)_{i+1/2}^{n+1}\left[(p_c^d)_{i+1}^{n+1} - (p_c^d)_i^{n+1}\right] + (T_o)_{i-1/2}^{n+1}\left[(p_c^d)_i^{n+1} - (p_c^d)_{i-1}^{n+1}\right]\end{aligned} \tag{12}$$

where,

$$c_i = \left(T_o\right)_{i-1/2}^{n+1} + \left(T_w\right)_{i-1/2}^{n+1};$$

$$a_i = \left(T_o\right)_{i+1/2}^{n+1} + \left(T_w\right)_{i+1/2}^{n+1} + \left(T_o\right)_{i-1/2}^{n+1} + \left(T_w\right)_{i-1/2}^{n+1};$$

$$b_i = \left(T_o\right)_{i+1/2}^{n+1} + \left(T_w\right)_{i+1/2}^{n+1};$$

$$f_i = -\left(T_o\right)_{i+1/2}^{n+1}\left[\left(p_c^d\right)_{i+1}^{n+1} - \left(p_c^d\right)_i^{n+1}\right] + \left(T_o\right)_{i-1/2}^{n+1}\left[\left(p_c^d\right)_i^{n+1} - \left(p_c^d\right)_{i-1}^{n+1}\right].$$

Therefore, Eq. 12 can be changed into the following form :

$$c_i\left(p_w\right)_{i-1}^{n+1} - a_i\left(p_w\right)_i^{n+1} + b_i\left(p_w\right)_{i+1}^{n+1} = f_i \tag{13}$$

Then we get the numerical solution with *IMPES* method. First, we linearize the finite difference equations: the coefficient matrix take the value of time n and the water phase pressure, p_w, take the value of time $n+1$. Second, the water phase pressure, p_w, can be gained through the solution of the linear equations and we can get the water saturation, S_w, by the finite difference equation of Eq. 5. Finally, the dynamic capillary pressure, P_{cd}, can be calculated and then the oil phase pressure, P_o.

2.3. Verification of the Numerical Solution Correctness

The convergence of the numerical solution is controlled by adjusting the spatial step length and time step length of the grids. In order to confirm the correctness of the numerical solution, a comparison of the numerical solutions which do not consider the dynamic capillary pressure and the B-L theory solutions which can gain the water saturation distributions is made (see Fig. **6**). If we take the results calculated by the B-L theory as the exact value, the numerical solution only has a relative error of 2% which is in the reasonable error range. This means the numerical solution is correct.

3. EFFECT OF CAPILLARY PRESSURE ON THE SEEPAGE OF OIL-WATER TWO-PHASE

3.1. Analysis of the Sensitive Factors

The coefficient τ and the variation rate of water saturation influence the dynamic capillary pressure. Next, we analyze the effect of the two sensitive factors on dynamic capillary pressure.

3.1.1. The Factor of Coefficient τ

First, we calculate the coefficient τ of ultra-low permeability reservoir (the parameters can be seen in Table **2**) which can reach to 10^{11}~10^{13}kg/(m·s). While the coefficient τ calculated by predecessors [7, 9, 11, 12] is only 10^4~10^7kg/(m·s). This indicates that the coefficient τ is very big in ultra-low permeability reservoir and that is

Table 2. The parameters used in the calculation of coefficient τ.

Sample	λ	P_e (*Mpa*)	α	μ_w (*mPa·s*)	φ (%)	*K* ($10^{-3}\mu m^2$)	ρ_w (kg/m^3)	*g* (m/s^2)	τ (*kg/(m·s)*)
3#	0.859	0.131	0.1	1.0	9.77	0.033	1000	9.8	6.10E+13
4#	0.775	0.049	0.1	1.0	12.65	0.039	1000	9.8	1.03E+13
5#	1.046	0.040	0.1	1.0	12.01	0.057	1000	9.8	3.42E+12
6#	0.374	0.009	0.1	1.0	12.00	0.100	1000	9.8	3.14E+11
7#	0.637	0.022	0.1	1.0	14.20	0.122	1000	9.8	9.52E+11
8#	0.568	0.031	0.1	1.0	12.27	0.083	1000	9.8	2.60E+12

Table 3. The parameters used in the case.

$K(10^{-3}\mu m^2)$	φ	$q_w(ml/min)$	$L(m)$	$d(m)$	$\mu_o(mPa{\cdot}s)$	$\mu_w(mPa{\cdot}s)$
0.1	0.1	0.1	1	0.025	2	0.5

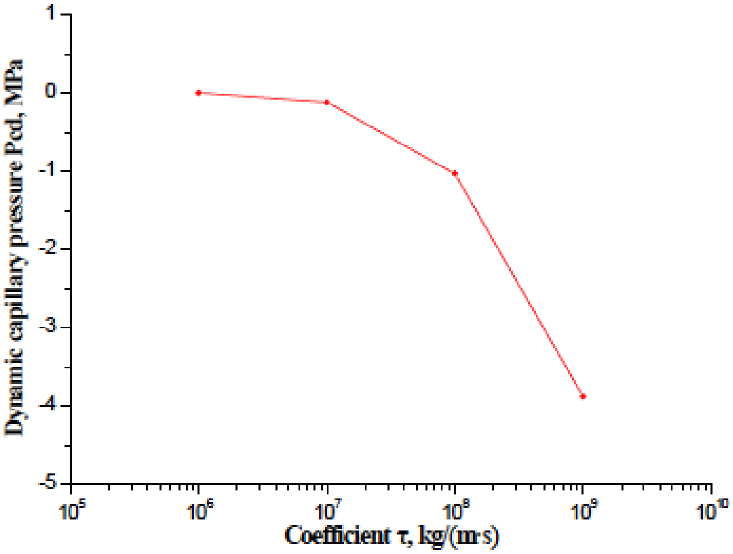

Fig. (7). The dynamic capillary pressure versus the coefficient τ.

the reason why the dynamic effect of capillary pressure is obvious.

Next, we analyze the dynamic capillary pressure and water saturation distributions under different coefficient τ. Where, the coefficient τ can be 10^7, 10^8, 10^9kg/(m·s), respectively.

On Fig. (**7**), we see that the capillary pressure is more obvious when the coefficient τ is bigger. On Fig. (**8**), the coefficient τ is 10^7kg/(m·s) (blue line), 10^8kg/(m·s) (red line), 10^9kg/(m·s) (black line), respectively. It indicates that the coefficient τ is bigger when the reservoir is tighter and the dynamic capillary pressure has a bigger resistance to water so that the dynamic capillary pressure hinders the fltting speed of waterflood front.

3.1.2. The Factor of Water Injection Rate

We calculate the dynamic capillary pressure under different water displacing speed which is 0.1, 0.2, 0.5 ml/min, respectively. When the injection rate is bigger, the dynamic effect of capillary pressure is more obvious (see Fig. **9**).

3.2. Effect of Dynamic Capillary Pressure on the Seepage

A comparison is made with the numerical model under two conditions: one is considering the dynamic capillary pressure and the other is not considering the dynamic capillary pressure.

3.2.1. Effect on the Cumulative Oil Production

We see that the cumulative oil production reduces much when the dynamic capillary pressure is considered (see Fig. **10**).

3.2.2. Effect on the Water Saturation

In Fig. (**11**), it indicates that the fltting speed of water saturation reduces when the dynamic capillary pressure is considered and the existence of dynamic capillary pressure influences the water saturation distribution which makes the saturation gradient smaller. That is the reason why the oil

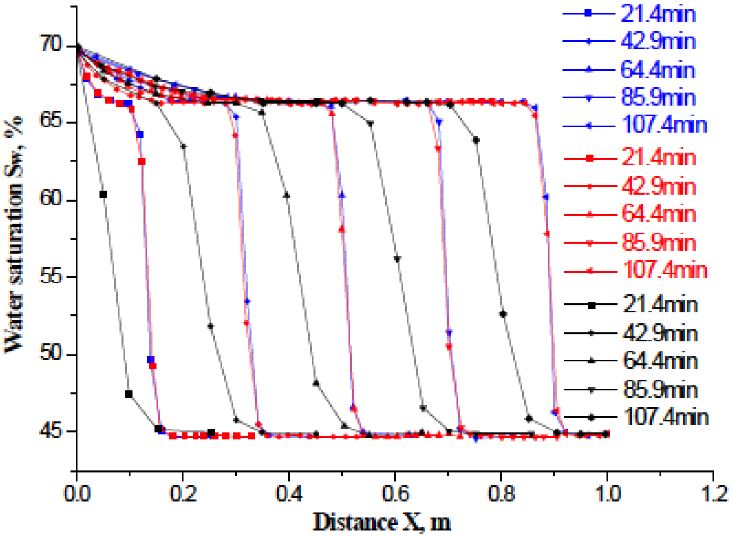

Fig. (8). The water saturation *versus* the coefficient τ.

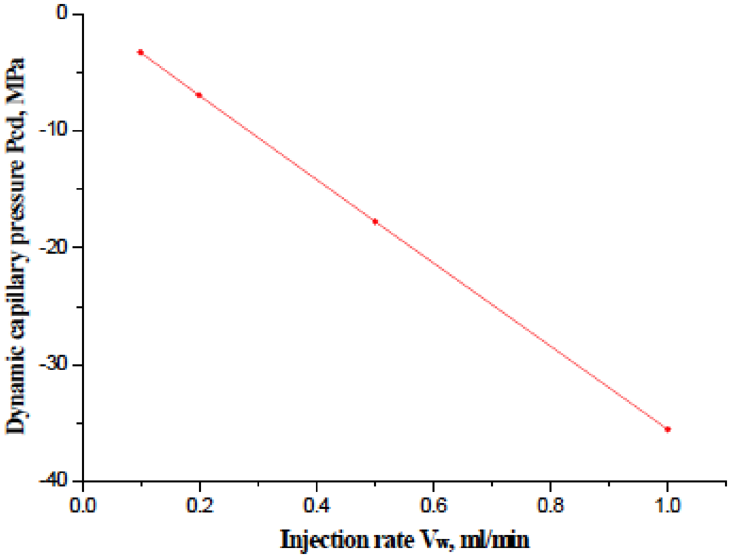

Fig. (9). The dynamic capillary pressure *versus* the injection rate.

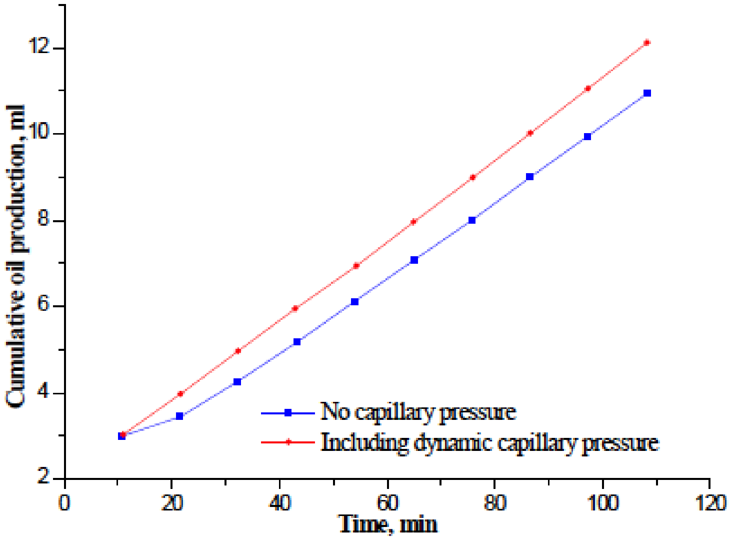

Fig. (10). The accumulated oil production in two cases.

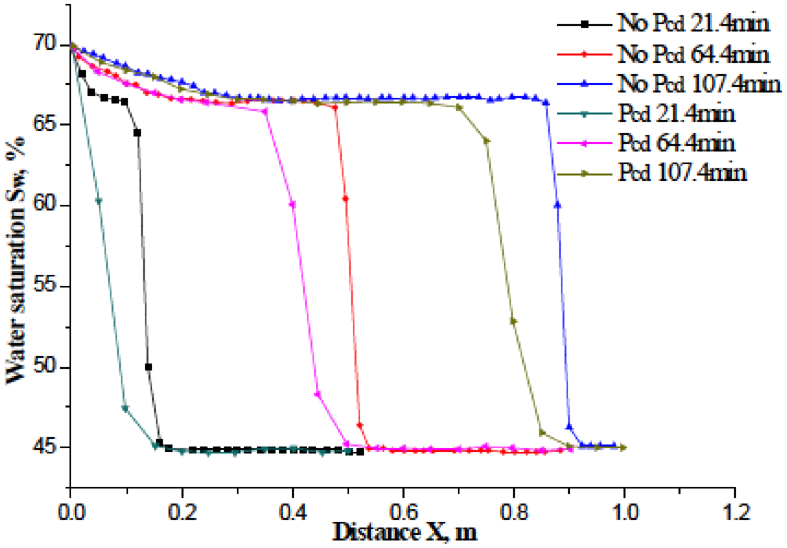

Fig. (11). The water saturation along the core in the different time: no capillary pressure, dynamic capillaty pressure.

production is lower. That is to say the dynamic capillary pressure is an obstructive force.

3.2.3. Effect on the Moisture Content

If we assume that the flow is one dimension in homogeneous, equal thickness and horizontal formation; the influence of gravity is ignored; the rock and fluid is not incompressible; the viscosity of fluid is a constant; then we can deduce the equation of moisture content combining with Eq.3 which is given as:

$$f_w = (-\frac{K_{rw}}{\mu_w}\frac{\partial p_w}{\partial x}) / (-\frac{K_{rw}}{\mu_w}\frac{\partial p_w}{\partial x} - \frac{K_{ro}}{\mu_o}\frac{\partial\left(p_w + p_c^e - \tau\partial S_{wet}/\partial t\right)}{\partial x}) \quad (14)$$

(1) When the capillary pressure is not considered, the equation is

$$f_w = (\frac{K_{rw}}{\mu_w}) / (\frac{K_{rw}}{\mu_w} + \frac{K_{ro}}{\mu_o}) \quad (15)$$

(2) When the static capillary pressure is considered, the equation is

$$f_w = V_w / V_t = (-\frac{KK_{rw}}{\mu_w}\frac{\partial p_w}{\partial x}) / (-\frac{KK_{rw}}{\mu_w}\frac{\partial p_w}{\partial x} - \frac{KK_{ro}}{\mu_o}\frac{\partial\left(p_w + p_c^e\right)}{\partial x}) \quad (16)$$

For water wetting reservoir, water is the wetting phase and oil is the nonwetting phase, the static capillary pressure is an increasing function of nonwetting phase (oil).

$$\frac{\partial p_c^e}{\partial S_w} < 0 \quad (17)$$

Then we can get

$$f_w = (-\frac{KK_{rw}}{\mu_w}\frac{\partial p_w}{\partial x}) / (-\frac{KK_{rw}}{\mu_w}\frac{\partial p_w}{\partial x} - \frac{KK_{ro}}{\mu_o}\frac{\partial\left(p_w + p_c^e\right)}{\partial x}) > (\frac{K_{rw}}{\mu_w}) / (\frac{K_{rw}}{\mu_w} + \frac{K_{ro}}{\mu_o}) \quad (18)$$

Hence, the moisture content is bigger when considers the static capillary pressure than that does not consider the static capillary pressure. The static capillary pressure makes the moisture content rise faster for water wetting reservoir.

For oil wetting reservoir, oil is the wetting phase and water is the nonwetting phase, the static capillary pressure is an increasing function of water.

$$\frac{\partial p_c^e}{\partial S_w} > 0 \quad (19)$$

Then we can get

$$f_w = (-\frac{KK_{rw}}{\mu_w}\frac{\partial p_w}{\partial x}) / (-\frac{KK_{rw}}{\mu_w}\frac{\partial p_w}{\partial x} - \frac{KK_{ro}}{\mu_o}\frac{\partial\left(p_w + p_c^e\right)}{\partial x}) < (\frac{K_{rw}}{\mu_w}) / (\frac{K_{rw}}{\mu_w} + \frac{K_{ro}}{\mu_o}) \quad (20)$$

Hence, the moisture content is smaller when considers the static capillary pressure than that does not consider the static capillary pressure. The static capillary pressure makes the moisture content rise slower for oil wetting reservoir.

(3) When the dynamic capillary pressure is considered:

For water wetting reservoir, water is the wetting phase and oil is the nonwetting phase,

$$S_{wet} = S_w \quad (21)$$

So

$$f_w = V_w / V_t = \frac{K_{rw}}{\mu_w}\frac{\partial p_w}{\partial x} / (\frac{K_{rw}}{\mu_w}\frac{\partial p_w}{\partial x} + \frac{K_{ro}}{\mu_o}\frac{\partial\left(p_w + p_c^e - \tau\partial S_w/\partial t\right)}{\partial x}) > \frac{K_{rw}}{\mu_w}\frac{\partial p_w}{\partial x} / (\frac{K_{rw}}{\mu_w}\frac{\partial p_w}{\partial x} + \frac{K_{ro}}{\mu_o}\frac{\partial\left(p_w + p_c^e\right)}{\partial x}) \quad (22)$$

Hence, the moisture content is bigger when considers the dynamic capillary pressure than that does not consider the dynamic capillary pressure. The dynamic capillary pressure makes the moisture content rise faster for water wetting reservoir.

For oil wetting reservoir, oil is the wetting phase and water is the nonwetting phase,

$$S_{wet} = 1 - S_w \quad (23)$$

So

$$f_w = V_w / V_t = (\frac{K_{rw}}{\mu_w}\frac{\partial p_w}{\partial x}) / (\frac{K_{rw}}{\mu_w}\frac{\partial p_w}{\partial x} + \frac{K_{ro}}{\mu_o}\frac{\partial\left(p_w + p_c^e - \tau\partial S_w / \partial t\right)}{\partial x})$$
$$< (\frac{K_{rw}}{\mu_w}\frac{\partial p_w}{\partial x}) / (\frac{K_{rw}}{\mu_w}\frac{\partial p_w}{\partial x} + \frac{K_{ro}}{\mu_o}\frac{\partial\left(p_w + p_c^e\right)}{\partial x}) \tag{24}$$

Hence, the moisture content is smaller when considers the dynamic capillary pressure than that does not consider the dynamic capillary pressure. The dynamic capillary pressure makes the moisture content rise slower for oil wetting reservoir.

DISCUSSION AND CONCLUSION

(1) The dynamic capillary pressure is obvious in ultra-low permeability reservoir. According to Eq. 1, we find the coefficient τ is 10^{11}~10^{13}kg/(m·s), which is very bigger than 10^4~10^7kg/(m·s), which is calculated by predecessors, when the reservoir is tighter (the permeability is less than $1\times10^{-3}\mu m^2$). The coefficient τ and the variation rate of water saturation influence the dynamic capillary pressure. When the coefficient τ or the injection rate is bigger, the dynamic effect of capillary pressure will be more obvious.

(2) The numerical model indicates that the dynamic capillary pressure of waterflood front is the largest and the existence of dynamic capillary pressure hinders the fltting speed of waterflood front and reduces the oil production.

(3) The dynamic capillary pressure makes the moisture content rise faster for water wetting ultra-low permeability reservoirs, while the dynamic capillary pressure reduces the rising velocity of moisture content for oil wetting ultra-low permeability reservoirs.

This study is of great benefit to finding out the percolation law of ultra-low permeability reservoir and the subsequent work of development.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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