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Investigation of the Effect of Dynamic Capillary Pressure on Waterflooding in Extra Low Permeability Reservoirs

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Abstract: The dynamic capillary pressure is one of the important factors affecting the two phase percolation mechanism of waterflooding in extra low permeability reservoir. It is crucial to understand the effect of dynamic capillary pressure on oil displacement process in order to improve the waterflooding effectiveness. In this paper the dynamic capillary pressure effect was investigated quantitatively and a numerical flow model was built, in which the dynamic capillary pressure is considered. The effects of dynamic capillary pressure and water injection rate on the waterflooding effectiveness were analyzed. The results show that the dynamic capillary pressure has a significant influence on the oil displacement effectiveness. The bigger the dynamic capillary pressure, the more adverse waterflooding effectiveness is obtained. The water injection rate will influence the change of fluid saturation in the reservoir, which leads to the different dynamic capillary pressure effect. There is an optimum water injection rate which causes the minimum dynamic capillary pressure and percolation resistance.

Keywords: Extra low permeability reservoir, dynamic capillary pressure, two-phase percolation flow, water injection, development effectiveness.

Nomenclature

p_o	oil phase pressure, MPa
p_w	water phase pressure, MPa
S_w	water saturation, %
t	displacing time, s
τ	dynamic capillary coefficient, kg/(m·s), measured by experiment
$p_{c,dyn}$	dynamic capillary pressure, MPa
$p_{c,stat}$	static capillary pressure, MPa
K	core permeablility, $10^{-3}\mu m^2$

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x	distance from water injector to oil producer, m
K_o	oil effective permeability, 10^{-3} μm^2
B_o	oil formation volume factor (FVF), m^3/m^3
μ_o	oil viscosity, mPa·s
Q_o	source or sink strength of oil, s^{-1}
Q_w	source or sink strength of water, s^{-1}
ϕ	porosity, %
S_o	oil saturation, %
K_w	water effective permeability, $10^{-3}\mu$m^2
B_w	water FVF, m^3/m^3
μ_w	water viscosity, mPa·s
α, β, γ	incremental coefficient of saturation
δ	incremental coefficient of pressure at different time steps
Δx	grid width, m
Δt	time step, s
F	distance calculation parameter, m^{-1}
λ	fluid mobility, m^2/(MPa·s)
C_f	comprehensive compressibility coefficient, MPa^{-1}
c	incremental coefficient of pressure calculation, m^2/(MPa·s)
f	saturation calculation parameter, m^2/s

Subscripts

o	oil
w	water
i	position node
n	time step

1 Dynamic capillary pressure effect

For extra low permeability oil reservoirs ($K < 1 \times 10^{-3}\mu m^2$), it is commonly developed using waterflooding. However, the effectiveness of waterflooding in extra low permeability reservoirs is not good as that in high permeability reservoirs. The water injection pressure in extra low permeability reservoirs is higher and pressure transmits much more slowly than that in high permeability reservoirs. One of the reasons is the big fluid flow resistance in extra low permeability reservoirs, which caused by the tiny pore radius of $1\mu m$, the low capacity of percolation and the significant effect of capillary pressure on oil-water percolation flow. A number of researchers have conducted the study regarding the capillary pressure, which has been focused on two aspects: the static capillary pressure when wetting phase and non-wetting phase interface reaches equilibrium and the dynamic capillary pressure when wetting phase and non-wetting phase interface has not reached equilibrium. Hassanizadeh, et al. (1993a, 1993b, 2002), Mirzaei and Das (2007), Bourgeat and Panfilov (1998) conducted a number of research on the dynamic capillary pressure. It was believed that capillary pressure is changing in the non steady-state flow condition and capillary pressure is not only the function of wetting phase saturation, but also the change rate of wetting phase saturation. However, the effect of dynamic capillary pressure on waterflooding in extra low permeability oil reservoirs is rarely considered. The relationship between effect of dynamic capillary pressure and non-Darcy percolation flow in low permeability reservoirs has not been investigated.

In this paper, the relationship of dynamic capillary pressure with wetting phase saturation and change rate of saturation in extra low permeability reservoirs is presented as Eq.1:

$$p_{c,dyn} = p_o - p_w = p_{\mathrm{c,stat}}\left(S_w\right) + 10^{-6}\tau\frac{\partial S_w}{\partial t} \tag{1}$$

The dynamic capillary pressure relationship is combined with oil-water percolation flow equations to construct the flow model to describe the flow mechanism of oil and water in waterflooding process in extra low permeability reservoirs.

2 Relationship between dynamic capillary pressure and non-Darcy percolation flow in low permeability reservoirs

In extra low permeability reservoirs, it was commonly believed that the fluid flow mechanism is non-Darcy percolation flow with a threshold pressure gradient. However, it is still not clear for exact reasons causing the non-Darcy percolation flow. In order to investigate the relationship between dynamic capillary pressure effect and the non-Darcy law, a core flooding experiment in the extra low permeability core sample ($K = 0.30.\times10^{-3}\ \mu m^2$) was conducted and the result was compared with the result of numerical model considering capillary pressure effect (Fig. 1). The result shows that the curve of production rate vs. pressure gradient doesn't cross the zero point of coordinate, which indicates the obvious threshold pressure gradient. There is a good match between the results of the experiment and that of the flow model. Therefore the dynamic capillary pressure effect is one of the reasons causing non-Darcy percolation flow law in extra low permeability reservoirs.

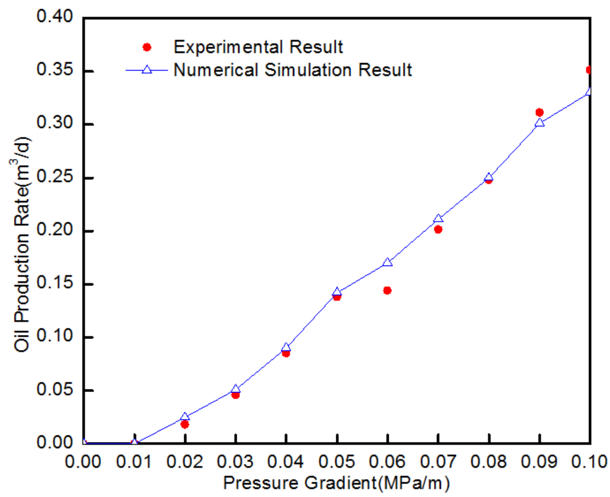

Figure 1: Comparison between experimental result and the result of numerical model considering the effect of dynamic capillary pressure for the extra low permeability core

3 Description of two-phase percolation flow model

A linear numerical waterflooding model for extra low permeability oil reservoirs considering the effect of dynamic capillary pressure was built (Fig. 2). The pressure and fluid saturation distribution from the water injector to the oil producer were calculated. The effect of dynamic capillary pressure on percolation flow in waterflooding was investigated. The basic parameters applied in the numerical model were from extra low permeability reservoirs of Changqing Oilfield and shown in Table 1.

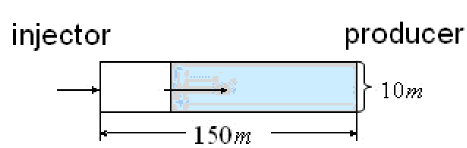

Figure 2: Schematic of the linear flow model of waterflooding

Table 1: Reservoir parameters of the numerical model

Parameter	value
Permeability	$0.30.\times10^{-3}$ μm^2
Effective thickness	10.0 m
Comprehensive compressibility coefficient	0.005 MPa^{-1}
Immobile Water saturation	35.0%
porosity	11.0%
Oil viscosity	3.5 mPa·s
In-situ water viscosity	1.0 mPa·s
Oil FVF	1.16 m^3/m^3
Original reservoir pressure	20 MPa
Well space	150 m

3.1 Equations of the model

The oil and water flow equations were written as follows:

$$10^{-6}\frac{\partial}{\partial x}\left(\frac{K_o}{B_o\mu_o}\frac{\partial p_o}{\partial x}\right)+Q_o=\frac{\partial}{\partial t}\left(\frac{\phi S_o}{B_o}\right) \quad (2)$$

$$10^{-6}\frac{\partial}{\partial x}\left(\frac{K_w}{B_w\mu_w}\frac{\partial p_w}{\partial x}\right)+Q_w=\frac{\partial}{\partial t}\left(\frac{\phi S_w}{B_w}\right) \quad (3)$$

The inner boundary condition was constant oil production rate or constant bottom hole pressure. The outer boundary condition was constant water injection rate.

3.2 Solutions of the model

The IMPES finite difference method was used to solve the equations with the implicit pressure and explicit saturation. The solution consists of the following steps:

(1) The flow equations are discreted and the oil and water differential equations are built. The pressure at n+1 time step is handled as the Taylor's expansion. The equations at n time step are written as:

$$a_{oi}\delta p_{i-1}+b_{oi}\delta p_{i+1}+c_{oi}\delta p_i=f_{oi}-\frac{\Delta x_i}{\Delta t}\phi_n\frac{\delta S_i}{B_o} \quad (4)$$

$$a_{wi}\delta p_{i-1}+b_{wi}\delta p_{i+1}+c_{wi}\delta p_i=\alpha_i\delta S_{i-1}+\beta_i\delta S_{i+1}+\gamma_i\delta S_i+f_{wi} \quad (5)$$

where,

$$a_{oi}=F_{i-\frac{1}{2}}\lambda_{oi-\frac{1}{2}},\quad b_{oi}=F_{i+\frac{1}{2}}\lambda_{oi+\frac{1}{2}},\quad a_{wi}=F_{i-\frac{1}{2}}\lambda_{wi-\frac{1}{2}},\quad b_{wi}=F_{i+\frac{1}{2}}\lambda_{wi+\frac{1}{2}},$$

$$F_{i+\frac{1}{2}}=\frac{1}{x_{i+\frac{1}{2}}},\quad F_{i-\frac{1}{2}}=\frac{1}{x_{i-\frac{1}{2}}},\quad \lambda_{oi+\frac{1}{2}}=\frac{10^{-6}K_{oi+\frac{1}{2}}}{B_{oi+\frac{1}{2}}\mu_{oi+\frac{1}{2}}},\quad \lambda_{oi-\frac{1}{2}}=\frac{10^{-6}K_{oi-\frac{1}{2}}}{B_{oi-\frac{1}{2}}\mu_{oi-\frac{1}{2}}},$$

$$\lambda_{wi+\frac{1}{2}}=\frac{10^{-6}K_{wi+\frac{1}{2}}}{B_{wi+\frac{1}{2}}\mu_{wi+\frac{1}{2}}},\quad \lambda_{wi-\frac{1}{2}}=\frac{10^{-6}K_{wi-\frac{1}{2}}}{B_{wi-\frac{1}{2}}\mu_{wi-\frac{1}{2}}}$$

$$c_{oi}=-F_{i+\frac{1}{2}}\lambda_{oi+\frac{1}{2}}-F_{i-\frac{1}{2}}\lambda_{oi-\frac{1}{2}}+\frac{\Delta x_i}{\Delta t}\left[(1-S_{i,n})\frac{\phi_n C_f}{B_o}+(1-S_{i,n})\,\phi_n\frac{\partial}{\partial p}\left(\frac{1}{B_o}\right)\right]$$

$$c_{wi}=-\left(F_{i+\frac{1}{2}}\lambda_{wi+\frac{1}{2}}+F_{i-\frac{1}{2}}\lambda_{wi-\frac{1}{2}}\right)-\left[\frac{\Delta x_i}{\Delta t}S_{i,n}\frac{\phi_n C_f}{B_w}+\frac{\Delta x_i}{\Delta t}S_{i,n}\phi_n\frac{\partial}{\partial p_w}\left(\frac{1}{B_w}\right)\right]$$

$$\alpha_i=\frac{10^{-6}a_{wi}\tau}{\Delta t},\quad \beta_i=\frac{10^{-6}b_{wi}\tau}{\Delta t},\quad \gamma_i=\frac{\Delta x_i}{\Delta t}\frac{\phi_n}{B_w}-\frac{10^{-6}\left(a_{wi}+b_{wi}\right)\tau}{\Delta t}$$

$$f_{wi}=a_{wi}\left(p_{i,n}-p_{i-1,n}+p_ci-1,n-p_{ci,n}\right)+b_{wi}\left(p_{i,n}-p_{i+1,n}+p_ci+1,n-p_{ci,n}\right)$$

$$f_{oi}=-F_{i+\frac{1}{2}}\lambda_{oi+\frac{1}{2}}\left(p_{i+1},n-p_{i,n}\right)+F_{i-\frac{1}{2}}\lambda_{oi-\frac{1}{2}}\left(p_{i,n}-p_{i-1,n}\right)$$

(2) The water saturation and dynamic capillary pressure are solved using the explicit expression. The oil phase pressure and water saturation at *n*+1 time step are solved using the iteration algorithm.

4 Results and discussion

The effect of the different dynamic capillary coefficient and water injection rates on waterflooding in extra low permeability reservoirs were investigated using the numerical model.

4.1 Effect of the different dynamic capillary coefficient on waterflooding

The dynamic capillary pressure effect is related to the dynamic capillary coefficient. The dynamic capillary coefficient can be measured by experiment. In general, the lower the rock permeability, the higher of the dynamic capillary coefficient is.

4.1.1 Effect of different dynamic capillary coefficient on waterflooding effectiveness

The three cases of different capillary coefficient (10kg(m.s), 100kg(m.s), 1000kg(m.s)) were studied. The results are shown in Table 2.

With the increasing of the dynamic capillary coefficient, the time of water breakthrough and the remaining oil saturation increase and the recovery factor decreases. The reason is that with increasing of the dynamic capillary coefficient, the dynamic

Table 2: Comparison of waterflooding effectiveness with different capillary dynamic coefficients

Capillary dynamic coefficient /kg(m.s)	Time of water breakthrough /d	Average remaining oil saturation while breakthrough /%	Recovery factor while breakthrough /%
10	309	48.2	25.9
100	327	49.5	23.8
1000	417	50.9	21.5

capillary pressure effect and flow resistance increase, which leads to the slower water displacement process and much more remaining oil in the reservoir after water sweeping.

4.1.2 Comparison of oil production rate with different dynamic capillary coefficient

The effect of different dynamic capillary coefficient on oil production rate was investigated. The results are shown in Fig. 3.

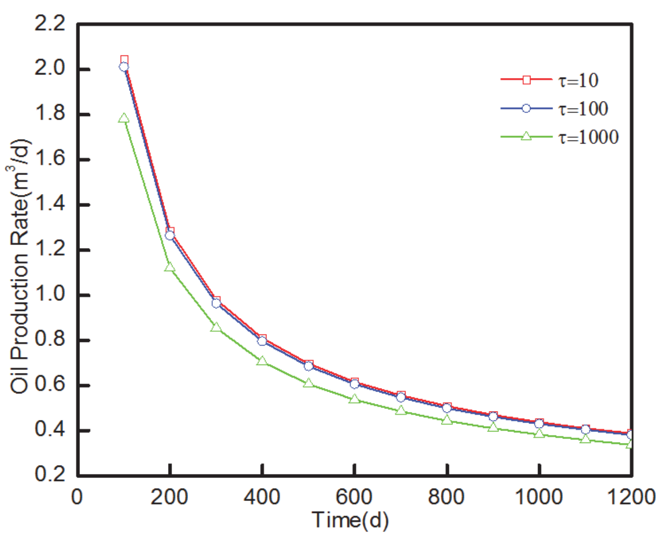

Figure 3: Comparison of oil production rate with different capillary dynamic coefficients.

With the increasing of the dynamic capillary coefficient, the oil production rate decreases due to the increasing of dynamic capillary pressure effect and flow resistance.

4.2 Effect of the different water injection rates on waterflooding

During the process of waterflooding, when different water injection rates are applied, the change rate of water saturation in the reservoirs will be different. The difference will cause the different effect of dynamic capillary pressure. The four cases of different water injection rates were studied. The results are shown in Table 3.

Table 3: Comparison of waterflooding effectiveness with different water injection rates.

Water injection rate/ m^3/d	Time of water breakthrough /d	Average remaining oil saturation while breakthrough /%	Recovery factor while breakthrough /%
1.5	563	43.3	33.4
2.0	552	44.6	31.4
3.0	523	45.7	29.7
4.0	506	46.5	28.5

With the increasing of the water injection rate, the time of water breakthrough decreases, the remaining oil saturation increases and the recovery factor decreases. The reason is that with increasing of the water injection rate, the change rate of water saturation in the reservoir and dynamic capillary pressure effect increase, which leads to much more remaining oil in the reservoir after water sweeping (shown in Fig. 4) . Therefore it is necessary to optimize the water injection rate when effect of capillary pressure effect is significant in extra low permeability reservoirs.

4.3 Comparison of pressure distribution with different water injection rates

The pressure distribution with different water injection rates (1 m^3/d,1.5 m^3/d, 2 m^3/d, 4m^3/d) are shown in Fig.5, Fig.6, Fig.7, Fig.8 and Fig.9. With the increasing of the water injection rate, velocity of the water driving front moving increases and pressure near the region of the injector increase. The reason is that the flow resistance and dynamic capillary pressure effect increase because of the change rate of water saturation in the reservoir increases. However it is shown in Fig.9 and Fig.10 that there is an optimal water injection rate (1.5 m^3/d) which leads to the low pressure distribution and high oil production rate. The effect of dynamic capillary pressure and water displacement should be considered simultaneously.

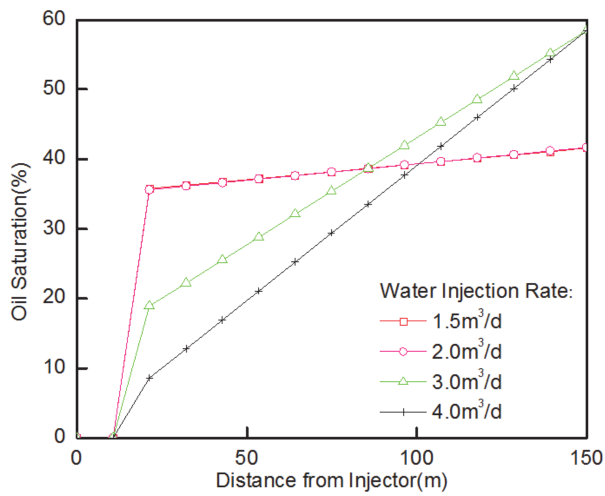

Figure 4: Comparison of oil saturation distribution with different water injection rates.

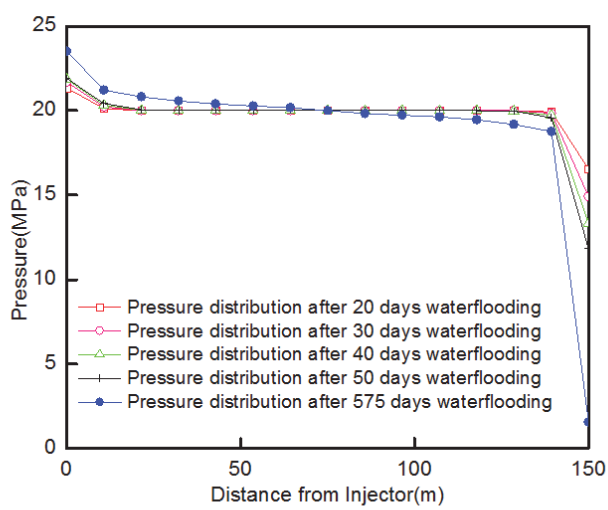

Figure 5: Pressure distribution at different displacement time (water injection rate $1m^3$ /d).

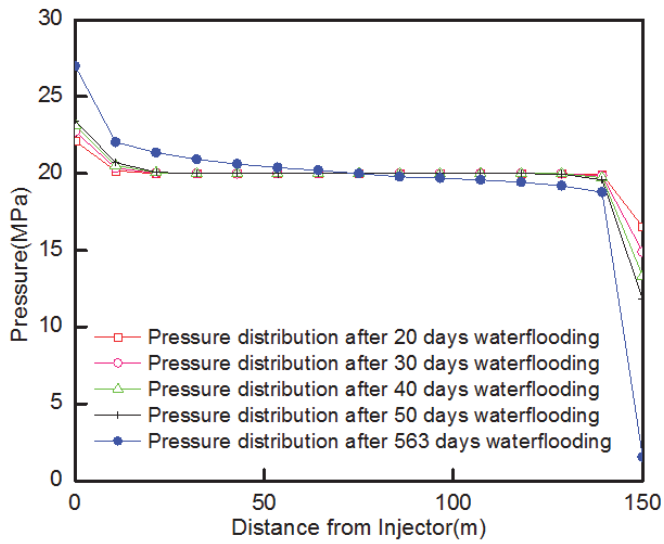

Figure 6: Pressure distribution at different displacement time(water injection rate 1.5m^3 /d).

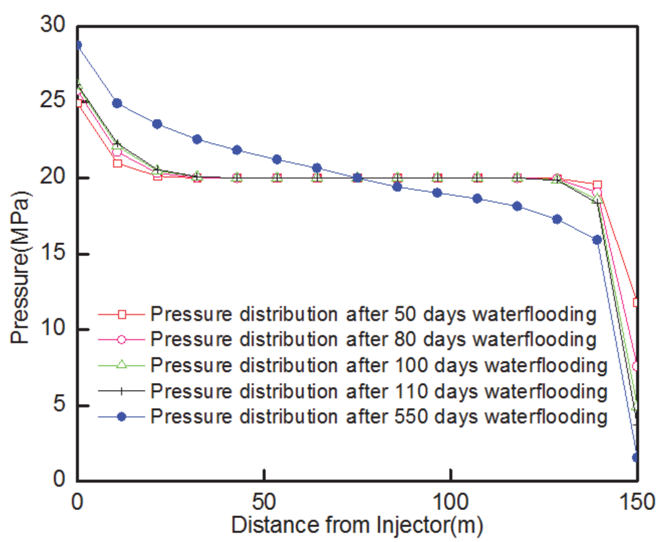

Figure 7: Pressure distribution at different displacement time(water injection rate 2m^3/d).

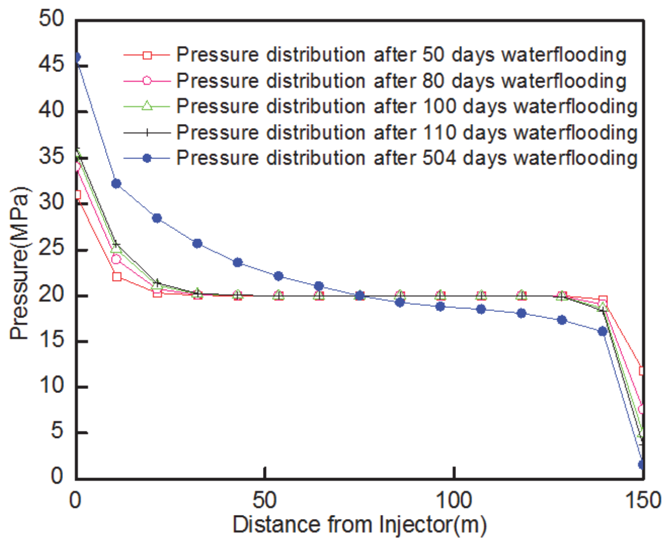

Figure 8: Pressure distribution at different displacement time(water injection rate $4m^3/d$).

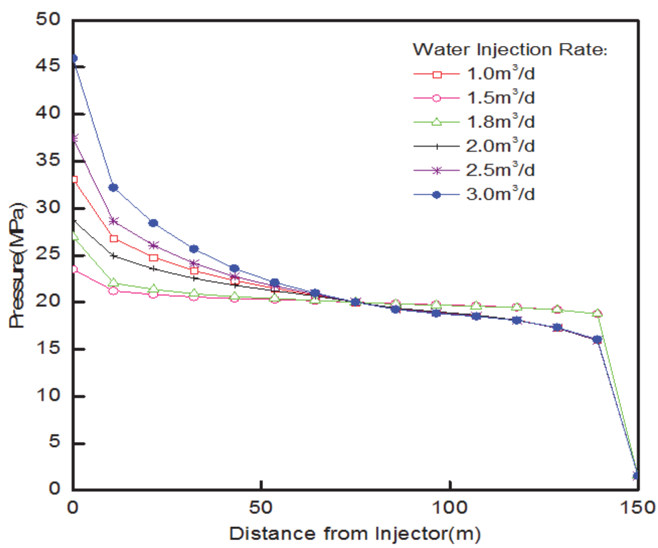

Figure 9: Comparison of pressure distribution with different water injection rate at the time of water breakthrough.

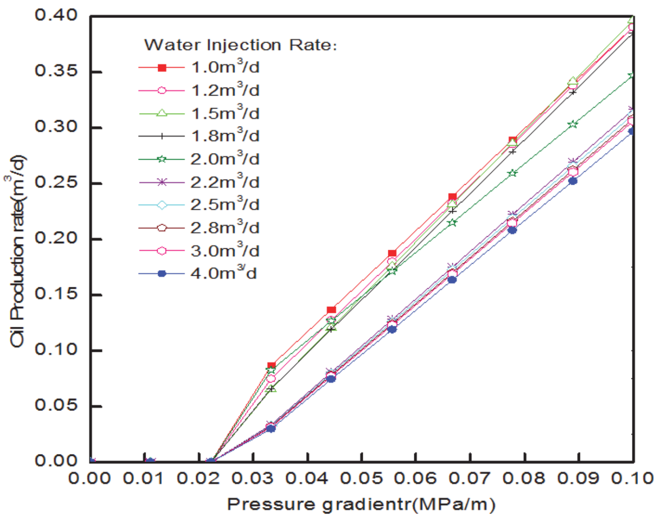

Figure 10: Comparison of production rate and pressure gradient relation with different water injection rates.

5 Conclusions

(1) In extra low permeability reservoir the effect of dynamic capillary pressure on waterflooding is significant and is one of the reasons of non-Darcy percolation flow.

(2)The dynamic capillary pressure coefficient has an important impact on time of water breakthrough, remaining oil saturation and recovery factor of waterflooding. The bigger the dynamic capillary pressure effect, the more adverse waterflooding effectiveness is obtained.

(3)It is necessary to optimize the water injection rate for waterflooding in extra low permeability reservoirs. The water injection rate has a significant impact on time of water breakthrough, remaining oil saturation and recovery factor of waterflooding. The high oil production rate and low flow resistance can be achieved with the optimal water injection design.

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