BOUNDARY EFFECT ON LIQUID INVASION IN TIGHT GAS RESERVOIRS

by

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Liquid invasion is an important transport phenomenon in many geophysical and environmental applications. A new capillary model considering boundary effect is proposed to reveal its mechanism. The boundary fluid layer not only reduces the effective flow radius, but also changes the viscosity of fluid. Thus the capillary force and viscosity resistance increases, however, the increase of capillary force is faster than that of viscosity resistance, therefore the invasion front arrives at the critical distance earlier.

Key words: *tight gas reservoirs, liquid invasion, boundary fluid layer, seepage model*

Introduction

Liquid invasion is an important transport mechanism in many geophysical and environmental applications [1]. That is, fluid enters into porous media due to capillary force and mechanical pressure or injection pressure. In many literatures, a porous medium is simplified as a bundle of capillary tubes with uniform or varied tube radius along the length [2]. In this paper, we choose the same method. The previous research on liquid invasion has mostly focused on non-tight porous media, seldom on tight porous media. Moreover, the effect of the boundary fluid layer is generally neglected. The boundary fluid layer has a pronounced effect on flow, especially in low permeable porous media [3]. Thus, the effect should be considered in analysis of liquid invasion in tight sandstone.

Liquid invasion considering boundary fluid layer in tight gas reservoirs

Characteristics of the boundary fluid layer and its effect on invasion

Pore-throat sizes are generally range from about 0.03 μm to 2 μm in tight-gas sandstones [4], micro scale effect is significant. It is well known that the micro channels have a higher surface to volume ratio, which leads to the strong adsorption of liquid on pore wall surface. An immobile fluid layer is formed near the surface, which not only reduces the radius of

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pore-throat but also changes the viscosity of fluid. An empirical equation for the thickness of boundary fluid layer was used in this paper [5]:

$$\delta = a\exp(-bG) \tag{1}$$

$$\begin{cases} a = 0.0725\ln R + 0.25594 \\ b = 0.00411R - 0.00121 \end{cases} \tag{2}$$

The effective flow radius is defined as:

$$R_e = R - \delta \tag{3}$$

The average viscosity of fluid is expressed as [6]:

$$\overline{\mu} = \mu_0 + \frac{\phi'}{H\delta^{n-1}(n-1)}, \quad 0 < n < 2 \tag{4}$$

In this paper, n is chosen as 1.8.

Figure 1(a) illustrates the relationship between capillary force and pressure gradient with different radius. With the increase of pressure gradient, the capillary force gradually decreases and tends to be a constant. For the same pressure gradient, the smaller capillary radius is, the stronger effect of boundary layer is. Figure 1(b) depicts the average viscosity values *vs.* pressure gradient. It could be seen that the average viscosity values gradually decreases and tends to be a constant value with the increase of pressure gradient. This can be attributed to that, the high enough pressure gradient can push more fluid in the capillary, which directly reduces the thickness of boundary fluid layer, thus the capillary force and average viscosity value decrease. It should be noted that at the same radius capillary force is more sensitive to the variation of pressure gradient than viscosity resistance.

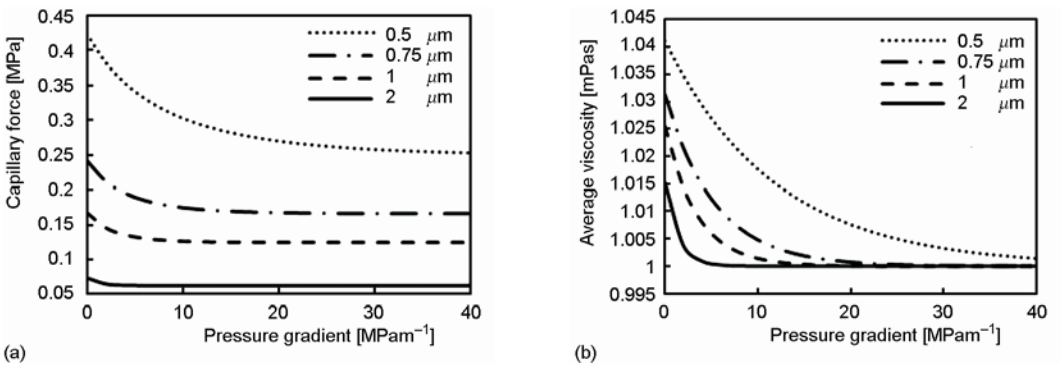


Figure 1. (a) Relation curve between capillary force and pressure gradient with different radius, and (b) relation curve between average viscosity and pressure gradient with different radius

Governing equations

Assumptions are: (1) The tight porous media (tight sandstone) are comprised of a bundle of tortuous capillary tubes, all with the same equivalent radius R_e, and neglecting wall roughness; (2) quasi-steady state, single phase, isothermal, incompressible fluid flow; (3) the flow can be described by the Hagen-Poiseuille equation. For more details about the derivation of the model, please refer to the author's previous work [6].

(1) Initial stage

$$\left(\frac{\mathrm{d}z_1}{\mathrm{d}t}\right)^2 + z_1\frac{\mathrm{d}^2 z_1}{\mathrm{d}t^2} = \frac{2\gamma\cos\theta}{R_e\rho} - \frac{8\mu}{R_e^2\rho}z_1\frac{\mathrm{d}z_1}{\mathrm{d}t} + \frac{F_p}{\pi R_e^2\rho} \tag{5}$$

The right terms in eq. (5) refer to the capillary pressure, the viscous pressure loss, mechanical pressure, respectively.

(2) Pseudo steady-state

At this time, the inertia term can be omitted, and the external force is no longer a constant due to pore pressure drawn down near the wellbore area, which should be modified as:

$$F_p = \left[p_w - \left(p_0 + \frac{p_e - p_0}{\ln\frac{r_e}{r_w}}\ln\frac{z}{r_w}\right)\right]\pi R_e{}^2 \tag{6}$$

Considering the effect of the boundary fluid layer, the governing equation can be expressed as:

$$\frac{\mathrm{d}z_2}{\mathrm{d}t} = \frac{2R_e\gamma\cos\theta + (p_w - p_0)R_e{}^2}{8\bar{\mu}z_2} - \frac{p_e - p_0}{\ln\frac{r_e}{r_w}}\frac{\ln\frac{z_2 + r_w}{r_w}}{8\bar{\mu}z_2}R_e{}^2 \tag{7}$$

Effect of absorbed fluid layer

In this section, we study the effect of boundary fluid layer on invasion. The calculation parameters are listed in tab. 1. The change of invasion distance and rate are calculated with and without boundary fluid layer, as shown in figs. 2(a) and (b).

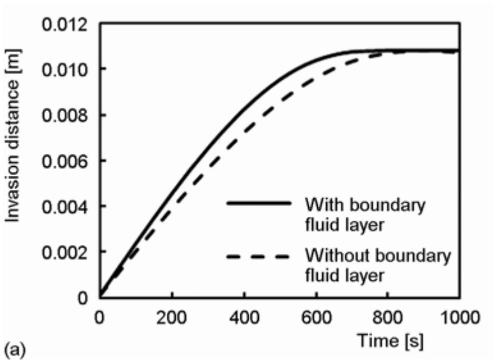
Table 1. Calculation parameters

K [μm^2]	ρ [kgm^{-3}]	μ [Pa·s]	θ [°]	γ [Nm^{-1}]	Φ [%]	P_e [MPa]	r_w [m]	r_e [m]	P_w [MPa]	P_o [MPa]
$0.203\cdot10^{-3}$	1000	0.001	30	0.072	8.92	22	0.108	5	20	19.9

It can be seen from fig. 2 that the invasion rate in terms of boundary fluid layer is higher than not considering boundary fluid layer. After 750 seconds, the invasion considering boundary fluid layer reaches a steady state, earlier than that without boundary fluid layer (850 seconds). Besides, the critical invasion distance is exactly similar in the two cases. Due to the existence of boundary fluid layer, the effective flow radius decreases, and the capillary force and viscosity resistance increase. However, the increase of capillary is more than that in viscosity resistance. A high capillary force is beneficial to invasion, which results in that the invasion front arrives at the critical distance earlier.

Conclusions

A modified capillary model for characterizing fluid invasion in tight sandstone is derived by introducing the boundary layer. It is found that the existence of boundary layer can increase capillary force and viscosity resistance by reducing the effective flow radius. It is also found that the increase in capillary force is more dominant than that in viscosity resistance.



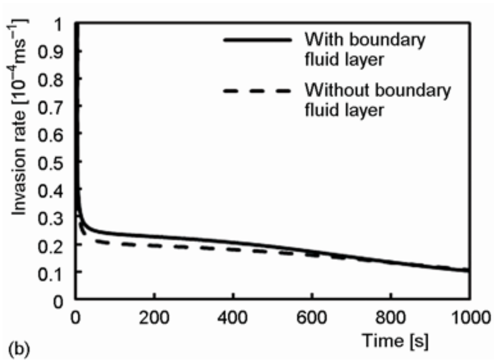


Figure 2. (a) Effect of boundary fluid layer on invasion distance, and (b) effect of boundary fluid layer on invasion rate

Nomenclature

F_p – external force, [Pa]
G – pressure gradient acting on the fluid, [Pam^{-1}]
K – permeability, [m^2]
p_0 – pore pressure around the wellbore, [Pa]
p_e – supply boundary pressure, [Pa]
p_w – down-hole fluid column pressure, [Pa]
R – average pore radius, [m]
r_e – supply boundary radius, [m]
R_e – effective of radius, [m]
r_w – wellbore radius, [m]
z – invasion distance, [m]

Greek symbols

γ – surface tension, [Nm^{-1}]
δ – layer thickness, [m]
θ – static contact angle, [°]
μ – viscosity, [Pa·s]
Φ – porosity, [–]

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