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A New Description of Multi-phase Flow Behavior at Boundary Layers of Low-permeability Porous Media

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Abstract

At present, the recovery factor of low permeability oilfield in China is only about 20%, which is enormously lower than the recovery factor index of 60% by using water-chemical flooding in medium and high permeability layer. There are a lot of causes that resulted in low recovery factor, among them that the complex pore structure, tiny throat, large pore throat ratio and non-Darcy flow in low-permeability oil layer are the main causes that restrict the low-permeability oil layer to enhance the recovery factor. Based on the research results about micro-fluid flow and non-Darcy flow, microflow of water drive and micro-acting force in the porous media are researched in this paper, establishing the expression of fluid viscosity factor, 2D flowing control equation and the relevant boundary condition under the conditions of liquid/solid interaction in the micro-pore media, all that gain the flowing rules of fluid under these two conditions of considering L/S interaction or not considering that. Numerical calculation shows that under the condition of L/S interaction, the radial velocity distribution near the solid wall changes obviously, and the curve form changes from convex to concave. The tinier the capillary radius, the stronger the L/S interaction is. The larger n value is, more obvious the flowing velocity decrease in the boundary layer. The results will help people dealing with improving recovery factor of low permeability reservoir, and understanding the fluid behavior in vessel.

Keywords: *low-permeability; micro-acting force; boundary layer; numerical simulation; pore structure; micro-flow PACS: 47.55.Mh, 47.50.+d, 34.20.Gj*

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INTRODUCTION

The reasons that result in low-velocity non-Darcy flow in the low-permeability oil layer are affected by porous media property, fluid property and the interaction of L/S boundary [1, 2]. Besides viscous force, the molecular acting force of L/S boundary also belongs to the resistance of fluid flow. All that is the difference of fluid flow between low-permeability reservoir and medium-high permeability reservoir, and is also the main mechanism that forms low-permeability non-Darcy flow.

In the macroscopic flow, because the characteristic dimension is larger than the average free path of fluid molecule enormously, fluid is supposed as the continuous medium [3–5]. However, in the micro-scale flow, when the characteristic dimension is similar with the average free path of fluid particle, the primary relevant importance of various affecting factors change, which result in that flowing rules are different from the macroscopic rules [6–8]. Therefore, some macroscopic concepts and rules based on continuous medium are not applicable any more, and viscosity factor and so on are also discussed again [9–11].

INTERMOLECULAR INTERACTION

In the low-permeability reservoir, the pore radius is tiny, and because of the viscosity affect of fluid and the interaction between fluid molecule and material molecule of solid surface, flowing in the solid surface forms boundary layer easily.

Intermolecular interaction includes oriention, induction and dispersion.The strength of oriention is determined by dipole moment of polar molecule, except for relating to the intermolecular distance. The larger the dipole moment, the stronger the oriention is. According to Coulomb's law, the interaction potential energy of a pair of permanent inter-dipole moment is as follows:

$$V_k = -\frac{\mu_1'\mu_2'}{R^3}[2\cos\theta_1\cos\theta_2 - \sin\theta_1\sin\theta_2\cos(\phi_1 - \phi_2)] \quad (1)$$

Where V_k is acting energy of a pair of inter-dipole moment, kJ. $\mu_1' = e_1 l_1$, $\mu_2' = e_2 l_2$, express the dipole moment of molecular, C.m. e is point charge, C. R is the distance of a pair of inter-dipole moment, m. l_1 , l_2 are the distances of plus-minus electron pair e_1 、 e_2 respectively, m.

When approach to balance, the average value of potential energy is:

$$\bar{V}_k = -\frac{2}{3}\frac{\mu_1'^2\mu_2'^2}{R^6 kT} \quad (2)$$

Where V_k is the average potential energy of intermolecular, kJ. k is Boltzmann constant, k =1.38×10-23J/K. T is the temperature, K. On account of xenogeneic molecular, induction interaction energy is:

$$V_D = -\frac{\alpha_1\mu_2'^2 + \alpha_2\mu_1'^2}{R^6} \quad (3)$$

where α_1 , α_2 are the deformed polarizability of molecular.

Similarly, on account of xenogeneic molecular, the interaction energy resulted from dispersion is:

$$V_L = -\frac{3}{2}\left(\frac{\alpha_1\alpha_2}{R^6}\right)\left(\frac{I_1 I_2}{I_1 + I_2}\right) \quad (4)$$

Where ionization energy $I = h\gamma_m \approx h\gamma_0$.

Hence, the intermolecular acting force is as follows:

$$V = -\frac{1}{R^6}[\frac{2}{3}\frac{\mu_1'^2\mu_2'^2}{kT} + (\alpha_1\mu_2'^2 + \alpha_2\mu_1'^2) + \frac{3}{2}(\alpha_1\alpha_2)(\frac{I_1 I_2}{I_1 + I_2})] \quad (5)$$

FLUID VISCOSITY IN THE LOW-PERMEABILITY POROUS MEDIA

In general, the fluid viscosity in the boundary layer can approach to several times of bulk phase viscosity, especially in the low-permeability reservoir, because the throat size is tiny, the effect of fluid flow from boundary layer can't be neglected.

In case that the fluid viscosity factor in the microflow boundary layer is [11]:

$$\mu = \mu_0 + \frac{\phi'}{y^n} \quad (6)$$

where μ_0 is the bulk phase viscosity of fluid, Pa.s. ϕ'/y^n is the additional viscosity resulted from gravitation in the solid surface, Pa.s. ϕ' is the factor related to solid surface property and water molecular property. n is the L/S index, zero dimension. y is the distance away from the solid surface, m.

According to expression (6), in the solid surface, $y \to 0$, the viscosity factor of water molecular is infinitely great, anyway, water molecular stays, which meet the no slip condition of classic boundary layer theory. Infinitely far away from the solid surface, $y \to \infty$, and the water viscosity is μ_0. Generally, n value is between 0 and 2.

In expression (6), ϕ' is the molecular factor of interaction between water and solid surface, using the following mathematical expression (10):

$$\phi' = \frac{2}{3}\frac{\mu_1^2 \mu_2^2}{kT} + (\alpha_1 \mu_2'^2 + \alpha_2 \mu_1'^2) + \frac{3}{2}(\alpha_1 \alpha_2)(\frac{I_1 I_2}{I_1 + I_2}) \qquad (7)$$

where μ_1'、α_1、I_1 express the dipole moment, polarizability and ionization energy of water molecular respectively. μ_2'、α_2、I_2 express the dipole moment, polarizability and ionization energy of solid surface molecular respectively.

FLUID FLOW CONTROL EQUATION IN THE 2D MICROFLOW BOUNDARY LAYER

Based on Navier-Stokes expression, revise the rheological equation of boundary layer inside the low-permeability porous media, and establish the control equation of boundary layer fluid inside the microporous channel considering the L/S interaction.

On account of 2D flow, velocity component: w^* =0, the whole flowing velocity variables are independent of z^*, meaning that the partial derivative of z^* is 0. The continuity equation is as following:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u^*)}{\partial x^*} + \frac{\partial(\rho v^*)}{\partial y^*} = 0 \qquad (8)$$

Momentum equation:

$$\frac{\partial u^*}{\partial t} + u^* \frac{\partial u^*}{\partial x^*} + v^* \frac{\partial u^*}{\partial y^*} = \frac{1}{\rho}\left\{\frac{\partial}{\partial x^*}\left[-p^* + 2\mu\frac{\partial u^*}{\partial x^*} - \frac{2}{3}\mu\left(\frac{\partial u^*}{\partial x^*} + \frac{\partial v^*}{\partial y^*}\right)\right] + \frac{\partial}{\partial y^*}\left[\mu\left(\frac{\partial v^*}{\partial x^*} + \frac{\partial u^*}{\partial y^*}\right)\right]\right\} \qquad (9a)$$

$$\frac{\partial v^*}{\partial t} + u^* \frac{\partial v^*}{\partial x^*} + v^* \frac{\partial v^*}{\partial y^*} = \frac{1}{\rho}\left\{\frac{\partial}{\partial x^*}\left[\mu\left(\frac{\partial v^*}{\partial x^*} + \frac{\partial u^*}{\partial y^*}\right)\right] + \frac{\partial}{\partial y^*}\left[-p^* + 2\mu\frac{\partial v^*}{\partial y^*} - \frac{2}{3}\mu\left(\frac{\partial u^*}{\partial x^*} + \frac{\partial v^*}{\partial y^*}\right)\right]\right\} \qquad (9b)$$

On account of stationary incompressible fluid, expression (8) and (9):

$$\frac{\partial u^*}{\partial x^*} + \frac{\partial v^*}{\partial y^*} = 0 \qquad (10a)$$

$$u^*\frac{\partial u^*}{\partial x^*}+v^*\frac{\partial u^*}{\partial y^*}=-\frac{1}{\rho}\frac{\partial p^*}{\partial x^*}+\frac{\mu}{\rho}\left(\frac{\partial^2 u^*}{\partial x^{*2}}+\frac{\partial^2 u^*}{\partial y^{*2}}\right) \tag{10b}$$

$$u^*\frac{\partial v^*}{\partial x^*}+v^*\frac{\partial v^*}{\partial y^*}=-\frac{1}{\rho}\frac{\partial p^*}{\partial y^*}+\frac{\mu}{\rho}\left(\frac{\partial^2 v^*}{\partial x^{*2}}+\frac{\partial^2 v^*}{\partial y^{*2}}\right) \tag{10c}$$

where $\mu=\mu_0+\frac{\phi'}{y^{*n}}$ is the viscosity factor of boundary layer fluid, Pa.s. u^* 、v^* are the velocity components of fluid particle, m/s. p^* is the normal pressure of fluid particle, Pa. The fluid flowing control equation is established based on equation (6) and (10).

Casting out the minor item of module in the viscosity force and inertia force of equation (9a), obtains:

$$\frac{\partial u^*}{\partial t}+u^*\frac{\partial u^*}{\partial x^*}+v^*\frac{\partial u^*}{\partial y^*}=\frac{1}{\rho}\left[-\frac{\partial p^*}{\partial x^*}+\frac{\partial}{\partial y^*}\mu\left(\frac{\partial u^*}{\partial y^*}\right)\right] \tag{11}$$

According to expression (11), in case that inertia force and viscosity force are the same module, the module of μ/ρ should be δ^2, which keep the item of supreme factorial, showing as following:

$$\frac{\partial p^*}{\partial y^*}=0 \tag{12}$$

For the 2D stationary incompressible micro-flowing boundary layer, substituting $\mu=\mu_0+\phi'/y^{*n}$ for expression (11) gains the continuity equation and momentum equation after simplification, as following:

$$\frac{\partial u^*}{\partial x^*}+\frac{\partial v^*}{\partial y^*}=0 \tag{13}$$

$$u^*\frac{\partial u^*}{\partial x^*}+\left(v^*+\frac{n\phi'}{y^{*n+1}}\right)\frac{\partial u^*}{\partial y^*}=-\frac{1}{\rho}\frac{\partial p^*}{\partial x^*}+\frac{1}{\rho}\left(\mu_0+\frac{\phi'}{y^{*n}}\right)\frac{\partial^2 u^*}{\partial y^{*2}} \tag{14}$$

The boundary condition is $y^*=0, u^*=v^*=0; y^*=\infty, u^*=U(x^*)$, and expression (13) and (14) are the approximate equation set of 2D stationary incompressible micro-flowing boundary layer.

CASE STUDY OF FLOW INSIDE CIRCULAR CAPILLARY

As Figure 1 shows, the flow inside the circular capillary that radius is R, can be expressed by the cylindrical coordinate presentation equation and the equation set of micro-flowing boundary layer. Simplify equation (13) and (14) for:

$$\frac{dp^*}{dx^*}=\frac{1}{y^*}\frac{d}{dy^*}\left((\mu_0+\frac{\phi'}{(R^*-y^*)^n})y^*\frac{du^*}{dy^*}\right) \tag{15}$$

Boundary condision: $y^*=R^*,\ u^*=0$.

where R^* is capillary radius in equation (15), m.

Figure 2 is the velocity distribution curve of different n values inside capillary that $\phi'=\mu_0$, pressure gradient $dp^*/dx^*=1\text{Pa/m}$, radius $R^*=0.05\text{m}$ for water under the L/S interaction, which considering the fluid molecular attraction from fixing-wall molecular. According to Figure 2, the form of velocity distribution curve near the wall is concave, which shows that with the effect of L/S interaction, the viscosity of fluid increase, and the nearer to the wall, the larger additional viscosity, and velocity gradient changes to little. However, the form of velocity distribution curve is shown convex out of considering the L/S interaction (n=0). The effect to fluid molecular from the solid molecular near the wall is not obvious, fluid viscosity is relevant low, and the velocity gradient is large. Moreover, with the increase of index n of L/S interaction, the overall velocity of fluid changes to low obviously. So the acting to fluid from solid is significant in the flow path that with tiny size.

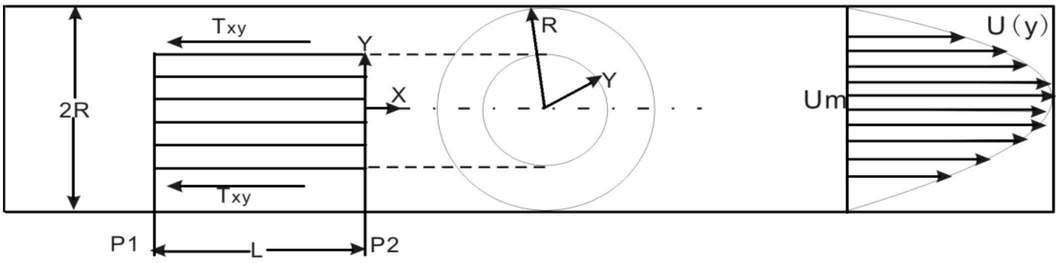

Fig. 1: *Flow in Circular Section of Capillary.*

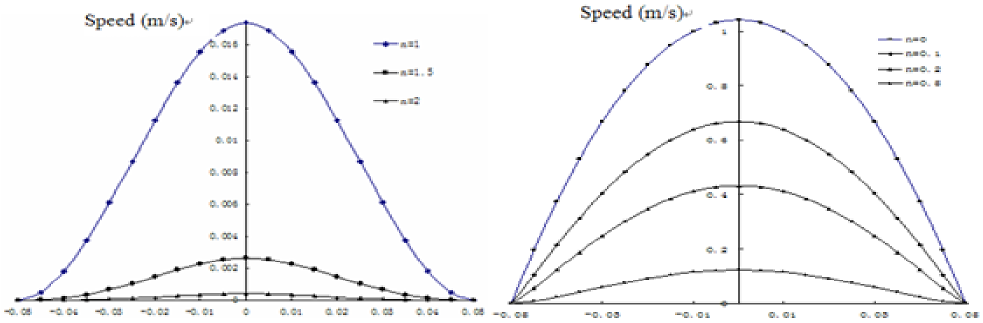

Fig. 2 *Velocity Distribution Graph in the Pipe Considering the L/S Interaction*（$R^* = 0.05\text{m}$，$dp^* / dx^* = 1\text{Pa/m}$，$\mu_0 = 0.0006\text{Pa.s}$，$\phi' = \mu_0$*).*

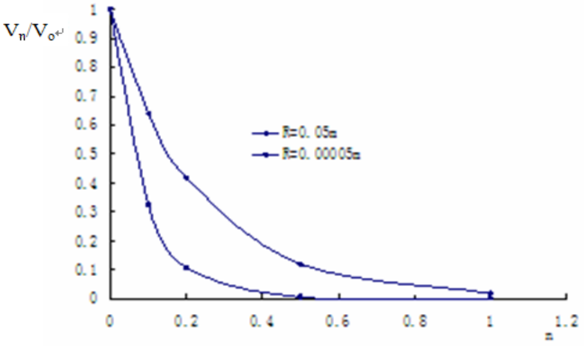

Fig. 3 *Velocity Distribution Graph in the Pipe Considering the L/S Interaction*（$R^* = 0.00005\,\text{m}$，$dp^* / dx^* = 2500\text{Pa/m}$ $\mu_0 = 0.0006\text{Pa.s}$，$\phi' = \mu_0$*).*

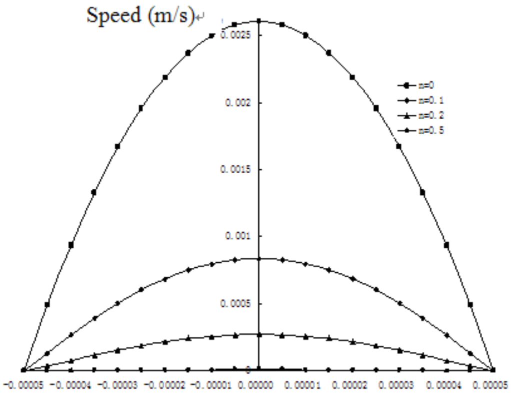

Fig. 4 *Relationship Curve of Average Velocity Ratio*（V_n / V_0） *and the L/S Interaction n in the Capillary both Considering Solid wall Gravitation and not Considering the Solid Wall Gravitation.*

Figure 4 is the relationship curve between the ratio of average flowing velocity V_n and V_0 in the capillary and the L/S index n. According to the curve, with the increase of L/S index and exponential type decrease of fluid velocity, and the tinier the capillary is, the larger the decline scope, which indicate that in the same L/S index, the tinier the capillary is, more obvious the L/S interaction is. By comparing the velocity distribution curve (Figures 2 and 3) of different capillary redius in the same L/S index, also obtain the same conclusion.

The above conclusions match up to the present understandings of low-permeability reservoir, which proves that the computational solution of numerical equation and selection of boundary condision are correct, and can meet the need for accuracy and calculation.

CONCLUSIONS

(i). The interaction between solid and fluid molecule is the main reason that form the micro-pore boundary layer flow of low-permeability reservoir. Such micro-interaction is shown as the increase of fluid viscosity in macrography. Hence, fluid viscosity equals to the sum of bulk phase viscosity and the additional viscosity resulted from L/S interaction, moreover, the nearer to the wall, the stronger the L/S interaction is.

(ii). According to introducing the viscosity factor expression of boundary layer fluid, estabilish the control equation of 2D boundary layer fluid under the L/S interaction, after simplifying the equation set, gain the velocity profile of circular capillary section.

(iii). Numerical calculation shows that under the condition of L/S interaction, the radial velocity distribution near the solid wall changes obviously, and the curve form changes from convex to concave. The tinier the capillary radius, the stronger the L/S interaction is. The larger n value is, the lower the overall flowing velocity.

(iv). The results will help people not only dealing with improving recovery factor of low permeability reservoir, but also understanding the fluid behavior in blood capillary.

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