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The Interfacial Interaction Effect on Characteristics of Fluid Flow in the Shale Reservoir Fractures

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Abstract: Shale reservoirs usually develop a lot of micro-fractures which provide the main fluid-flow pathways, but the flowing law in micro-fractures is unclear. This paper considered the effect on fluid flow of interface interaction between the micro-fracture surface and fluid surface, and established a mathematical model of fluid flow in micro-fractures. Through the numerical simulation of the relationship between flow rate and pressure in different fracture scale, it is found that numerical simulation results are in good agreement with the experimental data. Compared to the flow pressure curve without considering the interface interaction effect, the results showed that, at small fracture scale, the solid-liquid interface interaction has significant effect on fluid flow in micro-fracture. The effect of solid-liquid interface interaction declines as the fracture scale increases. When the fracture scale reaches 800μm, the solid-liquid interface interaction can be ignored.

Key words: Interface interaction, micro-fracture, fracture width, numerical simulation, micro flow

INTRODUCTION

The shale is a sort of reservoirs with ultra-low permeability whose rate is no more than Micro Darcy number (Zhou *et al*., 2012; Jia *et al*., 2012). Since fracture is the primary reservoir space and seepage channel of the shale, the study of fluid flow in the shale reservoir fractures is of significance for the development of shale. However, fluid flow in the shale reservoir fractures is of complex characteristics, and difficult to give mathematical description. Moreover, the available research on fracture put the main focus on how to conduct numerical simulations, and less attention is paid to the flowing law in fractures. The present study found that on the micro-scale (Chen *et al*., 2010; Ho and Tai, 1998; Gad-el-Hak, 1999; Giordano and Cheng, 2001), the effect of solid-liquid interface molecular exerts obvious influence on flowing law in fractures. In order to study and explore the flowing characteristics in fractures, the present study establishes a mathematical model of fluid flow in micro-fractures based on the study of single phase flow of the fractures through physical simulation experiment, and clarifies the flow law in fractures through theoretical prediction and comparison of experiments results.

BASIC FEATURE OF SHALE RESERVOIR FRACTURE

There are lots of natural micro-fractures (Montgomery *et al*., 2005) in shale reservoirs, and these fractures can be classified into structural fractures and non-structural fractures according to the formation. The structural fractures are visible to the naked eye with the features of long extension; and they are great in its width changes, smooth and regular fracture plane. And in most cases, these fractures appear in groups and perpendicular to the surface, which make these fractures have obvious directionality and regularity. For these non-structural fractures, they are irregular, curving and discontinuous; and there is no consistent in direction. They are distributed randomly without the influence of the structure. They are in small scale and most of them are micro fractures. The penetration depth is limited longitudinally. According to the width of the fracture, there are four ranks: large, medium, small, micro. The width of the these four types of fracture are respectively more than 1 mm, 0.5-1.0 mm, 0.25-0.5 mm, and less than 0.25 mm. To some extent, the existence of these fractures greatly improves the reservoir space of fluid and the permeability of reservoir. Meanwhile, it is found that there are small amounts of natural open fracture in large scale which is large in terms of width, length and spacing, steep. It is these fractures that improve the permeability of the shale reservoir locally.

In order to observe the size of the natural fracture in shale reservoir, please refer to the American Barnett shale core samples (Bowker, 2003; Gale *et al*., 2007). These shale core samples are cut into slices with the size of 2.5 cm×5 cm×1.5 mm. The observation of the shape and structure of all these samples by using the scanning

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Table 1: Summary of fracture parameters observed

Well name	Core length examined/m	No. of natural fractures	Fracture kinematic aperture/mm	Maximum observed fracture height/cm	No. of fracture sets
1	33.53	74	0.05-0.265	81	4
2	36.88	23	0.05-0.95	3.2	2
3	3.96	2	0.05-1	6	1
4	7.01	3	0-0.05	9	1

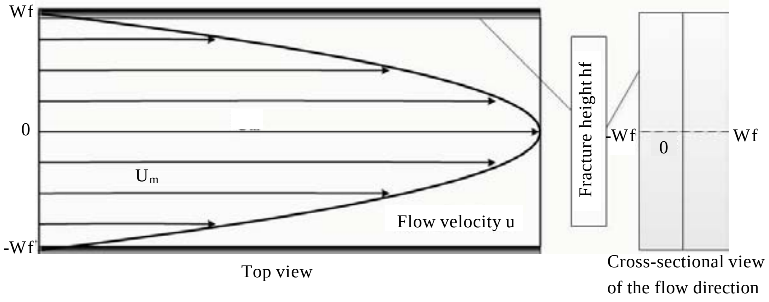

Fig. 1: Fracture parallel plate model

electron microscopy can be concluded by Table 1 according to the differences in coring wells.

It can be seen from Table 1 that the fracture aperture in shale reservoir is almost ranging from 50 μm to 1000 μm, which is narrower than the fracture in routine fractured reservoir. Therefore, the effect of interfacial interaction on characteristics of fluid flow in the shale reservoir fractures should be taken into consideration.

MATHEMATICAL MODEL OF SINGLE PHASE FLUID FLOW IN THE MICRO-FRACTURES OF SHALE RESERVOIR

Basic hypothesis: Suppose that two plates are arranged parallelly (Schilichting and Gersten, 2000) with fractures of $2w_f$ in width and h_f in height (as shown in Fig. 1). The coordinate axis takes the horizontal direction as the x-axis and takes the vertical direction as y-axis, believing that the flow is in parallel lines, i.e. the only flow rate is not zero and all fluid particles moving in one direction. Take the x-axis direction as the forward direction and then $v = w = 0$. the van der Waals force between the micro-fracture surface and crude oil should be taken into consideration.

Viscosity equation of the solid-liquid interface interaction: When the crude oil flows in the shale fractures, with small fractures and the large number of oil molecular, interaction of solid surface and oil molecular make the oil in the fractures produce additional viscosity in the flow so that the viscosity of the fluid near the wall surges and the flow rate of oil decreases. Therefore, for the oil in the shale fractures, the viscosity is consists of the free viscosity of the oil without the consideration of the solid-liquid interface interaction and the decreased viscosity due to the increasing of the van der Waals force function. The viscosity equation (You *et al*., 2007; Wen, 2002) is expressed as:

$$\mu = \mu_0 + \frac{\sigma}{y_0} \tag{1}$$

The width of the fracture is 2 w_f The y-axis is in the vertical direction. To calculate easily, we suppose $y_0 = w_f - y$. The viscosity equation can be changed as:

$$\mu = \mu_0 + \frac{\sigma}{w_f - y} \tag{2}$$

In the Eq. 2, μ_0: Without considering the viscosity of oil when the solid-liquid molecules affects, Pa•s; σ/y_0: The additional viscosity caused by the solid-liquid interface interaction, Pa•s; σ: The coefficient related with the character of fracture surface and character of oil; y_0: The distance to the fracture surface, m.

σ in Eq. 2 is the coefficient related with the van der Waals force, which is the result of combined effect orientation force (F_1), induction force (F_2) and dispersion force (F_3). σ is manifested in the form of van der Waals forces.

The van der Waals force (Zhang, 2006) exerted on oil in the fractures is $F = F_1+F_2+F_3$, in which:

$$F_1 = -\frac{2}{3}\frac{\varepsilon_s^2 \varepsilon_o^2}{R^6 kT} \tag{3}$$

$$F_2 = -\frac{\alpha_o \varepsilon_s^2 + \alpha_s \varepsilon_o^2}{R^6 kT} \tag{4}$$

$$F_3 = -\frac{3}{2}\left(\frac{\alpha_o\alpha_s}{R^6}\right)\left(\frac{I_o I_s}{I_o + I_s}\right) \tag{5}$$

The van der Waals force is the sum of the three forces, expressed as:

$$F = -\frac{1}{R^6}\left[\frac{2\varepsilon_s^2\varepsilon_o^2}{3kT} + \alpha_o\varepsilon_s^2 + \alpha_s\varepsilon_o^2 + \frac{3}{2}\alpha_o\alpha_s\left(\frac{I_o I_s}{I_o + I_s}\right)\right] \tag{6}$$

in which

$$\sigma = \frac{2\varepsilon_s^2\varepsilon_o^2}{3kT} + \alpha_o\varepsilon_s^2 + \alpha_s\varepsilon_o^2 + \frac{3}{2}\alpha_o\alpha_s\left(\frac{I_o I_s}{I_o + I_s}\right) \tag{7}$$

In Eq. 6: ?$_s$, ?$_o$ are used to express the dipole moment of fracture surface and fluid molecular; R represents the distance between molecules; T is the temperature. α_s, α_o represents deformation polarization between fracture surface and fluid molecular. I_s, I_o represents the ionization energy between fracture surface and fluid molecular.

From Eq. 6 we can see that when the oil is flowing in the shale reservoir fractures, it is under the solid-liquid interface interaction of the combined action of oil and fracture surfaces properties.

Motion equations of single-phase flow in the shale reservoir fractures: According to N-S equation

Continuity equation is:

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

Momentum equation is:

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

According to the model hypothesis of fracture parallel plate model, when only considering two-dimensional flow, the velocity component is w = 0. All flow velocity variables are independent of z, that is the partial derivative of z equals to zero. N-S equation can be simplifies to:

$$\frac{dp}{dx} = \frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right) \tag{10}$$

Boundary conditions is: when y = 0, $\partial u/\partial y = 0$; when $y = w_f$, u = 0.

Substitute viscosity Eq. 2 into 10, we can obtain

$$\frac{dp}{dx} = \frac{\partial}{\partial y}\left[\left(\mu_0 + \frac{\sigma}{w_f - y}\right)\frac{\partial u}{\partial y}\right] \tag{11}$$

Integral the both sides of Eq. 10, we can obtain

$$\frac{\partial u}{\partial y} = \frac{y(w_f - y)}{\mu_0(w_f - y) + \sigma}\frac{dp}{dx} + C_1 \tag{12}$$

Integral (12), we can obtain flow velocity

$$\begin{aligned} u = {} & \frac{y\sigma + \ln(\mu_0 w_f - \mu_0 y + \sigma)w_f}{\mu_0^2}\frac{dp}{dx} \\ & + \frac{\sigma\ln(\mu_0 w_f - \mu_0 y + \sigma)C_1}{\mu_0^2} \\ & + \frac{\sigma^2\ln(\mu_0 w_f - \mu_0 y + \sigma)}{\mu_0^3} \\ & + \frac{y^2}{2\mu_0}\frac{dp}{dx} + \frac{C_1 y}{\mu_0} + C_2 \end{aligned} \tag{13}$$

When substitute boundary conditions y = 0, $\partial u/\partial y = 0$; when $y = w_f$, u = 0;

$$C_1 = 0 \tag{14}$$

$$C_2 = -\frac{w_f^2\mu_0^2 + 2\sigma^2\ln\sigma}{2\mu_0^3}\frac{dp}{dx} - \frac{2\mu_0 w_f\sigma + 2\sigma\ln\sigma\mu_0 w_f}{2\mu_0^3}\frac{dp}{dx} \tag{15}$$

Substitute C_1, C_2 into (13), we can obtain the flow velocity in the fractures as:

$$\begin{aligned} u = {} & \left[\frac{y^2}{2\mu_0} + \frac{y\sigma + \sigma\ln(\mu_0 w_f - \mu_0 + \sigma)w_f}{\mu_0^2} + \frac{\sigma^2\ln(\mu_0 w_f - \mu_0 y + \sigma)}{\mu_0^3}\right. \\ & \left. - \frac{w_f^2\mu_0^2 + 2\sigma^2\ln\sigma + 2\mu_0 w_f\sigma}{2\mu_0^3} - \frac{2\sigma\ln\sigma\mu_0 w_f}{2\mu_0^3}\right]\frac{dp}{dx} \end{aligned} \tag{16}$$

Integral flow velocity u in the region with crack width of $2w_f$ height of $2h_f$ we can obtain the flow in the fractures as:

$$\begin{aligned} Q = {} & \left\{\frac{h_f\sigma^3\left[2\ln(w_f + \sigma) - 2\ln\sigma\right]}{\mu_0^4} - \frac{2h_f w_f^3}{3\mu_0}\right. \\ & + \frac{h_f w_f\sigma^2\left[4\ln(w_f + \sigma) - 4\ln\sigma - 2\right]}{\mu_0^3} \\ & \left. + \frac{h_f w_f^2\sigma\left[2\ln(w_f + \sigma) - 2\ln\sigma - 3\right]}{\mu_0^2}\right\}\frac{dp}{dx} \end{aligned} \tag{17}$$

Equation 17 is the flow equation in the fractures when takes the solid-liquid interface interaction into consideration. If we don't consider the solid-liquid interface interaction, then σ = 0. Then the equation simplify the classical theory model as:

$$Q = -\frac{2h_f w_f^3}{3\mu_0}\frac{dp}{dx} \tag{18}$$

PHYSICAL SIMULATION EXPERIMENT OF SINGLE PHASE FLOW IN THE SHALE RESERVOIR FRACTURES

Experimental equipment and condition: Figure 2 is the schematic diagram of the devices of experiment of single phase flow in fractures (Ju *et al*., 2013; Lu *et al*., 2010), in which the fracture devices are the manmade plate fractures with length of 30.48 cm and width of 10.16 cm. In the experiment, we control the fracture width by adopting different spacers.

- **Experimental temperature:** Room temperature
- **Required pressure:** Up flow pressure of the fracture model keeps stable
- **Experimental temperature:** 20 cp white oil (light crude oil properties)

In the physical simulation experiment of micrometer scale, the experiment uses the spacers used in the micrometer scale single fracture and single-phase experiment with the thickness of 15, 80, 190, 400, 650 and 800 μm.

Experiment results: Comparing the variation of pressure gradient and flow in different fractures width, the result is shown in Fig. 3.

We can know from Fig. 3 that in the same fracture width, the flow through the fractures is increasing linearly with the increasing of pressure gradient of flow.

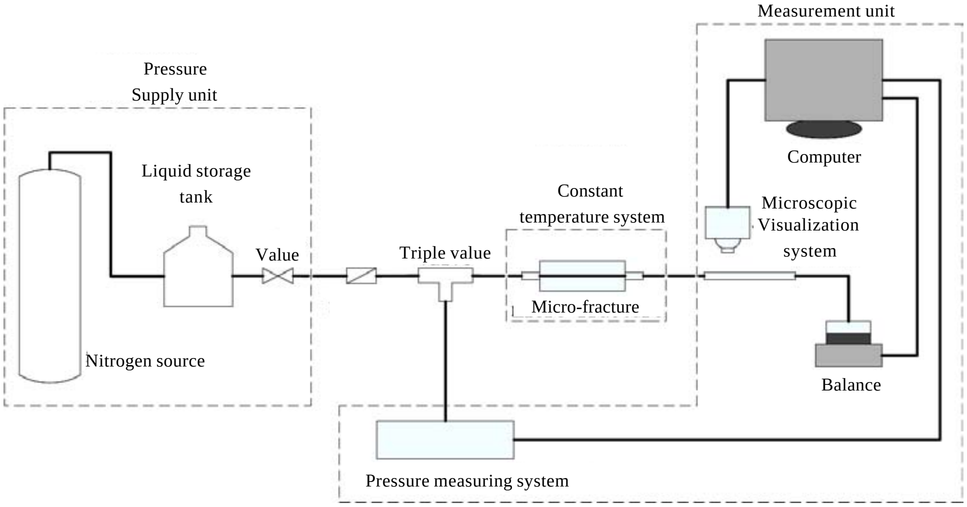

Fig. 2: Experimental instrument of single-phase flow in fractures

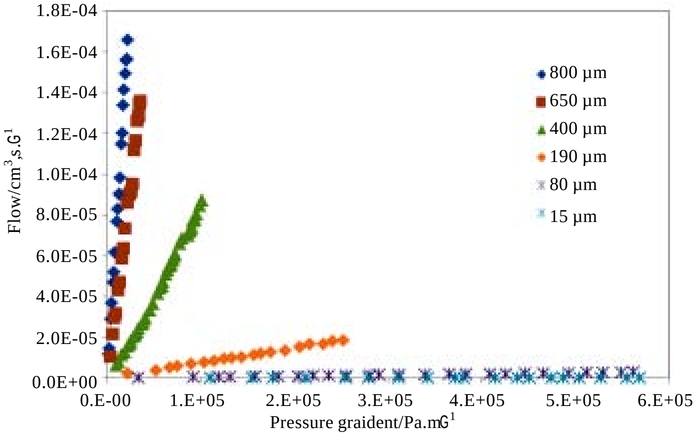

Fig. 3: Relation curve between flow and pressure gradient in different fracture width

Case study of mathematical model: According to Eq. 12 and 13, simulate the flow pressure gradient curve with the interface interaction taken into consideration. Stimulate the flow pressure curve under classical theory (without considering interface interaction). Compare the result with the experimental data, the result is Fig 4.

We can see from the Fig. 4 that the flow predicted by the model considering the solid-liquid interface interaction is in good agreement with the experimental data. But in different fracture width, the flow predicted by the classical theory is greatly different from that of experimental result. When the fracture width is small, such as 15 μm, 80 μm, the flow predicted by the classical theory is greatly different from that of experimental result. When the fracture width increases to the width such as 190 μm, 400 μm, 650 μm, 800 μm, the predicted solid-liquid interface interaction is more and more close to the experimental data. This is because that at small fracture scale, the solid-liquid interface interaction has significant effect on fluid flow in micro-fracture, so the solid-liquid interface interaction cannot be ignored. This is also the main reason of great difference between the curve ignoring the solid-liquid interface interaction in the Figure 4a and the experimental result; the effect of solid-liquid interface interaction declines as the fracture scale increases and the resistance of through the fractures decreases. When the fracture scale reaches 800μm, that numerical simulation results are in good agreement with the experimental data considering the solid-liquid interface interaction when the solid-liquid interface interaction can be ignored.

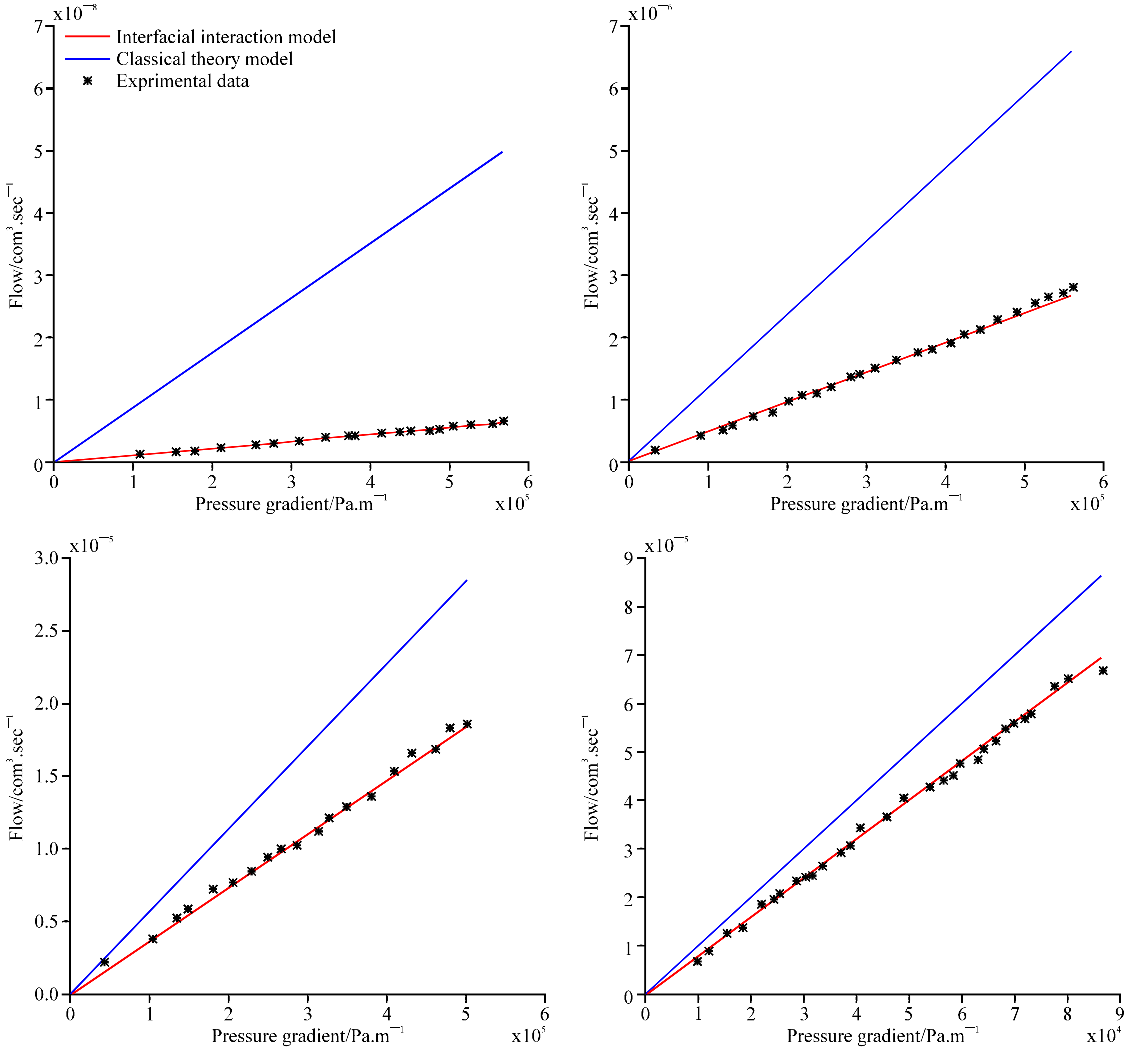

Fig. 1: Continue

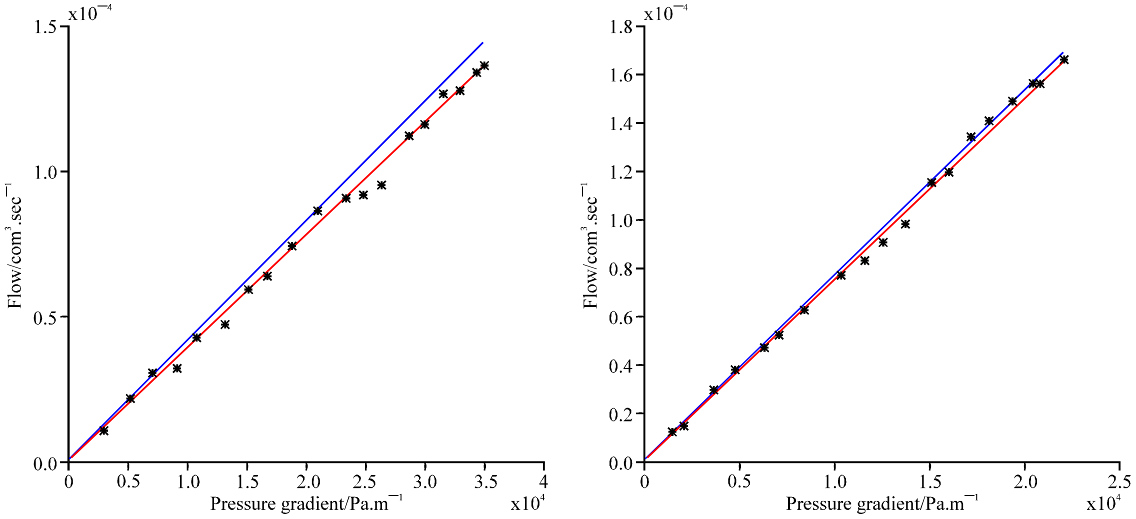

Fig. 4: Comparison diagram between numerical and experimental results. (a) $w_f = 15$ μm, (b) $w_f = 80$ μm, (c) $w_f = 190$ μm, (d) $w_f = 400$ μm, (e) $w_f = 650$ μm and (f) $w_f = 800$ μm

CONCLUSIONS

The physical simulation experiment of the single-phase flow in the shale reservoir fractures indicates that in the same fracture width, the flow through the fracture increase linearly with the increase of pressure gradient; compare the curves of different fracture width, we can see that the wider the fracture, the larger amount of flow through the fractures.

Establish mathematic model of single-phase flow in the micro-fracture considering the solid-liquid interface interaction. After comparing the result with the experimental data, we found that they are in good agreement with each other, which verifies the reasonability and correctness of this mathematic model.

Fitting the classical model without considering the solid-liquid interface interaction with the experimental data, The result indicates that the smaller the fracture width, the greater difference between them. With the increasing of the fracture width, the fitting precision increases. This is because at small fracture scale, the solid-liquid interface interaction has significant effect on fluid flow in micro-fracture. The effect of solid-liquid interface interaction declines as the fracture scale increases. When the fracture scale reaches 800μm, the solid-liquid interface interaction can be ignored.

The study of the flow law in the shale reservoir fractures will provide the theoretical basis for the efficient development of the shale reservoir and provide guidance for the increase of the shale reservoir development level.

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