A Flow - Solid Coupling Permeability Model of Shale Gas Reservoir Based on Dual Media

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Abstract: The study of shale gas seepage mechanism can provide theoretical basis for the production capacity evaluation and prediction of shale gas reservoir. The shale gas permeability model is an important part of the theoretical research of shale gas seepage. In this paper, the spring system model is applied to the shale reservoir, and the shale reservoir is simplified as the ideal dual porosity medium model. By analyzing and considering the influence of adsorption layer, diffusion, seepage, matrix deformation and slippage, the dual porosity permeability model of shale gas under various factors is given. In addition, the model is compared with the Civan permeability model and permeability experiment to verify its rationality. The results show that the model proposed in this paper is reasonable and reliable. The model has certain theoretical and practical significance for perfecting the theory of shale gas seepage flow.

1. Introduction

As an important unconventional oil and gas resource, shale gas has received the attention of most countries in the world[1-5]. Shale gas reservoir is an unconventional gas reservoir with low porosity, low permeability and adsorption characteristics, and its pore radius has reached the nanometer level and has a strong multi-scale characteristic, so that the gas flow mechanism in shale reservoir is obviously different from that of conventional gas reservoirs.

In the process of migration, the shale gas is affected by pressure and geostress, and the coupled transport mechanism of seepage field and stress field is formed. This mechanism has been widely concerned and studied by experts and scholars, and different seepage-stress coupling models have been proposed. These models include equivalent continuum model, fracture network model, dual medium model, fracture mechanics model, continuum damage mechanics model and statistical model, etc[6]. And for shale gas reservoir, in order to establish the mathematical model of shale gas seepage-stress coupling mechanism, it is often necessary to study the change of pore structure and the change of medium permeability resulting from the change of reservoir stress, thus a lot of shale gas permeability model was presented[7-10].

The fracture-pore dual media model was proposed by the former Soviet scholar Barenblatt[11]. On this basis, Warren et al. proposed the classical dual medium model, which is divided by orthogonal fracture grid, and natural fractures are replaced by a series of equivalent horizontal and vertical fractures[12]. Based on the classical dual medium model, Liu et al. proposed a spring system model...
suitable for porous media[13], and the model is applied to the study of fracture hydraulic characteristics of two phase flow[14]. For the study of dual medium permeability, the more classical model, such as P&M model[15], holds that permeability is related to pore pressure and stress, and the ratio between apparent permeability and absolute permeability is the ratio of porosity to initial porosity to the third power. Due to the complicated migration mechanism of shale gas, the influence of diffusion, slip and stress sensitivity on permeability cannot be ignored. The research of shale gas permeability under the influence of many factors has attracted the attention of experts and scholars[16-19]. Zhao et al.[20] coupled the diffusion effect in the form of weighted coefficient and established a multi-field coupling calculation model for shale gas permeability. In addition, for the influence of the sliding action, the slippage coefficient F proposed by Javadpour[21] is adopted to modify the shale gas permeability mostly, or the Klinkenberg slip coefficient is adopted too. Guo et al.[22] adopted Klinkenberg slippage coefficient and deduced the apparent permeability of shale gas reservoir based on experimental data, and compared with the Javadpour model to verify the rationality of the model. Singh et al.[23] combined the Darcy flow and Knudsen flow, and presented a non-empirical expression of shale gas permeability with ignoring the Klinkenberg effect. Dong et al.[24] studied the crack permeability and analyzed the influence of reservoir pressure and effective stress on permeability. In addition, the study on permeability can also establish the seepage mathematical model of shale gas reservoir through differential equation or obtain relevant data of permeability through experiment[25-28], and the relationship between stress, pore pressure and shale gas permeability change is verified and analyzed by means of numerical simulation. In addition to the above research factors, the presence of organic matter can also affect the change of permeability. For example, Song et al. proposed a fully coupled visual permeability model for organic and inorganic pores respectively[29].

Due to the diversity of shale gas migration mechanism and influencing factors, the coupling process of shale gas is complicated. There have been some achievements in this field, but they are not rich enough. Besides, the focus on many shale gas permeability models is often different, and the multi-field coupling permeability model with multiple factors of the real reservoir, such as adsorption, diffusion, slippage and stress sensitivity, needs further research.

2. Variation model of permeability

2.1. The dual porosity media model of shale gas

In order to analyze the coupling relationship between seepage field and stress field of shale gas, a suitable model is needed to describe the structural characteristics of shale rock mass. Currently, the Warren-Root model[12] is commonly used, as shown in figure 1. The model is a geological model of the hexahedron of orthogonal fracture cutting matrix, and the direction of fracture is consistent with that of main permeability. This model assumes that the matrix and fracture are both the storage space of the fluid and have different porosity. However, the matrix permeability can be ignored relative to the fracture system, and the fluid flows only in the fracture.

![Figure 1. Warren-Root dual medium model [12]](image-url)
Based on the dual medium model, the dual porosity model used in this paper is to treat the shale reservoir as two seepage systems of matrix and fracture, which overlap each other in space, and has the following assumptions:

- Fractured rock mass is divided into two parts: matrix system and fracture system, and they overlap in space position.
- There are different flow equations in the matrix system and the fracture system.
- The free gas exists in the matrix and fissure system, but the adsorption gas exists only in the matrix, and it is believed that the desorption process is instantaneous.
- The matrix system and fracture system have different porosity and permeability respectively, and they are affected by stress state at the same time.
- The model is isothermal state, and the fluid in the unit is a single component saturated state gas.

2.2. The variation model of permeability

According to the definition of Bear, the porous medium can be considered as a continuous medium, and porosity is defined as a continuous function, and the unit size of the model is greater than that of a representation cell REV with sufficient pore size to treat the porous medium as a continuous medium[30]. For the mechanical properties of porous media, Liu et al. proposed a TPHM model based on Hooke's law[13], as shown in figure 2. They divided the homogeneous rock mass under hydrostatic pressure into two parts. Some of which is composed of rock pores, whose volume and stress are exponential and relatively soft. The other part is composed of rock skeleton, its volume and stress are linear, relatively hard. And the pore and skeleton are consistent with Hooke's law, that is, the stress-strain relationship is linear.

![Figure 2. The spring system model](image)

Based on this assumption, the change of matrix volume in the stress state can be composed of two parts:

$$dV = dV_e + dV_t$$

(1)

Where subscript e,t refers to the skeleton part and the pore part of the matrix respectively.

The matrix volume in the stress-free state is:

$$V_0 = V_{0,e} + V_{0,t}$$

(2)

Where subscript 0 means zero stress.

Considering $V_p$ as part of pore volume, the pore volume under stress state can be expressed as:

$$V^p = V^p_e + V^p_t$$

(3)

Where superscript $p$ refers to the pore.

The pore volume under stress-free state is:

$$V^p_0 = V^p_{0,e} + V^p_{0,t}$$

(4)

According to Hooke's law, the strain of the pore part and the volume strain of the skeleton part can be respectively expressed as:

$$d\varepsilon_{v,t} = -\frac{dV}{V}$$

(5)
Due to $\sigma = 0$, $\gamma = \gamma_0$, the integral of equation (5) and (6) can be respectively obtained:

$$V_i = V_0, \exp \left( -\frac{\sigma}{K_i} \right)$$  

(7)

$$V_e = V_0, \exp \left( -\frac{1-\sigma}{K_e} \right)$$  

(8)

Where $K$ is the volume modulus.

Equation (7) and (8) are substituted into equation (1) to obtain:

$$-\frac{dV}{V_0} = \gamma_e \frac{d\sigma}{K_e} + \gamma_i \exp \left( -\frac{\sigma}{K_i} \right) \frac{d\sigma}{K_i}$$  

(9)

$$\gamma_i = \frac{V_{0,i}}{V_0}$$  

(10)

$$\gamma_e = 1 - \gamma_i$$  

(11)

The pore volume includes the connected pore volume and the closed pore volume in the skeleton, and the derivative of the equation (7) can be obtained to the connected pore volume:

$$dV_i = -\frac{V_{0,i}}{K_i} \exp \left( -\frac{\sigma}{K_i} \right) d\sigma$$  

(12)

The derivative of the pore volume in the skeleton can be obtained:

$$dV_e = -C_e V_0 d\sigma$$  

(13)

Where $C_e$ is the compressibility factor of the closed pore part in the pore volume.

Matrix porosity can be expressed as:

$$d\phi = \frac{dV_p}{V} = \frac{dV_p}{V} + dV_i$$  

(14)

Substituting equation (12) and (13) into equation (14) can be obtained:

$$d\phi = -\phi C_e C_i d\sigma - \frac{\gamma_i \exp \left( -\frac{\sigma}{K_i} \right) d\sigma}{K_i}$$  

(15)

Due to $\sigma = 0$, $\phi_i = \phi_0$, the integral of equation (15) is obtained to matrix porosity in the stress state:

$$\phi = \phi_0 \left(1-C_e C_i\sigma\right) + \gamma_i \exp \left( \frac{\sigma}{K_i} \right)$$  

(16)

The adsorption of gas can be expressed by the temperature adsorption equation of Langmuir. It is assumed that the gas is adsorbed by monolayer, and the thickness of the adsorption layer can be calculated by the following formula[31]:

$$h = 2.04 \times \frac{V_m P}{S(p_i + p)} \times 10^6$$  

(17)

The effective pore radius is:

$$r_e = r - h$$  

(18)

Where $r$ is the average pore radius of the matrix.

In the process of shale gas, because of the gas extraction, adsorption gas on the pore surface of the
matrix is desorbed, and the pore pressure drops, and these will cause the matrix shrinkage, which in turn reduces the permeability. That is, stress sensitivity. The permeability modulus $\alpha$ of the stress sensitivity can be expressed as:

$$\alpha = \frac{1}{k} \frac{d k}{d \sigma}$$  \hspace{1cm} (19)

Where $k$ is the permeability.

For the dual porosity model, the derivative of matrix permeability is obtained:

$$dk = \frac{r^2}{8} \frac{d \phi}{d \sigma}$$  \hspace{1cm} (20)

Equation (15) and equation (19) were substituted into equation (20) to obtain matrix permeability of matrix deformation, gas adsorption and stress sensitivity:

$$k_i = \frac{(r - h)^2}{8 \alpha} \left[ \phi C_e + \frac{Y_e}{K_i} \exp \left( -\frac{\sigma}{K_i} \right) \right]$$  \hspace{1cm} (21)

Moreover, the matrix pore size of shale reservoir is within the nanometer range, and 4nm-200nm is the main flow path, that is, the influence of transition diffusion should be considered in the normal gas flow, and it contains slip flow. When calculating shale permeability, if handled as Knudsen diffusion, apparent permeability will significantly larger. However, in the case of transition diffusion treatment, it is close to the actual apparent permeability\[32\], so the diffusion form of permeability model will be considered as a transitional diffusion in this paper. Single transition diffusion permeability can be expressed as:

$$k_i = \left( \frac{6 \pi r_A}{k_b T} + \frac{3}{4 \mu (r - h)} \right) \frac{1}{(2 RT)^{1/2}} \frac{\phi}{p} \frac{\pi M}{2 RT}$$  \hspace{1cm} (22)

Where $r_A$ represents the molecular radius of the gas, 1.9×10⁻¹⁰m; $M$ is the molar mass, 0.016kg/mol; $\mu$ is the viscosity, 1.18×10⁻¹¹MPa·s; $T$ is the temperature, 318.15K; $p$ is the pore pressure; $K_B$ is Boltzmann constant, 1.3805×10⁻²³J/K.

According to the study of Javaidpour, the effect of slippage on the gas flow is corrected by the slip correction factor $F$ \[21\]:

$$F = 1 + \left( \frac{8 \pi RT}{M} \right)^{0.5} \frac{\mu}{p_{avg}} \left( \frac{2}{\alpha} - 1 \right)$$  \hspace{1cm} (23)

Where $\alpha$ is the coefficient of tangential momentum, and the value range is 0~1; $p_{avg}$ is the average of internal and external pressure.

Matrix permeability of coupled matrix deformation, gas adsorption, stress sensitivity, gas diffusion and slippage:

$$k_m = \frac{1 + F}{\alpha} \left[ \frac{6 \pi r_A}{k_b T} + \frac{3}{4 \mu C_e} \frac{\pi M}{2 RT} \right]^{-1} \left[ \frac{1}{p} + \frac{2}{8} \right] \frac{\phi C_e + \frac{Y_e}{K_i} \exp \left( -\frac{\sigma}{K_i} \right)}{}$$  \hspace{1cm} (24)

The first term on the right of equation (24) denotes slippage and stress sensitivity, and the second term denotes diffusion and adsorption, and the last term denotes matrix deformation under stress.

2.3. The variation model of fracture porosity and permeability

Because this paper assumes that the two systems of matrix and fracture overlap each other in space, so it is considered as a spring system model for fracture systems too. Different from the matrix, the fracture system is divided into the rock mass with the linear relation between the volume and the stress and the fracture with the exponential relationship between the volume and the stress in the direction perpendicular to the fracture plane. And the fracture and rock mass are consistent with Hooke's law, that is, the stress-strain relationship is linear. Due to the large fracture scale formed after fracturing of shale reservoir, the number of knudsen is small, so the gas flow in the fracture can
consider the influence of deformation, stress sensitivity and slippage. The research literature shows that crack opening has a great influence on crack permeability. In this paper, the average crack opening degree of the unit volume is \( b \), there are:

\[
b = b_e + b_t
\]  
(25)

\[
b_0 = b_{0,e} + b_{0,t}
\]  
(26)

Hooke's law is applied to crack and rock mass respectively:

\[
d\sigma = -K_{f,f} \frac{db}{b_{0,f}}
\]  
(27)

\[
d\sigma = -K_{f,e} \frac{db}{b_{0,e}}
\]  
(28)

Where \( f \) refers to fracture system; \( \sigma \) refers to geostress. Simultaneous equations are obtained:

\[
db = -b_{0,e} \frac{d\sigma}{K_{f,e}} - b_{0,t} \exp\left(\frac{-\sigma}{K_{f,t}}\right)\frac{d\sigma}{K_{f,t}}
\]  
(29)

The average crack opening degree \( b \) (fracture porosity) can be obtained by integrating equation (29):

\[
b = b_{0,e}\left(1 - \frac{\sigma}{K_{f,e}}\right) + b_{0,t} \exp\left(\frac{-\sigma}{K_{f,t}}\right)
\]  
(30)

Similarly, considering the stress sensitivity and gas slippage, the fracture permeability can be expressed as:

\[
k_f = b^2 \left(1 + F\right) \frac{b_{0,e}}{4\alpha} \frac{b_{0,t}}{K_{f,e}} \frac{b_{0,t}}{K_{f,f}} \exp\left(\frac{-\sigma}{K_{f,t}}\right)
\]  
(31)

The \((1+F)/\alpha\) in equation (31) represents stress sensitivity and slippage, while the rest represents deformation under stress.

The total permeability equation of shale gas can be obtained by equation (31) and equation (24):

\[
k = \frac{1 + F}{\alpha} + \frac{b_e^2}{4} \frac{b_{0,e}}{K_{f,e}} \frac{b_{0,t}}{K_{f,t}} \exp\left(\frac{-\sigma}{K_{f,t}}\right)
\]  
(32)

In the formula, parameters \( r_h, k_0, M, R, T \) and \( \mu \) are constants; parameters \( F, r, \sigma, \alpha, p, K_e, K_{f,e}, K_{f,t}, C_e, \phi_e, \gamma_t, b_{0,e}, \) and \( b_{0,t} \) can be measured by experiment; parameter \( b \) and \( h \) can be calculated by formula.

3. The validation of the model

3.1. Validation with the classical model

In terms of shale gas permeability, many experts and scholars have proposed a validated model. The Civan model\[33,34\] is compared with the permeability model of this paper to verify the rationality of the model. The relation between permeability of Civan model and the model of this paper and pore radius is shown in figure 3, and the value of relevant parameters is shown in table 1.

| Parameter | Value |
|-----------|-------|
| \( b_{0,e} \) (nm) | 300 |
| \( b_{0,t} \) (μm) | 8 |
| \( F \) | 1.017 |
| \( \alpha \) | 0.002 |
| \( M/\text{kg/mol} \) | 0.016 |
| \( T/K \) | 318.15 |
| \( \mu/\text{MPa·s} \) | 1.8×10^{-11} |
| \( R/\text{MPa·m}^3 \) | 8.314 |
As can be seen from the figure, the permeability nonlinearly increases with the increase of pore radius. The error between the model of this paper and Civan model is between 2% and 10%. As the pore radius increases, the pore connectivity increases, and the gas flow capacity increases, so the permeability increases. The variation trend of the model is consistent with the theory, and it can be seen from the figure that the calculation results of the model in this paper are basically consistent with those of Civan model, which indicate that the permeability model is reasonable.

![Figure 3. The relationship between pore radius and permeability](image)

3.2. Validation with the experiment
Due to the difficulty in drilling shale core column, there are few core column samples. In this paper, pressure pulse attenuation method was used to test the permeability of core column samples from the longmaxi formation shale in changning county, sichuan province, as shown in figure 4. In this paper, the ultra-low permeability gas permeability measuring instrument is used to test the rock sample through pressure pulse attenuation method. The test gas is nitrogen, and the experimental instrument is shown in figure 5.

![Figure 4. Shale core samples](image) ![Figure 5. The ultra-low permeability gas permeability measuring instrument](image)

At the beginning of the experiment, the pressure of upstream and downstream containers and sample chamber is equal. In the experiment, a small pressure pulse is applied to make the upstream gas flow into the sample chamber from the upstream. At this time, the pressure in the upstream container decreases, the pressure in the downstream begins to increase, and the pressure difference between the upstream and downstream gradually decreases until the pressure is equal again. During the experiment, the change of pressure difference between upstream and downstream with time can be recorded by the pressure sensor, and the experimental permeability can be calculated through the data.
obtained in the experiment and the theoretical pressure attenuation model. When the internal pressure is 2MPa, the confining pressure gradually increases from 10MPa to 30MPa to measure the permeability under different confining pressures. The above experiment was repeated by increasing the internal pressure successively.

As the core obtained is very dense, the permeability of the core samples measured in the experiment is as low as $1.03 \times 10^{-5}$ mD. The changes of the permeability of shale core measured by the experiment with the effective stress are shown in figure 6. It can be seen from the figure that the permeability decreases with the increase of the effective stress. The main reason why the permeability decreases with the increase of effective stress is that the pores in the rock sample compress or close under the stress condition, so that the flow space of the gas in the rock sample decreases. When the effective stress is constant, core permeability decreases with the increase of pore pressure due to gas adsorption and expansion effect under low pore pressure[35,36]. When the pore pressure is constant, the change range of permeability decreases with the increase of effective stress. It can be seen from the figure that the experimental permeability is basically consistent with the theoretical model permeability, indicating that the model proposed in this paper is reasonable and reliable.

![Figure 6. The relationship between effective stress and permeability](image)

**4. Conclusion**

Based on the dual medium model, the shale reservoir is considered as a linear elastic medium with dual porosity in this paper, and the spring system model is applied to the study of shale gas permeability. In the shale gas permeability model proposed in this paper, permeability is influenced by geostress, pore pressure, stress sensitivity coefficient, pore radius, crack opening under stress-free state, the thickness of the adsorption layer and slip coefficient. The results show that the permeability model proposed in this paper which is influenced by multiple factors is reasonable and accurate. Due to the difference of matrix and fracture permeability, the permeability should be calculated separately in the numerical simulation of shale gas. The permeability model proposed in this paper has certain theoretical and practical significance for improving the theory of shale gas seepage and improving the scientific nature of hydraulic fracturing optimization design.

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