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Shale gas transport model considering gas adsorption and desorption

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Abstract: The gas migration mechanism and apparent permeability in shale reservoirs are significantly different from those in conventional gas reservoirs, which is mainly caused by nanoscale phenomena and organic matter as gas storage and supply media. However, in shale reservoirs, gas flow behavior plays an important role in well performance, so it is necessary to develop a new apparent permeability model considering gas transport mechanism. Therefore, in order to study the change of matrix permeability under different pressures in the development process of shale adsorption layer, combined with previous studies, considering the seepage mechanism of stress sensitivity, real gas effect and adsorption, a new model of apparent permeability is created by combining multiple gas transmission mechanisms. The sensitivity analysis of the new model is carried out by changing the corresponding parameters, and the corresponding conclusions are drawn. In this work, the established model can accurately calculate the apparent permeability of viscous flow, Knudsen diffusion and desorption, which makes us have a more accurate understanding of the transmission mechanism of shale gas and contributes to the efficient and sustainable development of shale gas.

Keywords: Desorption adsorption; Nanopores; Shale gas; Apparent permeability.

1. Introduction

In recent decades, shale gas has attracted great attention worldwide. Because of its considerable reserves and successful development in North America and China, it has become a research hotspot and is expected to become a long-term clean energy replacement [1-4]. The large-scale production of shale gas benefits from long horizontal wells and large-scale hydraulic fracturing technology. However, although great progress has been made in the past few years, the theoretical understanding of the microscopic seepage mechanism in shale matrix is still superficial and confusing. Therefore, the study of gas transport mechanism and transport simulation in shale nanopores is the key technology for efficient and stable development of shale gas.

Nanopores in shale gas reservoirs are extremely developed and randomly distributed. Due to the thin conditions of shale formations, a variety of gas migration mechanisms coexist [5-6], which needs further understanding. Therefore, it is of great significance to accurately understand the microscopic seepage mechanism of shale gas for numerical simulation and productivity prediction. The classical seepage theory cannot establish the fluid seepage characteristics in shale matrix, while the existing models are quite different [7-8]. This paper mainly explains the characteristics of shale reservoirs and the mechanism of nanopore gas transmission, and introduces the mechanisms of adsorption / desorption, real gas effect, stress sensitivity, etc., and divides the possible flow states in actual shale reservoirs according to Knudsen number. Considering the effects of viscous flow, slippage effect and Knudsen diffusion, the gas transport models are classified [9-11]. Firstly, the shale transmission mechanism and characteristics are proposed. Then, different complex transmission mechanisms in shale nanopores are established to establish a comprehensive apparent permeability model. Finally, the influence of different factors on the model is studied and the conclusion is drawn.

2. Shale gas seepage characteristics

2.1. Stress sensitivity

Under the original formation conditions, the gas reservoir pressure, overburden pressure and skeleton stress are in equilibrium. In the process of shale gas reservoir development, with the continuous production of gas, the pressure of gas reservoir decreases, which leads to the increase of skeleton stress borne by rock, and then changes the size of flow channel, which is manifested as the change of porosity and permeability in the process of gas reservoir development. This is the so-called stress sensitivity effect, also known as pressure sensitivity effect. In general, in fractured reservoirs, the increase of rock skeleton stress can easily lead to fracture closure, resulting in a significant reduction in permeability, showing strong stress sensitivity. Micro-fractures and induced fractures produced by fracturing in shale gas reservoirs are extremely developed, and the influence of pressure sensitivity must be considered in reservoir modeling and permeability calculation.

We know that in unconventional reservoirs, porosity and permeability change with pressure depletion during production. As shale gas is extracted from the reservoir, the effective stress of the formation increases continuously, resulting in shale rock being compacted and permeability decreasing. This may significantly reduce gas delivery capacity and gas productivity, especially in stress-sensitive reservoirs, which is essential for accurately estimating formation characteristics from well test analysis and formulating accurate long-term production forecasts [12].

There is an exponential relationship between shale permeability and effective stress:

$$k_\infty{}' = k_\infty e^{-mp_s} \tag{1}$$

Where m is the stress sensitivity coefficient of shale matrix, 1/MPa; p_s is the effective stress on shale matrix, MPa; $k_\infty{}'$ is

the effective permeability of shale matrix, mD; k_∞ is the inherent permeability of dense porous media, generally measured by pulse method, mD.

According to the Hagen-Poisenille law, the relationship between intrinsic permeability of shale and pipe radius can be obtained:

$$k_\infty = \frac{\varphi_0 r^2}{8} = \frac{N\pi r^4}{8A}$$
$$k_\infty' = \frac{\varphi_0' r'^2}{8} = \frac{N\pi r'^4}{8A} \quad (2)$$

The initial radius of the shale nanopore pipe and the effective radius after stress sensitivity can be obtained by substituting the real-time effective radius :

$$r_p = r \cdot e^{-\frac{mp_s}{4}} \quad (3)$$

2.2. Gas desorption-adsorption

There is a large amount of gas adsorbed on the organic matter and pore wall of shale gas reservoirs. During the development process, with the decrease of pressure, the adsorbed gas adsorbed on the rock surface is desorbed into free gas, which is also an important feature of shale gas reservoirs different from conventional gas reservoirs in the development process. Gas adsorption and desorption is a surface phenomenon, mainly caused by intermolecular forces (van der Waals force). A large number of laboratory studies have shown that the isothermal adsorption curve of shale gas is in good agreement with the shape of the Langmuir isothermal adsorption curve. Therefore, the Langmuir isothermal adsorption model is widely used to describe the adsorption-desorption process during shale gas development. In the original state of the gas reservoir, the adsorbed gas in shale gas and the original formation pressure are in a dynamic equilibrium process. After shale gas drilling, completion and production, reservoir fracturing gradually decreases, and the original equilibrium state of the formation is broken. The shale gas adsorbed on the surface of the shale matrix is desorbed and converted into free shale gas stored in the micro-pore space until the adsorbed shale gas and free shale gas reach equilibrium again.

Adsorbed gas is a unique form of gas storage in shale formations, because organic nanopores are very developed and provide huge adsorption sites for gas adsorption. In nanopores, the size of gas molecules becomes comparable to the diameter of the flow path. Therefore, the effect of molecular size on gas migration cannot be ignored. During shale depletion, the organic pore radius can change or remain approximately constant, depending on the rate of adsorption and desorption. When studying the effect of gas adsorption on pore radius, it is usually assumed that gas adsorption satisfies the Langmuir adsorption isotherm [13]. Therefore, considering the real gas effect of gas in the actual gas reservoir, when shale gas adsorption occurs, it can be expressed as :

$$V_E = V_L \frac{p/Z}{p_L + p/Z} \quad (4)$$

Where V_E is adsorption volume, m3/m3; P_L is Langmuir pressure, MPa; V_L is the Langmuir volume, m3/m3. Gas coverage:

$$\theta = \frac{\beta p/Z}{1+\beta p/Z} \quad (5)$$

Where β is a constant related to adsorption, which can be obtained through experiments, Pa-1?

The above formula is based on the assumption of ideal porous media with uniform surface and the same pore size, which is widely used in the study of microscopic seepage mechanism of shale gas reservoirs. However, this assumption is difficult to represent strong heterogeneous shale, which is characterized by complex mineral composition (clay minerals, kerogen) and variable flow paths with different pore scales and geometries. Based on the assumption of uniformity, the adsorption heat is constant, which is not in line with the actual situation. In future research, a more accurate transport model based on multi-site adsorption theory can be established. Another problem to note is that fugacity is better used to describe the chemical potential balance between the bulk phase and the adsorbed phase when considering the real gas effect. At present, there is no relevant explanation in the study of shale gas seepage behavior. Therefore, in the future research, it is necessary to establish a more theoretical robustness model based on the concept of fugacity to obtain higher accuracy.

The equivalent radius occupied by the adsorbed gas molecules can be expressed as:

$$r_{ad} = d_m \theta \quad (6)$$

Where d_m is gas molecular diameter, m.

In addition to the influence of stress sensitivity, the effective pore size will change due to the adsorbed gas molecules, thus affecting the gas transport capacity. Because in the process of depressurization, with the continuous desorption of adsorbed gas, the effective pore size becomes larger. Therefore, considering the influence of stress sensitivity and gas adsorption / desorption, the expression of effective pore diameter of organic matter is:

$$r_{eff} = r_p - \theta d_m \quad (7)$$

Where r_{eff} is the effective pore radius of gas flow in shale nanopores?

Then, the effective pore radius is used to establish the permeability model of organic nanopores in shale gas reservoirs. The equivalent permeability considering the effect of adsorbed gas on pore occupation and stress sensitivity in nanoscale capillary can be expressed as:

$$k_{ad} = \frac{r_{eff}^2}{8} = \frac{\left(r_p - r_{ad}\right)^2}{8} \quad (8)$$

3. Gas transport model in shale nanopores

The formation of shale gas belongs to typical multi-scale porous media, with a variety of reservoir and migration mechanisms, and its transmission rules are different. It can be divided into the following transport mechanisms: viscous flow, Knudsen diffusion and surface diffusion [14]. For shale nanopores, the permeability of shale matrix is mainly determined by slippage effect and free molecular flow effect. Therefore, we introduce a weight coefficient to couple the continuous flow and Knudsen diffusion, and the full flow permeability of gas in pores can be obtained as [15]

$$k_g = f \cdot k_{slip} + (1-f) \cdot k_{Knudsen} \quad (9)$$

The weight factor is expressed as :

$$f = \frac{1}{1+(\frac{K_n}{K_{n_{0.5}}})^{n-1}} \quad (10)$$

When 10-3<Kn<10-1, The ideal gas permeability under slippage effect can be expressed as [16]:

$$k_{slip} = k_\infty (1+5K_n) \quad (11)$$

When Kn>10, Gas transport in pores can be described by Knudsen diffusion：

$$k_{K_{nudsen}} = k_\infty (\frac{128\tau^2\mu_g\delta^2}{3K_B\phi}\sqrt{\frac{\pi R}{MT}})K_n \quad (12)$$

For tubular pores, the absolute permeability is expressed as：

$$k_\infty = \frac{\phi r^2}{8\tau^2} \quad (13)$$

Therefore, considering the real gas effect, reservoir stress sensitivity, gas adsorption and desorption effect, coupled slippage effect and Knudsen diffusion effect, the comprehensive apparent permeability model can be expressed as:

$$k_{app} = \frac{\phi r_{eff}^2}{8\tau^2}[\frac{4.5^4+(1+5K_n)}{4.5^4+K_n^4} + \frac{128\tau^2\mu_g\delta^2}{3K_B\phi}\sqrt{\frac{\pi R}{MT}}(\frac{K_n^5}{4.5^4+K_n^4})] \quad (14)$$

Where k_{app} is the apparent permeability of shale matrix,10-3μm2; τ is the tortuosity,dimensionless; R is the gas constant, J·K－1·kmol－1 ; M is the molar mass of gas,kg /mol;T is the temperature, K; K_n is Knudsen number, dimensionless; δ is the molecular collision diameter, m; K_B is Boltzmann gas constant,1.38×10 -23,J /K.

4. Sensitivity analysis of permeability influencing factors

We use the experimental data in the literature [17] to analyze the sensitivity of the model. The specific calculation parameters are the same as the experimental core parameters.

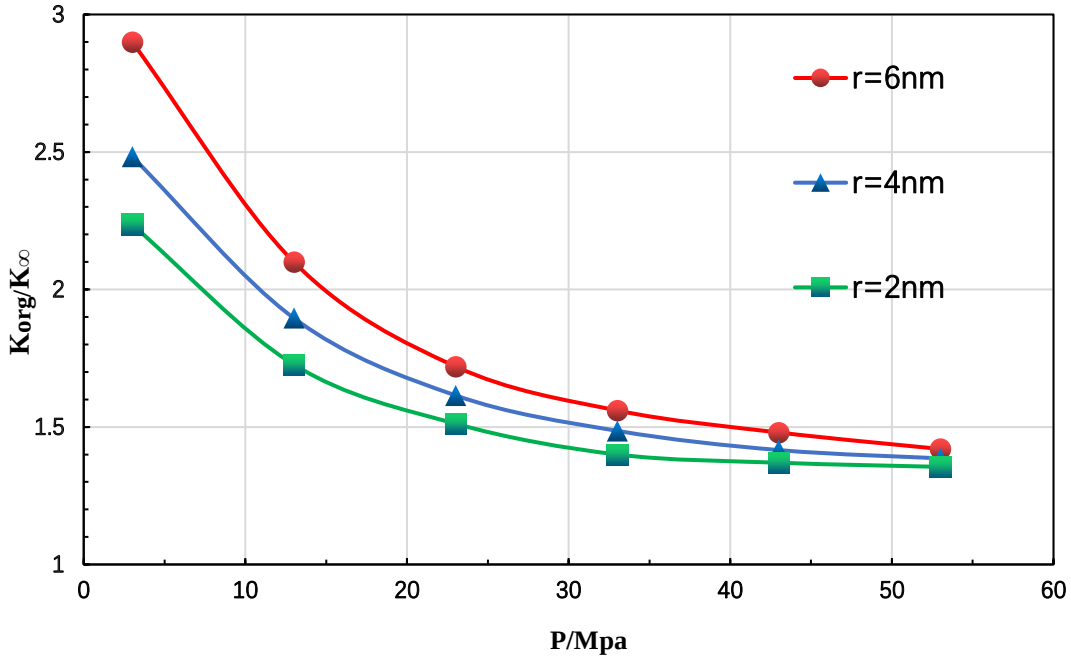


Figure 1. Variation of apparent permeability with different pore radius and pore pressure

It can be inferred from Fig.1 that the apparent permeability decreases with the increase of pore pressure, but the decrease rate slows down. When the pore pressure is the same, the larger the pore radius, the greater the apparent permeability. When the pore radius becomes larger, the slippage effect becomes weaker, and the ratio of apparent permeability to absolute permeability gradually becomes the same. When the pore pressure becomes smaller, the ratio of apparent permeability to absolute permeability becomes larger due to gas slippage. When the pore pressure increases, the average free path of gas molecules decreases, the flux caused by slip flow and Knudsen diffusion and surface diffusion also decreases, the increase rate of apparent permeability decreases, and the ratio of absolute permeability decreases rapidly. Therefore, from the seepage mechanism, the apparent permeability of shale gas is affected by gas slippage and diffusion, and is affected by the pore radius and pore pressure of shale.

The Langmuir isothermal adsorption model is actually a hypothetical model, which assumes that the temperature remains constant during the adsorption process. However, in fact, the physical process of adsorption is related to temperature changes, because adsorption is an exothermic process. From the adsorption desorption equilibrium equation, gas adsorption will release heat, resulting in an increase in the surrounding temperature, which will make the balance move in the direction of ' desorption ', which may hinder the adsorption process. Generally, the content of adsorbed gas and organic matter (TOC) in shale is related to temperature, which increases with the increase of organic matter content and decreases with the increase of temperature.

The volume of gas molecules and the interaction force between molecules cannot be ignored under reservoir conditions, that is, the influence of real gas effect on gas transport needs to be considered. Real gas effect is usually characterized by gas compressibility, viscosity and MFP.

As shown in Figure 1, pressure, temperature and Langmuir parameter b affect the gas coverage rate together. As the pressure decreases during the development process, the gas coverage rate also decreases, and the rate of decline gradually accelerates; when the Langmuir parameter b increases, the gas coverage also increases. When the Langmuir parameter b is constant, the higher the temperature, the smaller the gas coverage.

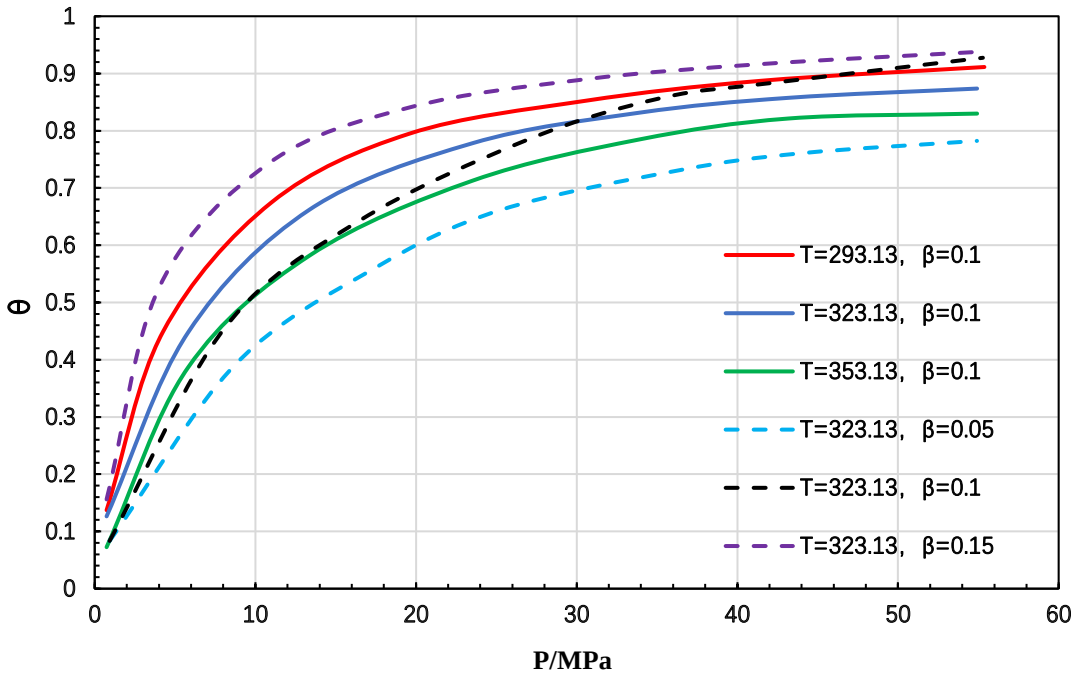


Fig.2 Real gas coverage ratio θ at different pressures, temperatures and Langmui parameter β

In 1996, French scientists proposed Langmuir equation and adsorption theory, which believed that there were adsorption sites on the solid surface that could adsorb molecules or atoms. These adsorption sites can be evenly distributed throughout the surface or unevenly distributed on the surface of the adsorbent. The Langmuir equation assumes that there are a certain number of adsorption sites on the solid surface, and each adsorption site can only adsorb one gas molecule. At the same time, the adsorption capacity of the adsorption sites is equal, and the adsorption process is reversible. In this case, the Langmuir equation can be used to describe the relationship between the amount of gas adsorbed on the solid surface and the gas partial pressure in the gas phase.

There is adsorbed gas in shale pores. When the pressure in the pores decreases, the adsorbed gas will desorb and become free gas. At the same time, the adsorbed gas will also flow on the pore surface, that is, surface diffusion. In addition, because the adsorption layer has a certain thickness, the thickness of the adsorption layer will have a certain influence on the flow of gas in the pores for nanopores. This study will focus on the desorption and flow characteristics of adsorbed gas in nanopores.

There are two main mechanisms of gas adsorption: physical adsorption and chemical adsorption. Physical adsorption: also known as van der Waals force adsorption. In this case, the gas molecules interact with the rock surface through the intermolecular van der Waals force to form an adsorption layer. This adsorption is reversible, and the adsorption layer can be released or formed with the change of pressure or temperature. Physical adsorption usually occurs at low temperature and high pressure. Chemical adsorption: also known as chemical bond adsorption. In this case, gas molecules form chemical bonds with the rock surface through chemical reactions and form a stable adsorption layer. This adsorption is irreversible and can only be released if chemical changes occur on the rock surface. Chemical adsorption usually occurs at high temperature and high pressure.

The desorption of shale gas refers to the process in which gas molecules are separated from the surface of shale pores and become free gas. The process can be divided into two stages: first, when the reservoir pressure decreases continuously during production, the equilibrium state of the system is destroyed. When the pressure drops to the critical desorption pressure of the gas, the adsorbed gas molecules in the pores gradually desorb into free gas ; secondly, under the action of concentration gradient, free gas enters the seepage channel to produce diffusion. In actual production, the content and desorption of adsorbed gas play an important role in maintaining the stable production of shale gas wells.

5. Conclusion

According to the seepage mechanism of shale gas, a comprehensive apparent permeability mathematical model considering stress sensitivity, real gas effect, adsorbed gas desorption / adsorption and slip Knudsen diffusion is established. The new model fully considers the effect of adsorbed gas on apparent permeability, which can correct the calculation deviation caused by adsorption effect.

Different parameters were changed and the overall effect of the model was studied. The effects of gas transport and gas adsorption / desorption on apparent permeability at different development stages were quantitatively described.

It is found that under high pressure conditions, the gas is mainly viscous flow, and decreases rapidly with the decrease of pressure. Under low pressure, the bulk gas undergoes Knudsen diffusion and adsorption / desorption, and the permeability gradually increases with the decrease of pressure.

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