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Similar structure of solution for unsteady seepage flow model of shale gas reservoirs

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Abstract—In view of the problem that the flow model of shale gas reservoir is generally more complex, a simple and convenient method – similar constructive method to solve the shale gas seepage model is proposed. According to the model of unsteady shale gas flow in the double medium, the bottom hole pseudo pressure with similar structure is constructed by introducing the leading solution functions and similar kernel functions. On this basis, draw the characteristic curves and carry on the sensitivity analysis with the drawing software. The study shows that the bottom hole pseudo pressure is different from the kernel function under different boundary conditions. So when using the similar structure theory to draw the characteristic curves of different boundary conditions, only need to change the kernel functions. It also provides a new way of thinking for the research and development of new well testing analysis software.

Keywords —Shale gas, seepage model, similar structure, similar kernel function, sensitivity analysis.

I. INTRODUCTION

Shale gas as a new unconventional energy sources with low permeability, low porosity, rich yield [1]-[4] and so on. The United States is the first country to develop shale gas, with the most advanced mining technology. Shale gas production in China is also in full swing in progress. At the beginning of 2016, Xinjiang opened a unconventional energy treasure shale gas forecast resources of up to one hundred billion. Due to the conventional energy gradually exhausted, and alternative energies are in the phase of research and development, can not be a large-scale application, so the unconventional oil and gas with the development of the urgent and necessary. Therefore shale gas as a new non conventional energy is slowly into the field of vision, and become an important role in the international energy strategy.

Because of the special geological characteristics and reservoir characteristics of shale gas reservoirs, the influence of seepage mechanism and the main control parameters on the characteristics of the reservoir is different from that of conventional gas reservoirs. In order to improve the efficiency of shale gas extraction, we need to study the percolation mechanism of shale gas. At home and abroad, a number of scholars have established mathematical model for shale gas seepage mechanism [5]–[7].. However, the solving process is complex and the use of perturbation rules leads to a certain deviation between the model prediction and the actual production data. The boundary value problem of differential equation and the problem of reservoir seepage have been obtained by using the theory of similar structure [8]-[9]. Therefore, this paper extends the theory of similar structure to the solution of the seepage model of unconventional gas reservoirs. It is proved that the similar structure theory is not only suitable for reservoir, but also suitable for unconventional gas reservoir. After getting the bottom hole pseudo pressure with similar structure under different boundary conditions. The Stehfest numerical inversion method [10] is used to inverse the bottom hole pseudo pressure to the real space. Then draw characteristic curves and sensitivity analysis based on similar structure theory. The research shows that under different boundary conditions, the bottom hole pseudo pressure structure is similar, just the kernel function is different. So it is necessary to change the kernel function when using the similar structure theory to draw the characteristic curves under different boundary conditions. This will greatly simplify the drawing process of the characteristic curves, and will have a profound impact on the development and research of well testing analysis software in the future.

II. MATHEMATICAL MODEL

A. Model Hypothesis

Firstly, the following model assumptions are made according to the Swaan De model [11]:

Shale rock matrix contains the primary pore, and divided into homogeneous shape and uniform size small spherical matrix. These small pieces of matrix are separated by fractures. That is to say, the shale matrix block is idealized as a spherical rock mass. Shale layer is slightly compressible, gas can be compressed. In the original state, the gas is stored in the pore of the shale matrix and the pore wall surface of the shale matrix by the state of free gas and adsorbed gas. In the actual situation, the pore diameter of shale matrix is generally small; the liquid can not enter the matrix porosity, so only the gas phase. Assuming the model for the double and single permeability model, that is to say that the fluid from the spherical substrate surface and uniform flow into fractures. The gas then flows from the fractures to the bottom hole, and there is a flow between the matrix and the rock mass. Gas flow from the matrix system to the fracture system is a non steady state process. The gas flow in the fracture system follows the Darcy's law. Do not take into account the effects of gravity and capillary pressure. Finally, it is assumed that all the flows

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in the model are carried out under isothermal conditions.

B. Shale Gas Reservoir Flow Equation

According to the above hypothesis, the unsteady shale gas flow equation [12]:

$$\begin{cases} \frac{1}{r^2}\frac{\partial}{\partial r}\left\{r^2\left[\frac{MD_{k,pm}}{RTZ}+\frac{\pi r\rho}{8p}\left(\frac{2}{F}-1\right)\sqrt{\frac{8RT}{\pi M}}\right]\frac{\partial p}{\partial r}\right\} \\ =\frac{\partial}{\partial t}\left(\frac{Mp_m\phi_m}{RTZ}+\frac{V_m p_m}{p_L+p_m}\right) \\ \frac{\partial}{\partial t}\left(\frac{\phi_{fg}s_{fg}p_{fg}}{Z}\right)=\frac{1}{r}\frac{\partial}{\partial r}\left(\frac{p_{fg}}{Z}\frac{k_{fg}}{\mu_g}r\frac{\partial p_{fg}}{\partial r}\right)+\frac{RT}{M}q_m \end{cases} \tag{1}$$

Where: M for gas molar mass; p_m for the pressure of the matrix system; ϕ_m for the porosity of the matrix system; R for the universal gas constant; T as temperature; Z for the deviation coefficient for gas; V_m for the Langmuir adsorption constant; p_L for the pressure when adsorption capacity reaches 50% of the maximum adsorption capacity; $D_{k,pm}$ is the diffusion coefficient of Knudsen is modified based on the diffusion coefficient of the long straight tube; ρ for the gas density; p for the average formation pressure; F for the tangential momentum coordination coefficient; r for the pore radius; q_m as a source of quality; f on behalf of the cracks; g representative gas; s as saturation.

Introducing pseudo pressure:

$$m=\frac{\mu_i Z_i}{p_i}\int\frac{p}{\mu Z}dp \tag{2}$$

On the basis of dimensionless change and Laplace transform can be:

$$\begin{cases} \frac{\partial^2\overline{m_D}}{\partial r_{mD}^2}+\frac{2}{r_{mD}}\frac{\partial\overline{m_D}}{\partial r_{mD}}=W^2\overline{m_D} \\ \frac{\partial^2\overline{m_{fD}}}{\partial r_{fD}^2}+\frac{1}{r_{fD}}\frac{\partial\overline{m_{fD}}}{\partial r_{fD}}=f(z)\overline{m_{fD}} \end{cases} \tag{3}$$

Where: m_D is the pseudo pressure of matrix which after dimensionless; m_{fD} is the pseudo pressure of crack which after dimensionless.

$$W^2=\frac{15(1-\omega)}{\lambda}z\square f(z)=\omega z+\frac{3D_{k,pm}\mu_{fg}r_w^2}{r_1^2k_{fg}p_{fg}}(W\coth W-1)$$

$$\omega=\frac{(V\phi C_{1m})_f}{(V\phi C_{1m})_{(f+m)}}=\frac{\phi_f C_{1f}}{\phi_f C_{1f}+\phi_f\left[C_m+\frac{\rho_{gsc}V_Lp_L}{\phi_m\rho_m(p_L+p_m)^2}\right]}$$

$$\lambda=\frac{15r_w^2}{r_1^2}\frac{K_{app}}{K_f}=\frac{15r_w^2}{r_1^2K_f}\left[\frac{\mu D_k}{p}+\frac{Fr^2}{8}\right].$$

Combined with the following internal boundary conditions:

$$\begin{cases} \left[C_Dz\overline{m_{wD}}-r_{fD}\frac{\partial\overline{m_{fD}}}{\partial r_{fD}}\right]_{r_{fD}=1}=\frac{1}{z} \\ \overline{m_{wD}}=\left(\overline{m_{fD}}-S\frac{\partial\overline{m_{fD}}}{\partial r_{fD}}\right)_{r_{fD}=1} \end{cases} \tag{4}$$

Outer boundary condition:

$$\begin{cases} \overline{m_{fD}}(r_{fD}\to\infty,z)=0, & (IOB) \\ \frac{\partial\overline{m_{fD}}}{\partial r_{fD}}|_{r_{fD}=R_D}=0, & (CVOB) \\ \overline{m_{fD}}(r_{fD}=R_D,z)=0, & (COB) \end{cases} \tag{5}$$

Where IOBS represents an infinite outer boundary condition. CVOB represents the external boundary condition of constant pressure. COB represents the closed boundary condition.

The general solution of equations can be obtained for

$$\overline{m_{fD}}=AK_0\left(\sqrt{f(z)}r_{fD}\right)+BI_0\left(\sqrt{f(z)}r_{fD}\right) \tag{6}$$

By boundary conditions:

$$\overline{m_{fD}}=\frac{1}{z}\cdot\frac{1}{C_Dz+(C_DSz+1)\cdot\frac{1}{\phi_i(1\square\ z)}}\cdot\frac{\phi_i(r_{fD}\square\ z)}{\phi_i(1\square\ z)} \tag{7}$$

$$\phi_i(z\square\ r_{fD}\square\ R_D)=\begin{cases} \frac{k_0\left(\sqrt{f(z)}r_{fD}\right)}{\sqrt{f(z)}k_1\left(\sqrt{f(z)}\right)} & (IOB) \\ \frac{\varphi_{0,0}(z\square\ r_{fD}\square\ R_D)}{\varphi_{1,0}(z\square 1,R_D)} & (CVOB) \\ \frac{\varphi_{0,1}(z\square\ r_{fD}\square\ R_D)}{\varphi_{1,1}(z\square 1,R_D)} & (COB) \end{cases} \tag{8}$$

$$\begin{cases} \varphi_{0.0}\square\ z,r_{fD},R_D\square=K_0(W_fr_{fD})I_0(W_fR_D)-I_0(W_fr_{fD})K_0(W_fR_D) \\ \varphi_{1.0}\square\ z,r_{fD},R_D\square=W_f\left[K_1\square\ W_fr_{fD}\square\ I_0(W_fR_D)+I_1(W_fr_{fD})K_0(W_fR_D)\right] \\ \varphi_{0.1}\square\ z,r_{fD},R_D\square=W_f\left[K_0(W_fr_{fD})I_1(W_fR_D)+I_0(W_fr_{fD})K_1(W_fR_D)\right] \\ \varphi_{1.1}\square\ z,r_{fD},R_D\square=W_f^2\left[K_1(W_fr_{fD})I_1(W_fR_D)-I_1(W_fr_{fD})K_1(W_fR_D)\right] \end{cases} \tag{9}$$

So

$$\overline{m_{wD}}(z)=\frac{1}{s}\cdot\frac{1}{C_Dz+\frac{1}{S+\phi_i(z,1,R_D)}} \tag{10}$$

C. Characteristic curve drawing and sensitivity analysis

Firstly, the Stehfest numerical inversion method [10] is used to inverse the bottom hole pseudo pressure to the real space. Then the influence of the main control parameters on the bottom hole pseudo pressure and its derivative of the unsteady state shale gas reservoir under three kinds of boundary conditions are analyzed by means of MATLAB software.

Wellbore storage coefficient C_D influence on characteristic curve:

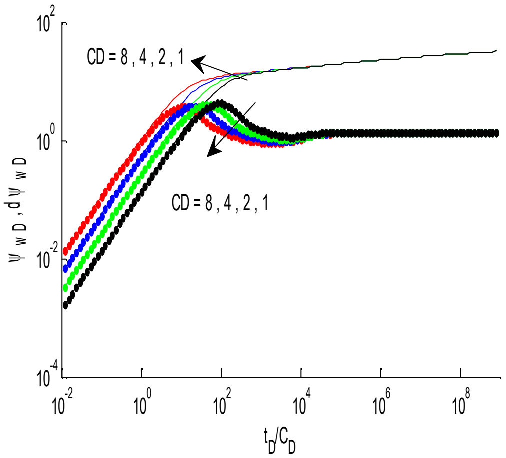

Fig 1: Effect of C_D on type curves (IOB)

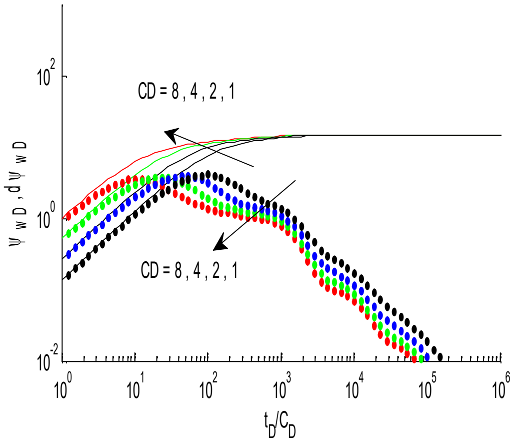

Fig2: Effect of C_D on type curves (CVOB)

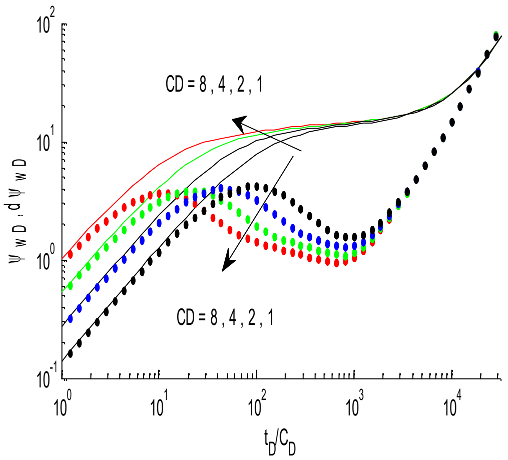

Fig 3: Effect of C_D on type curves (COB)

$S = 2$; namda $= 0.0002$; omiga $= 0.008$; RD $= 10000$; f $= 0.8$;

Figure 3 to figure 1 shows the influence of different wellbore storage coefficient C_D on the bottom hole pseudo pressure and its derivative curves. The characteristic curves of three kinds of different boundary conditions are compared and analyzed, which shows that the wellbore storage coefficient influences the early stage of mining. Under the condition that the other parameters are kept constant, the characteristic curves are similar to the shape of the hump in this period. When C_D is bigger, the time point of the bottom hole to be pressure and its derivative appears is later.

Effect of skin factor S on the characteristic curves:

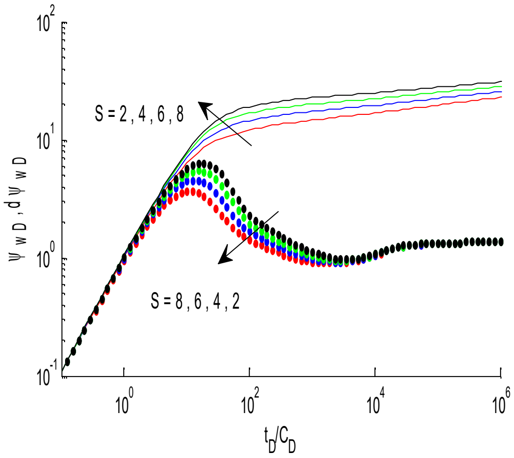

Fig 4: Effect of S on type curves (IOB)

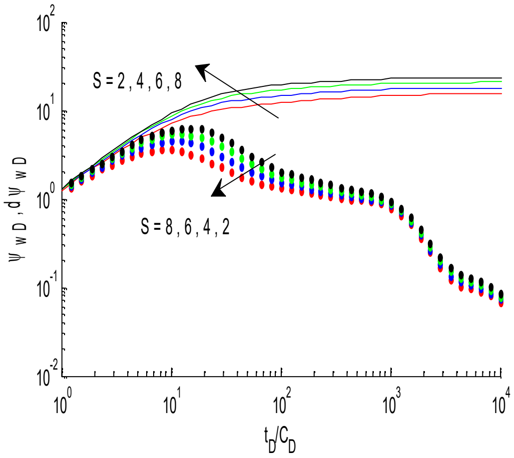

Fig 5: Effect of S on type curves (CVOB)

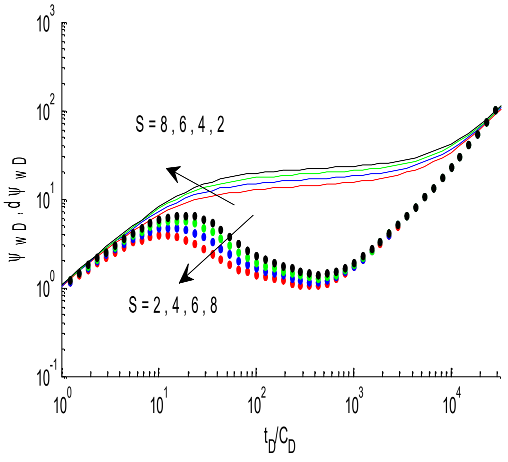

Fig 6: Effect of S on type curves (COB)

$CD = 1$; namda $= 0.0002$; omiga $= 0.008$; RD $= 10000$; f $= 0.8$;

Figure 6 to figure 4 shows the effect of different skin factors on the bottom hole pseudo pressure and its derivative curves. Comparative analysis shows that the skin factor greater dimensionless pressure and its derivative positions appear hump higher.

Effect of different boundary distances on characteristic curves:

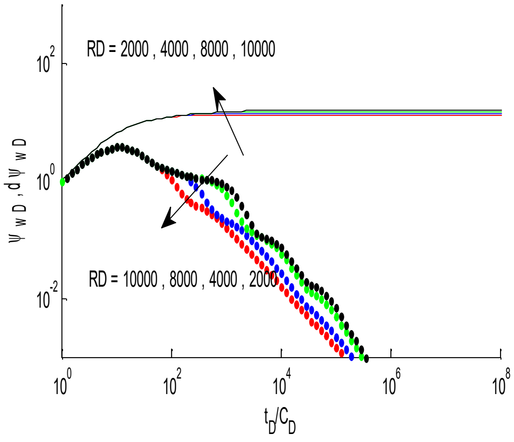

Fig7: Effect of R_D on type curves (CVOB)

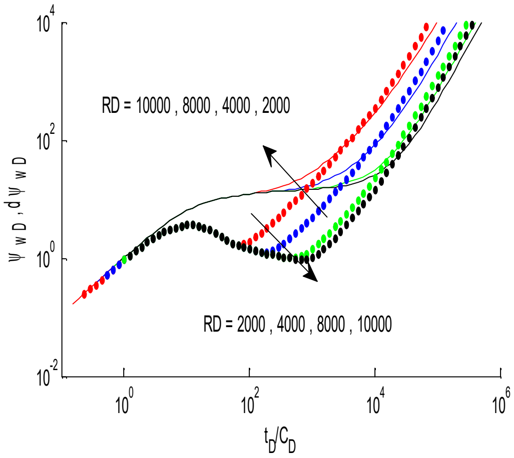

Fig 8: Effect of R_D on type curves (COB)

$S = 2$□ $CD = 1$□ namda $= 0.0002$□ omiga $= 0.008$□f $= 0.8$;

Figure 8, Figure 7 shows the influence of different boundary distance R_D on the bottom hole quasi pressure and its derivative curves. The comparison and analysis show that the main control parameter R_D mainly affects the latter part of the flow (Late pseudo radial flow). And the greater the R_D, the later turning point appears.

CONCLUSION

1) By using the similar structure to solve the seepage equation of oil and gas reservoirs, the complicated seepage differential equations can be simplified to a simple algebraic calculation. The application value of the differential equation in practical engineering is greatly strengthened.

2) From Figure 1 to figure 8 we can see that the wellbore storage coefficient and skin factor have a significant impact on the early stage of flow. Therefore, in the process of establishing the model of shale gas flow, it should be taken into account. Otherwise, the accuracy of the model will be reduced.

3) The research shows that under different boundary conditions, the bottom hole pseudo pressure has similar structure and only the kernel function is different. So it is only needed to change the kernel function to draw the characteristic curves of different boundary conditions by using the theory of similar structure. This will greatly simplify the rendering of the characteristic curve. And contribute to the research and development of well testing analysis software in the future.

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