A Well Testing Model on Pressure Characteristics of the Heterogeneous Composite Gas Reservoir

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Summary (Heading in Arial 12pt bold)

In consideration of the strong heterogeneity in Sulige low permeability gas reservoir of Chanqing oilfield, a well test analytical model for non-isopachous and lateral heterogeneity composite gas reservoir is established. This model comprehensively takes into consideration the skin effect, wellbore storage effect, formation characteristics of gas reservoir and variation of formation thickness. It provided the numerical solution of gas reservoir pseudo-pressure under two typical outer boundary conditions, infinity and closed boundary in order to plot the typical curve of bottom-hole pressure and to analyze the pressure behavior characteristics. More specifically, the theoretical model of the three target heterogeneous gas reservoirs with different boundary conditions are established and analyzed. Moreover, for the multi-zone heterogeneous composite gas pool, the pressure derivative curve of the radial section is increased gradually and becomes higher than 0.5 horizontal line; For a multi-zone heterogeneous composite gas pool but the gas flow is getting better, the pressure derivative curve is decreased to be lower than 0.5 horizontal line for the horizontal gas reservoir; For a multi-zone heterogeneous composite gas pool with an closed boundary, the pressure derivative curve is performed as an upward straight line. In addition, the thicker the outer strata with a higher permeability, the lower the horizontal radial flow line of the pressure derivative curve of horizontal heterogeneous gas reservoirs in the three zones. This model has been used to interpret the real well test data of Sulige gas reservoir, whose interpretation results are in good agreement with the actual production performance. It is found to be practical for studying the characteristics of low permeability gas reservoir.

Key Words: Heterogeneity; Composite reservoir; Well Testing Model; Pressure Dynamic Feature

1 Establishment of complex heterogeneous Well Test Model

1.1 Physical Model of three districts non-isopachous and lateral heterogeneity Composite gas reservoir

In recent years, the behavior of composite reservoirs has attracted much attention and many studies have appeared on this subject. A composite reservoir is made up of two or more regions. Rock and fluid properties are different in each region. The origin of composite systems may be natural or artificial[1]. Examples of naturally created multi-zone composite systems include a reservoir with different permeability zones, an oil reservoir in communication with an aquifer, and an oil well with a finite-thickness skin zone surrounding the wellbore.

We suppose that there are three annular region ,which have different properties of rock in formation[2](Fig.1).Others are supposed with two non-isopachous and lateral heterogeneity Composite gas reservoir model.

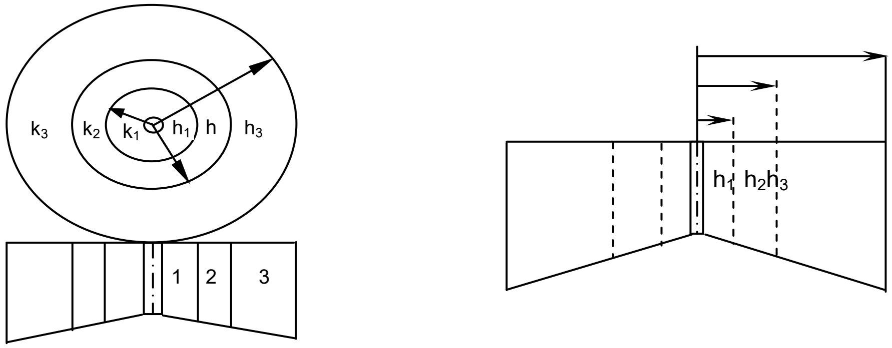

Fig. 1 Sketch showing three districts, non-isopachous and heterogeneity composite gas reservoirs

1.2 The mathematical Model of three districts non-isopachous and lateral heterogeneity Composite gas reservoir

Suppose that there are three annular region ,which have different properties of rock and fluid in formation(Fig.1).And having the following characteristics[3]:（1）Single-phase fluid flow radialy in the reservoir ;（2）Ignore gravity and capillary force;（3）The formation pressure throughout are the original reservoir pressure before test;（4）The formation are unequal thickness, gas production at fixed yield;（5）Fluid flow to meet the linear Darcy flow, isothermal flow;（6）Consider the effect of wellbore storage effect and skin effect;（7）There is no additional pressure drop in Vadose zone.

According to the equation of motion, the continuity equation and the equation of state, and the assumptions, the fundamental differential equation of oil-gas two-phase flow, and their corresponding conditions for the solution[4]. The mathematic model of well test analysis of dimensionless gas reservoir is obtained.

By using effective hole diameter model, to get on flowing control equations and boundary conditions with pseudo-pressure and zero dimension,we canget thedimensionless andmathematical Model of three districts non-isopachous and lateral heterogeneity Composite gas reservoir.

$$\frac{\partial^2 \psi_{1D}}{\partial {r_D}^2} + \frac{1}{r_D}\frac{\partial \psi_{1D}}{\partial r_D} = \frac{1}{C_D e^{2s}}\frac{\partial \psi_{1D}}{\partial t_D} \tag{1}$$

$$\frac{\partial^2 \psi_{2D}}{\partial {r_D}^2} + \frac{1}{r_D}\frac{\partial \psi_{2D}}{\partial r_D} = \frac{1}{C_D e^{2s}}\frac{1}{\eta_{2D}}\frac{\partial \psi_{2D}}{\partial t_D} \tag{2}$$

$$\frac{\partial^2 \psi_{3D}}{\partial {r_D}^2} + \frac{1}{r_D}\frac{\partial \psi_{3D}}{\partial r_D} = \frac{1}{C_D e^{2s}}\frac{1}{\eta_{3D}}\frac{\partial \psi_{3D}}{\partial t_D} \tag{3}$$

$$\psi_{1D}(r_D,0) = \psi_{2D}(r_D,0) = \psi_{3D}(r_D,0) = 0 \tag{4}$$

$$\psi_{1D}\big|_{r_D=r_{1D}} = \psi_{2D}\big|_{r_D=r_{1D}} \tag{5}$$

$$\psi_{2D}\big|_{r_D=r_{2D}} = \psi_{3D}\big|_{r_D=r_{2D}} \tag{6}$$

$$\left.\frac{\partial \psi_{1D}}{\partial r_D}\right|_{r_D=r_{1D}} = h_{D1}\lambda_{D1}\left.\frac{\partial \psi_{2D}}{\partial r_D}\right|_{r_D=r_{1D}} \tag{7}$$

$$\left.\frac{\partial \psi_{2D}}{\partial r_D}\right|_{r_D=r_{2D}} = h_{D2}\lambda_{D2}\left.\frac{\partial \psi_{3D}}{\partial r_D}\right|_{r_D=r_{2D}} \tag{8}$$

$$\frac{d\psi_{wD}}{d(t_D/C_D)} - r_D \frac{\partial \psi_{1D}}{\partial r_D}\bigg|_{r_D=1} = 1 \tag{9}$$

$$\psi_{wD} = \psi_{1D}\big|_{r_D=1} \tag{10}$$

$$\psi_{3D}\big|_{r_{3D}\to\infty} = 0 \qquad \text{(Infinite ground)} \tag{11}$$

$$\frac{\partial \psi_{3D}}{\partial r_D}\bigg|_{r_D=r_{3D}} = 0 \qquad \text{(Closed formation)} \tag{12}$$

In model, the dimensionlessquantity was defined by the based on fluid properties and the nature of the bedrock of the first zone.among them:

$$\psi_{1D} = \frac{1}{1.2733\times10^{-2}}\frac{k_1h_1(\psi_i-\psi_1)}{q_{sc}T}, \quad \psi_{2D} = \frac{1}{1.2733\times10^{-2}}\frac{k_1h_1(\psi_i-\psi_2)}{q_{sc}T}$$

$$\psi_{3D} = \frac{1}{1.2733\times10^{-2}}\frac{k_1h_1(\psi_i-\psi_3)}{q_{sc}T}, \quad t_D = \frac{3.6k_1t}{(\phi\mu c_t)_1 {r_w}^2}, \quad C_D = \frac{C}{2\pi(\phi c_t h)_1 {r_w}^2}$$

$$r_D = \frac{r}{r_we^{-s}}, \quad r_{1D} = \frac{r_1}{r_we^{-s}}, \quad r_{2D} = \frac{r_2}{r_we^{-s}}, \quad r_{3D} = \frac{r_3}{r_we^{-s}}, \quad \lambda_{D1} = \frac{k_2}{k_1}, \quad \lambda_{D2} = \frac{k_3}{k_2},$$

$$\eta_{2D} = \frac{\eta_2}{\eta_1} = \frac{\left(k/\phi\mu c_t\right)_2}{\left(k/\phi\mu c_t\right)_1}, \quad \eta_{3D} = \frac{\eta_3}{\eta_1} = \frac{\left(k/\phi\mu c_t\right)_3}{\left(k/\phi\mu c_t\right)_1}, \quad h_{D1} = \frac{h_2}{h_1}, \quad h_{D2} = \frac{h_3}{h_2}.$$

1.3 The Solution of mathematical Model of three districts non-isopachous and lateral heterogeneity Composite gas reservoir

To (1-1), (1-2), (1-3) takes on t_D/C_D Laplace transform, Taking into account the zero initial conditions, we can get following:

$$\frac{d^2\overline{\psi}_{1D}}{{dr_D}^2} + \frac{1}{r_D}\frac{d\overline{\psi}_{1D}}{dr_D} - \frac{z}{C_De^{2s}}\overline{\psi}_{1D} = 0 \tag{13}$$

$$\frac{d^2\overline{\psi}_{2D}}{{dr_D}^2} + \frac{1}{r_D}\frac{d\overline{\psi}_{2D}}{dr_D} - \frac{z}{C_De^{2s}\eta_{2D}}\overline{\psi}_{2D} = 0 \tag{14}$$

$$\frac{d^2\overline{\psi}_{3D}}{{dr_D}^2} + \frac{1}{r_D}\frac{d\overline{\psi}_{3D}}{dr_D} - \frac{z}{C_De^{2s}\eta_{3D}}\overline{\psi}_{3D} = 0 \tag{15}$$

Make $z_1 = \dfrac{z}{C_De^{2s}}$, Then (1-13), (1-14), (1-15) the formula for the general solution:

$$\overline{\psi}_{1D} = A_1I_0\left(r_D\sqrt{z_1}\right) + B_1K_0\left(r_D\sqrt{z_1}\right) \tag{16}$$

$$\overline{\psi}_{2D} = A_2 I_0\left(r_D\sqrt{\frac{z_1}{\eta_{2D}}}\right) + B_2 K_0\left(r_D\sqrt{\frac{z_1}{\eta_{2D}}}\right) \tag{17}$$

$$\overline{\psi}_{3D} = A_3 I_0\left(r_D\sqrt{\frac{z_1}{\eta_{3D}}}\right) + B_3 K_0\left(r_D\sqrt{\frac{z_1}{\eta_{3D}}}\right) \tag{18}$$

2. The Model of Well Testing and Pressure Characteristics of Infinite Composite Gas Reservoir

2.1 The Model of Well Testing of Infinite Composite Gas Reservoir

According to the characteristics of Bessel function and outer boundary conditions of the infinite formation, $\overline{\psi}_{3D}\Big|_{r_{3D}\to\infty} = 0$,we can get: $A_3 = 0$

Therefore, pressure equation about the one district, the Second District, three areas as following:

$$\overline{\psi}_{1D} = A_1 I_0\left(r_D\sqrt{z_1}\right) + B_1 K_0\left(r_D\sqrt{z_1}\right) \tag{19}$$

$$\overline{\psi}_{2D} = A_2 I_0\left(r_D\sqrt{\frac{z_1}{\eta_{2D}}}\right) + B_2 K_0\left(r_D\sqrt{\frac{z_1}{\eta_{2D}}}\right) \tag{20}$$

$$\overline{\psi}_{3D} = B_3 K_0\left(r_D\sqrt{\frac{z_1}{\eta_{3D}}}\right) \tag{21}$$

According to boundary conditions can be obtained Laplace space 6 order linear equations:

$$\begin{bmatrix} a_{11} & a_{12} & 0 & 0 & 0 & a_{16} \\ a_{21} & a_{22} & 0 & 0 & 0 & a_{26} \\ a_{31} & a_{32} & a_{33} & a_{34} & 0 & 0 \\ 0 & 0 & a_{43} & a_{44} & a_{45} & 0 \\ a_{51} & a_{52} & a_{53} & a_{54} & 0 & 0 \\ 0 & 0 & a & a_{64} & a_{65} & 0 \end{bmatrix} \begin{bmatrix} A_1 \\ B_1 \\ A_2 \\ B_2 \\ B_3 \\ \overline{\psi}_{wD} \end{bmatrix} = \begin{bmatrix} b_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Among them:

$a_{11} = \sqrt{z_1} I_1\left(\sqrt{z_1}\right)$； $a_{12} = -\sqrt{z_1} K_1\left(\sqrt{z_1}\right)$； $a_{16} = -z$； $a_{21} = I_0\left(\sqrt{z_1}\right)$； $a_{22} = K_0\left(\sqrt{z_1}\right)$； $a_{26} = -1$；

$a_{31} = I_0\left(r_{1D}\sqrt{z_1}\right)$； $a_{32} = K_0\left(r_{1D}\sqrt{z_1}\right)$； $a_{33} = -I_0\left(r_{1D}\sqrt{\frac{z_1}{\eta_{2D}}}\right)$ $a_{34} = -K_0\left(r_{1D}\sqrt{\frac{z_1}{\eta_{2D}}}\right)$； $a_{43} = I_0\left(r_{2D}\sqrt{\frac{z_1}{\eta_{2D}}}\right)$

； $a_{44} = K_0\left(r_{2D}\sqrt{\frac{z_1}{\eta_{2D}}}\right)$； $a_{51} = I_1\left(r_{1D}\sqrt{z_1}\right)$ $a_{45} = -K_0\left(r_{2D}\sqrt{\frac{z_1}{\eta_{3D}}}\right)$； $a_{52} = -K_1\left(r_{1D}\sqrt{z_1}\right)$；

$$a_{53}=-h_{D1}\lambda_{D1}\sqrt{\frac{1}{\eta_{2D}}}I_1\left(r_{1D}\sqrt{\frac{z_1}{\eta_{2D}}}\right);\quad a_{54}=h_{D1}\lambda_{D1}\sqrt{\frac{1}{\eta_{2D}}}K_1\left(r_{1D}\sqrt{\frac{z_1}{\eta_{2D}}}\right);\quad a_{63}=I_1\left(r_{2D}\sqrt{\frac{z_1}{\eta_{2D}}}\right);$$

$$a_{64}=-K_1\left(r_{2D}\sqrt{\frac{z_1}{\eta_{2D}}}\right);\quad a_{65}=h_{D2}\lambda_{D2}\sqrt{\frac{\eta_{2D}}{\eta_{3D}}}K_1\left(r_{2D}\sqrt{\frac{z_1}{\eta_{3D}}}\right);\quad b_1=-\frac{1}{z}。$$

At this point that is determined based on unequal thick complex gas reservoirs downhole t_D/C_D Quasi pressure Laplace space solution: $\overline{\psi}_{wD}(z)$ and pseudo pressure Laplace space solution $\overline{\psi}_{1D}(z)$、$\overline{\psi}_{2D}(z)$、$\overline{\psi}_{3D}(z)$ of an area, second district, third District.

2.2 Pressure characteristics of Infinite composite reservoir

According Stehfest's numerical inversion method[5],as known C_De^{2s}、h_{D1}、h_{D2}、λ_{D1}、λ_{D2}、r_{1D}、r_{2D}、η_{2D}、η_{3D}, we can calculate the model curve of the proposed pressure at bottom in each case.

Figure 2 is a typically infinite about thick heterogeneous composite gas reservoirs of three areas curve. Curve1 of Figure 2 is typical Tibetan curve of infinite homogeneous atmosphere. The flowing capacity of gas is stable in the gas reservoir. after the flow enters an infinite radial flow effect, Pressure derivative become a horizontal line that the number is 0.5.

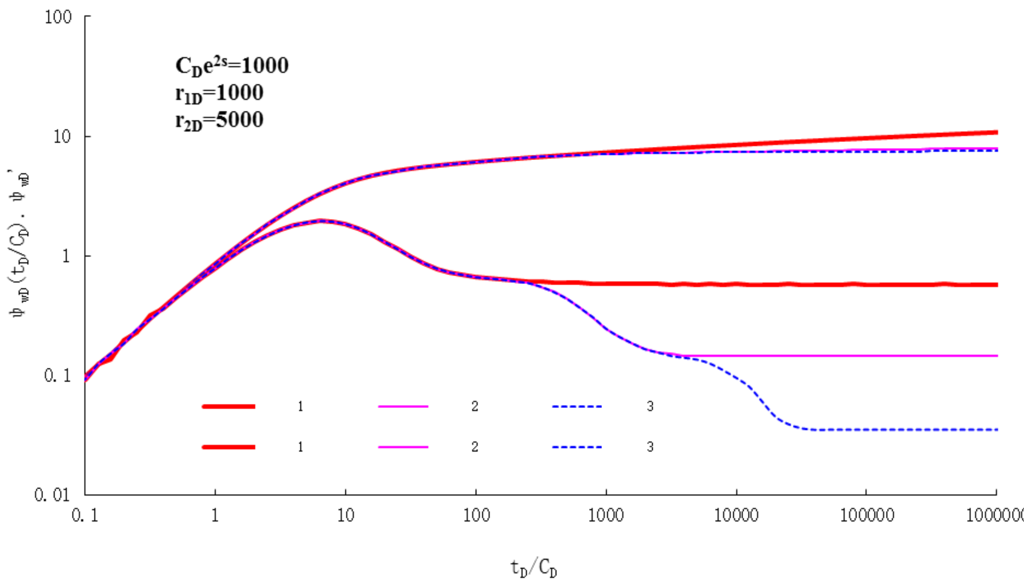

Fig. 2 Thetypically curve of three areas equal thickness heterogeneous composite gas reservoirs

A well test model for a multi-region radially composite reservoir was established, which comprehensively took into consideration the effect of stress sensitivity, wellbore storage effect and skin effect[6]. The Perturbation technique and Laplace transformation were used to obtain the analytical solution to the model. Type curves were calculated and plotted and the characteristics of type curves were analyzed.

3 The mathematical model and pressure characteristics of complex gas reservoir in closed boundary

3.1 The mathematical model of complex gas reservoir in closed boundary

The pressure equation of An area, Second District, three districts is:

$$\overline{\psi}_{1D} = A_1 I_0\left(r_D\sqrt{z_1}\right) + B_1 K_0\left(r_D\sqrt{z_1}\right) \quad (22)$$

$$\overline{\psi}_{2D} = A_2 I_0\left(r_D\sqrt{\frac{z_1}{\eta_{2D}}}\right) + B_2 K_0\left(r_D\sqrt{\frac{z_1}{\eta_{2D}}}\right) \quad (23)$$

$$\overline{\psi}_{3D} = A_3 I_0\left(r_D\sqrt{\frac{z_1}{\eta_{3D}}}\right) + B_3 K_0\left(r_D\sqrt{\frac{z_1}{\eta_{3D}}}\right) \quad (24)$$

According to boundary conditions[7],We can get Laplace space 7-order linear equations:

$$\begin{bmatrix} a_{11} & a_{12} & 0 & 0 & 0 & 0 & a_{17} \\ a_{21} & a_{22} & 0 & 0 & 0 & 0 & a_{27} \\ a_{31} & a_{32} & a_{33} & a_{34} & 0 & 0 & 0 \\ 0 & 0 & a_{43} & a_{44} & a_{45} & a_{46} & 0 \\ a_{51} & a_{52} & a_{53} & a_{54} & 0 & 0 & 0 \\ 0 & 0 & a_{63} & a_{64} & a_{65} & a_{66} & 0 \\ 0 & 0 & 0 & 0 & a_{75} & a_{76} & 0 \end{bmatrix} \begin{bmatrix} A_1 \\ B_1 \\ A_2 \\ B_2 \\ A_3 \\ B_3 \\ \overline{\psi}_{wD} \end{bmatrix} = \begin{bmatrix} b_1 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

Among them:

$a_{11} = \sqrt{z_1} I_1\left(\sqrt{z_1}\right)$; $a_{12} = -\sqrt{z_1} K_1\left(\sqrt{z_1}\right)$; $a_{17} = -z$; $a_{21} = I_0\left(\sqrt{z_1}\right)$; $a_{22} = K_0\left(\sqrt{z_1}\right)$;

$a_{27} = -1$; $a_{31} = I_0\left(r_{1D}\sqrt{z_1}\right)$; $a_{32} = K_0\left(r_{1D}\sqrt{z_1}\right)$; $a_{33} = -I_0\left(r_{1D}\sqrt{\frac{z_1}{\eta_{2D}}}\right)$;

$a_{34} = -K_0\left(r_{1D}\sqrt{\frac{z_1}{\eta_{2D}}}\right)$; $a_{43} = I_0\left(r_{2D}\sqrt{\frac{z_1}{\eta_{2D}}}\right)$; $a_{44} = K_0\left(r_{2D}\sqrt{\frac{z_1}{\eta_{2D}}}\right)$; $a_{45} = -I_0\left(r_{2D}\sqrt{\frac{z_1}{\eta_{3D}}}\right)$;

$a_{46} = -K_0\left(r_{2D}\sqrt{\frac{z_1}{\eta_{3D}}}\right)$; $a_{51} = I_1\left(r_{1D}\sqrt{z_1}\right)$; $a_{52} = -K_1\left(r_{1D}\sqrt{z_1}\right)$;

$a_{53} = -h_{D1}\lambda_{D1}\sqrt{\frac{1}{\eta_{2D}}} I_1\left(r_{1D}\sqrt{\frac{z_1}{\eta_{2D}}}\right)$; $a_{54} = h_{D1}\lambda_{D1}\sqrt{\frac{1}{\eta_{2D}}} K_1\left(r_{1D}\sqrt{\frac{z_1}{\eta_{2D}}}\right)$ $a_{63} = I_1\left(r_{2D}\sqrt{\frac{z_1}{\eta_{2D}}}\right)$;

$a_{64} = -K_1\left(r_{2D}\sqrt{\frac{z_1}{\eta_{2D}}}\right)$; $a_{65} = -h_{D2}\lambda_{D2}\sqrt{\frac{\eta_{2D}}{\eta_{3D}}} I_1\left(r_{2D}\sqrt{\frac{z_1}{\eta_{3D}}}\right)$;

$a_{66} = h_{D2}\lambda_{D2}\sqrt{\frac{\eta_{2D}}{\eta_{3D}}} K_1\left(r_{2D}\sqrt{\frac{z_1}{\eta_{3D}}}\right)$; $a_{75} = I_1\left(r_{3D}\sqrt{\frac{z_1}{\eta_{3D}}}\right)$; $a_{76} = -K_1\left(r_{3D}\sqrt{\frac{z_1}{\eta_{3D}}}\right)$; $b_1 = -\frac{1}{z}$。

At this point that is determined based on unequal thick complex gas reservoirs downholet_D/C_D Quasi pressure Laplace space solution: $\overline{\psi}_{wD}(z)$ and pseudo pressure Laplace space solution $\overline{\psi}_{1D}(z)$、$\overline{\psi}_{2D}(z)$、$\overline{\psi}_{3D}(z)$ of an area, second district, third district.

3.2 Pressure characteristics of complex gas reservoir in closed boundary

According to Stehfest's numerical inversion method, After C_De^{2s}、h_{D1}、h_{D2}、λ_{D1}、λ_{D2}、r_{1D}、r_{2D}、r_{3D}、η_{2D}、η_{3D} were given, we can calculate the model curve of the proposed pressure at bottom in each case.

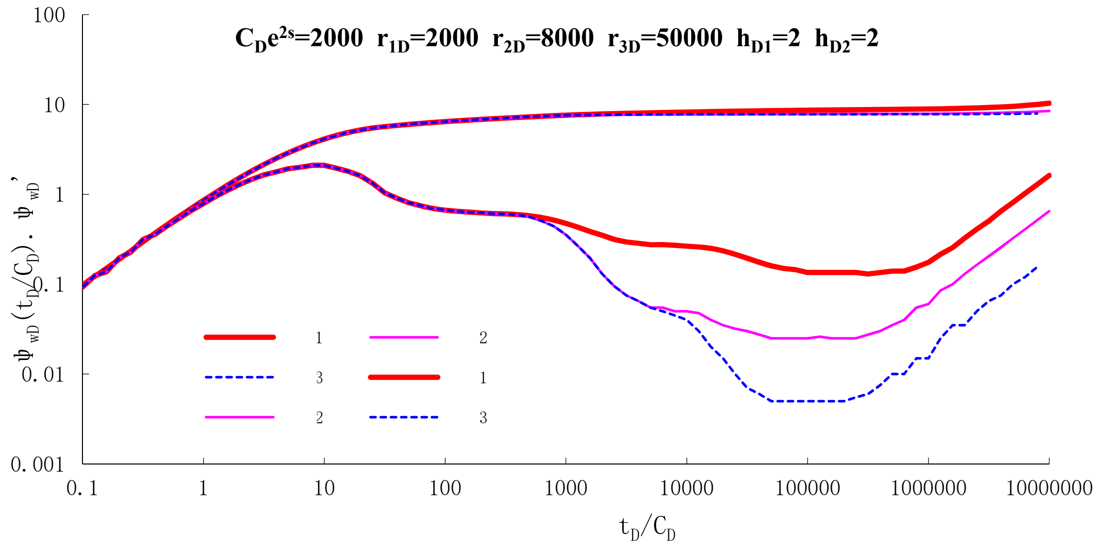

Fig. 3 The typically curve of three areas different thickness heterogeneous circular closed boundary composite gas reservoirs

Figure 3 is a typically curve that stratigraphic thickness increases of three-zone circular heterogeneous closed boundary composite gas reservoirs. Curve 1 is a typical curve in three districts homogeneous composite circular closed boundary gas reservoirs. Gas flow evenly in gas reservoirs, After pressure derivative curve enters the 0.5 horizontal radial flow, Gradually reduced to two horizontal radial flow area, Finally, and then reduced to three horizontal radial flow area gradually, Finally appears as a straight line upwards.

4 Examples of applications

The well of Su-25's gas layers is in depth of 3307.2m, Formation temperature T=380.95K. P_i = 28.03Mpa, Gas compressibility factor under the original state C_{ti}=0.03195MPa^{-1}, Viscosity μ_i= 0.02045mPa.s, z =0.976,q=10×10^{4}m^3/d, r_w=0.06m, Reservoir porosityφ=11.3%, Effective thickness h= 9.6m.

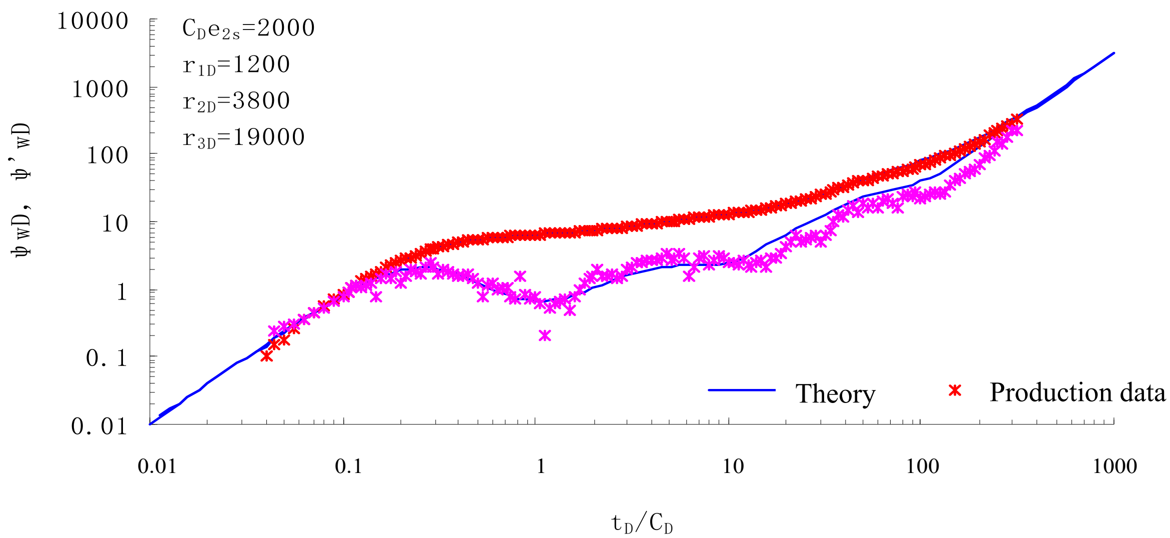

Fig. 4 The typical fitting curve of Su -25 well

Figure 4 shows that we can achieve satisfactory fitting result by using composite model ofthird district.

Match value: C_De^{2s} =2000 r_{1D}=1200 r_{2D}=3800 r_{3D}=19000

h_{D1}=0.7 h_{D2}=0.5 λ_{D1}=0.7 λ_{D2}=0.2

p_M= 0.000594 t_M=23.84

The results of interpretation:

C=1.34 m^3/Mpa，S=0.08

$k_1=3\times10^{-3}\mu m^2$，$r_1$ =66.5m，

$k_2=2.1\times10^{-3}\mu m^2$，$r_2$ =210.5m，h_2 =6.7m

$k_3=0.42\times10^{-3}\mu m^2$，$r_3$ =1052.4m，h_3 = 3.4m

The results of interpretation showed that: Su-25 wells has a certain range of the gas supply, It showed a faster recovery and a higher level restoreafter fixed isochronous well test. This indicates that the analysis results coincide with the actual situation.

5 Conclusion

(1) The theoretical model of the test for three horizontal heterogeneous gas reservoirs with different boundary conditions is established, and the corresponding theoretical curves are drawn, and the pressure dynamic characteristics are analyzed.

(2) Both the pressure and the pressure derivative curves show a slope of 1 and pass through the origin at the stage of pure well reservoir effect;

(3) For the multi-zone heterogeneity composite gas pool, the radial section of the pressure derivative curve rises gradually and is higher than the 0.5 horizontal line. For the three zones with better gas flow ability, In the heterogeneous horizontal heterogeneous gas reservoirs, the radial derivative of the pressure derivative curve decreases gradually and is lower than 0.5 horizontal line. The pressure derivative curve of three - zone heterogeneity heterogeneous gas reservoir with closed boundary shows as an upward straight line;

(4) The thicker the outer strata and the higher permeability, the lower the horizontal radial flow line of the pressure derivative curve of heterogeneous horizontal heterogeneous gas reservoirs in the three zones;

(5) The heterogeneity gas reservoir model can give a good fitting analysis to the gas well test data which reflect the heterogeneity of the reservoir and provide a reasonable explanation result. This is of great value in understanding reservoir characteristics of low permeability gas reservoirs.

Symbol Description

ψ Gas pseudo pressure MPa^2/(mPa·s)； ψ_i the pressure of the original gas reservoir pi corresponding to the pseudo-pressure, MPa^2/(mPa·s)； ψ_j j-zone pressure corresponding to the pseudo-pressure, MPa^2/(mPa·s) ； ψ_{jD} J area of dimensionless quasi-pressure; ψ_{wD} bottom-hole dimensionless quasi-pressure; $\overline{\psi}_{jD}$ J-zone Laplace space dimensionless pseudo pressure; $\overline{\psi}_{wD}$ Downhole Laplace space dimensionless quasi - pressure; P_i OriOriginal gas reservoir pressure, MPa； P_j The gas pressure in the jth zone, MPa； P_w Bottom gas reservoir pressure, MPa； P_{sc} Standard atmospheric pressure, 0.101325 MPa； h_j The thickness of the jth zone formation,m; h_D Dimensionless thickness, Dimensionless; h_{Dj} The thickness ratio of the jth zone to the j-1th zone, Dimensionless; k Formation permeability, Dimensionless; μm^2； k_j The permeability of formation j, μm^2； λ_D Dimensionless permeability, Dimensionless; λ_{Dj} The ratio of the j + 1th to the jth zone permeability, Dimensionless; ϕ Formation porosity, Decimal; ϕ_j The porosity of formation j, Decimal; μ Natural gas viscosity, mPa·s； μ_j The jth zone natural gas viscosity, mPa·s； C_t Integrated compression factor, MPa^{-1}； C_{tj} The jth district comprehensive compression coefficient, MPa^{-1}； r The radial radius of any point in the gas reservoir to the well,m; r_w Borehole radius,m; r_j The j-th radial radius,m; r_D Dimensionless radius, Dimensionless; r_{jD} The jth area has dimensionless radius, Dimensionless; η_j J-zone pressure coefficient, (μm^2·MPa)/（mPa·s）； η_{jD} The jth zone and the first area of the conductivity coefficient ratio, Dimensionless; t Production time,h; t_p Dimensionless time, Dimensionless; C Wellbore storage factor m^3/MPa； C_D Dimensionless wellbore storage factor, Dimensionless; B_g Gas volume coefficient, m^3/m^3； q Natural gas wellhead production, $10^4 m^3$/d； S Skin factor, Dimensionless; Z Gas deviation factor; z Laplace variable; I_0 The modified first - order Bessel functions of zero order; I_1 Modified first - order first - order Bessel function; K_0 The modified second - order Bessel function; K_1 Modified second - order first - order Bessel function; T The formation temperature, K； T_{sc} The temperature of Ground standard conditions, 293.15K.

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