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THE PRESSURE TRANSIENT ANALYSIS OF DEFORMATION OF FRACTAL MEDIUM*

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Abstract: The assumption of constant rock properties in pressure-transient analysis of stress-sensitive reservoirs can cause significant errors in the estimation of temporal and spatial variation of pressure. In this article, the pressure transient response of the fractal medium in stress-sensitive reservoirs was studied by using the self-similarity solution method and the regular perturbation method. The dependence of permeability on pore pressure makes the flow equation strongly nonlinear. The nonlinearities associated with the governing equation become weaker by using the logarithm transformation. The perturbation solutions for a constant pressure production and a constant rate production of a linear-source well were obtained by using the self-similarity solution method and the regular perturbation method in an infinitely large system, and inquire into the changing rule of pressure when the fractal and deformation parameters change. The plots of typical pressure curves were given in a few cases, and the results can be applied to well test analysis.

Key words: stress-sensitive reservoir, fractal, permeability modulus, pressure analysis

1. Introduction

Numerous experiments have proved that the formation of oil reservoir and the fracture network distribution of fractured reservoir are fractal structures. Therefore, the flow theory of fractal reservoir has been developed and applied to oilfield. Fluid flow in hydrocarbon reservoirs and ground water aquifers have been traditionally studied by assuming the formation permeability is constant[1-6]. These assumptions in the fluid flow analysis have given good results in many situations, but with increasing exploitation of petroleum and geothermal resources from low-permeability and fractured formations, these assumptions need to be re-evaluated. Kikani[7] presented the flow model for cylindrical flow systems of deformed media. A perturbation technique was applied to determine the approximate solution and analyze the flow characteristics of deformed media reservoir. Yeung[8] considered the spherical flow problem of deformed media reservoir. A simple technique was applied to obtain approximate solutions, but the error is large. The generalized pseudo pressure function was introduced to characterize the gas flow in pressure-sensitive reservoir[9]. The flow analysis for stress-sensitive reservoirs with double porosity was studied[10-16]. But the flow analysis for stress-sensitive fractal reservoirs has not been performed. Radial and spherical flow in homogeneous reservoir are special cases of fractal reservoir[1] ($d_f = 2$ or 3 , and $\theta = 0$). In this article, the fractal and deformed characteristics of stress-sensitive reservoir are considered. A permeability modulus is introduced to

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derive the radial flow equation for the stress-sensitive fractal reservoir. The perturbation solutions for a constant pressure production and a constant rate production of linear-source well are obtained by using the self-similarity solution method and the regular perturbation method in an infinitely large system, and inquire into the changing rule of pressure when the fractal and deformation parameters change.

2. Flow equation

The following assumptions are made in constructing the mathematical model:

(1)The permeability is stress-sensitive , that is, it depends on pore pressure.

(2)The porous medium is the fractal system with similar structure, the fractal permeable network embedded in impermeable Euclidean matrix, where the fractal network dimension is d_f, and the Euclidean matrix dimension is ($d=1,2,3$).

The permeability modulus is defined as[1]

$$\gamma=\frac{1}{k}\frac{\mathrm{d}k}{\mathrm{d}p} \tag{1}$$

The parameter γ plays a very important role in the system where changes in effective stress affect the permeability. Basically, it measures the dependence of formation permeability on pore pressure. For practical purpose, γ can be assumed as a constant.

Thus the permeability of fractal reservoir varies exponentially with pore pressure

$$k=k_0\mathrm{e}^{-\gamma(p_0-p)}\left(\frac{r}{r_w}\right)^{d_f-\theta-d} \tag{2}$$

where k_0 , p_0 are initial permeability and initial pressure respectively, r, r_w are the radial distance from well and the radius of wellbore respectively, and θ is the fractal diffusion exponent.

The continuity equation for the flow of a single–phase liquid in an isotropic and fractal reservoir can be given by assuming fluid to be slightly compressible and using Darcy's law, which is

$$\frac{1}{r}\frac{\partial}{\partial r}(r\rho\frac{k}{\mu}\frac{\partial p}{\partial r})=\frac{\partial(\phi\rho)}{\partial t} \tag{3}$$

where $\rho=\rho(p)$ is density, and μ is viscosity.

Expanding Eq.(3) under the assumption of pressure-dependent rock properties leads to

$$\frac{\partial^2 p}{\partial r^2}+\frac{\beta}{r}\frac{\partial p}{\partial r}+(\gamma+c_L)\left(\frac{\partial p}{\partial r}\right)^2=$$

$$\frac{\phi_0\mu}{k_0}\left(\frac{r}{r_w}\right)^{\theta}(c_L+c_{ma})\mathrm{e}^{-(c_{ma}-\gamma)(p_0-p)}\frac{\partial p}{\partial t} \tag{4}$$

where

$$c_L=\frac{1}{\rho}\frac{\partial\rho}{\partial p},\quad c_{ma}=\frac{1}{\phi}\frac{\partial\phi}{\partial p},$$

$$\phi=\phi_0\mathrm{e}^{-c_{ma}(p_0-p)}\left(\frac{r}{r_w}\right)^{d_f-d}$$

Then, assume $\gamma>>c_L$, then Eq.(4) becomes

$$\frac{\partial^2 p}{\partial r^2}+\frac{\beta}{r}\frac{\partial p}{\partial r}+\gamma\left(\frac{\partial p}{\partial r}\right)^2=$$

$$\frac{\phi_0 c_t\mu}{k_0}\left(\frac{r}{r_w}\right)^{\theta}\mathrm{e}^{\gamma(p_0-p)}\frac{\partial p}{\partial t} \tag{5}$$

where

$$c_t=c_L+c_{ma}$$

For the case of production of fluid at a constant rate from an infinite reservoir into wellbore, the dimensionless groups are defined as

$$p_D=\frac{2\pi k_0 h(p_0-p)}{\mu q},\quad t_D=\frac{k_0 t}{\phi_0\mu c_t r_w^{\,2}},$$

$$r_D=\frac{r}{r_w},\quad \alpha_D=\frac{\mu q\gamma}{2\pi k_0 h}$$

Under the constant-pressure production condition, the dimensionless groups are defined as

$$p_D=\frac{p_0-p}{p_0-p_w},\quad t_D=\frac{k_0 t}{\phi_0\mu c_t r_w^{\,2}},$$

$$r_D=\frac{r}{r_w},\quad \alpha_D=\gamma(p_0-p_w)$$

In dimensionless coordinates, Eq.(5) becomes

$$\frac{\partial^2 p_D}{\partial {r_D}^2}+\frac{\beta}{r_D}\frac{\partial p_D}{\partial r_D}-\alpha_D\left(\frac{\partial p_D}{\partial r_D}\right)^2=r_D^{\theta}e^{\alpha_D p_D}\frac{\partial p_D}{\partial t_D} \quad (6)$$

3. The line-source solution for deformed fractal reservoir

The mathematical model is made of Eq.(6) and initial and boundary value conditions.

(1)The flow problem of fluid in an infinite reservoir with the constant rate production is as follows:

$$\frac{\partial^2 p_D}{\partial {r_D}^2}+\frac{\beta}{r_D}\frac{\partial p_D}{\partial r_D}-\alpha_D\left(\frac{\partial p_D}{\partial r_D}\right)^2=r_D^{\theta}e^{\alpha_D p_D}\frac{\partial p_D}{\partial t_D} \quad (7)$$

$$p_D(r_D,0)=0 \quad (8)$$

$$\lim_{r_D\to 0}(r_D^{\beta}e^{-\alpha_D p_D}\frac{\partial p_D}{\partial r_D})=-1 \quad (9)$$

$$\lim_{r_D\to\infty} p_D=0 \quad (10)$$

Rewrite the unknown function as

$$p_D(r_D,t_D)=-\frac{1}{\alpha_D}\ln[1-\alpha_D\eta(r_D,t_D)] \quad (11)$$

Equations (7)-(10) can be simplified as

$$\frac{\partial^2\eta}{\partial r_D^2}+\frac{\beta}{r_D}\frac{\partial\eta}{\partial r_D}=\frac{r_D^{\theta}}{(1-\alpha_D\eta)}\frac{\partial\eta}{\partial t_D} \quad (12)$$

$$\eta(r_D,0)=0 \quad (13)$$

$$\lim_{r_D\to 0}(r_D^{\beta}\frac{\partial\eta}{\partial r_D})=-1 \quad (14)$$

$$\lim_{r_D\to\infty}\eta=0 \quad (15)$$

The strong nonlinearities in Eq.(7) are thus considerably weakened in Eq.(12) and are restricted to the coefficient of the nonlinear term on the right side only.

Introduce a parameter perturbation in α_D by defining the series

$$\eta=\eta_0+\alpha_D\eta_1+\alpha_D^2\eta_2+\cdots \quad (16)$$

and expanding the coefficient of the partial derivative on the right side in a binomial series with the stipulation that $\alpha_D\eta<1$, we obtain the zeroth-order approximate equation

$$\frac{\partial^2\eta_0}{\partial r_D^2}+\frac{\beta}{r_D}\frac{\partial\eta_0}{\partial r_D}=r_D^{\theta}\frac{\partial\eta_0}{\partial t_D} \quad (17)$$

The initial and boundary value conditions are also Eqs.(13)-(15).

In order to obtain the zeroth-order approximate solution, the following transforms are introduced:

$$u=d_f^{\,2-\frac{\theta+2}{d_f}}\eta_0,\ x=\frac{1}{d_f}r_D^{d_f},\ t_1=d_f^{\,2-\frac{\theta+2}{d_f}}t_D \quad (18)$$

The zeroth-order approximate initial and boundary value problem become

$$\frac{\partial}{\partial x}(x^{2-\frac{\theta+2}{d_f}}\frac{\partial u}{\partial x})=\frac{\partial u}{\partial t_1}$$

$$\lim_{x\to 0}x^{2-\frac{\theta+2}{d_f}}\frac{\partial u}{\partial x}=-1 \quad t_1>0$$

$$\lim_{x\to\infty}u=0 \quad t_1>0$$

$$u\big|_{t_1=0}=0 \quad 0\le x\le\infty$$

The above zeroth-order approximate initial and boundary value problem can be seen as the continuous source problem. First, we solve the instantaneous source problem corresponding to the continuous source problem.

The instantaneous source problem is formulated with Eqs.(19)-(22)

$$\frac{\partial}{\partial x}(x^{2-\frac{\theta+2}{d_f}}\frac{\partial u}{\partial x})=\frac{\partial u}{\partial t_1} \quad (19)$$

$$\lim_{x\to 0}x^{2-\frac{\theta+2}{d_f}}\frac{\partial u}{\partial x}=0 \quad t_1>0 \quad (20)$$

$$\lim_{x\to\infty} u = 0 \tag{21}$$

$$u\big|_{t_1=0} = \delta(x) \quad 0 \le x \le \infty \tag{22}$$

where $\delta(x)$ is the Dirac- δ function

Let us seek similarity solutions of Eq.(19) subject to conditions (20), (21) and (22) by introducing the similarity transforms

$$u = w(\rho)t_1^{-m}, \quad \rho = xt_1^{-m}, \quad m > 0 \tag{23}$$

Substituting transforms (23) into Eq. (19), we find that similarity demands that

$$m = \frac{d_f}{\theta+2} = 1-\nu \tag{24}$$

For $d_f > 0,\ \theta > 0$, the requirement $m > 0$ is satisfied. Use of transforms (23) and Eq.(24) reduces Eq.(19) to the ordinary differential equation

$$-(\frac{d_f}{\theta+2})\frac{\mathrm{d}}{\mathrm{d}\rho}(\rho w) = \frac{\mathrm{d}}{\mathrm{d}\rho}(\rho^{2-\frac{\theta+2}{d_f}}\frac{\mathrm{d}w}{\mathrm{d}\rho}) \tag{25}$$

subject to

$$\lim_{\rho\to 0}\rho^{2-\frac{\theta+2}{d_f}}\frac{\mathrm{d}w}{\mathrm{d}\rho} = 0 \tag{26}$$

Two integrations give

$$w(\rho) = w_0 \exp\left[-(\frac{d_f}{\theta+2})^2 \rho^{\frac{\theta+2}{d_f}}\right] \tag{27}$$

with w_0 the value of $w(\rho)$ at $\rho = 0$.

We complete the solution by noting that

$$\int_0^\infty u(x)\mathrm{d}x = 1$$

so

$$\int_0^\infty w(\rho)\mathrm{d}\rho = 1$$

That is,

$$w_0 = \left\{\int_0^\infty \exp\left[-(1-\nu)^2\rho^{\frac{1}{1-\nu}}\right]\mathrm{d}\rho\right\}^{-1} =$$

$$\left[\frac{1}{(1-\nu)^{1-2\nu}}\Gamma(1-\nu)\right]^{-1} \tag{28}$$

As Duhamel's principal, we secure the continuous source solutions by integrating the instantaneous source solution with respect to t

$$u = \int_0^{t_1} w_0 \exp\left[-(1-\nu)^2\rho^{\frac{1}{1-\nu}}\right]t_1^{-(1-\nu)}\mathrm{d}t_1 =$$

$$w_0\int_0^{t_1} t_1^{-(1-\nu)}\exp\left[-(1-\nu)^2 x^{\frac{1}{1-\nu}}t_1^{-1}\right]\mathrm{d}t_1$$

Making transform $y = (1-\nu)^2 x^{\frac{1}{1-\nu}}t_1^{-1}$ gives

$$u = w_0[(1-\nu)^2 x^{\frac{1}{1-\nu}}]^\nu \int_y^\infty y^{-(1+\nu)}\exp(-y)\mathrm{d}y =$$

$$w_0[(1-\nu)^2 x^{\frac{1}{1-\nu}}]^\nu\,\Gamma(-\nu, y) \tag{29}$$

where $\Gamma(a, y)$ is the incomplete Gamma function Inserting Eqs.(28) and (29) into Eq.(18), we get

$$\eta_0 = \frac{r_D^{\theta+2-d_f}}{(\theta+2)\Gamma(1-\nu)}\Gamma\left[-\nu, \frac{r_D^{\theta+2}}{(\theta+2)^2 t_D}\right] \tag{30}$$

(2)The problem of fluid flow in an infinite reservoir with the constant pressure production is as follows:

$$\frac{\partial^2 p_D}{\partial {r_D}^2} + \frac{\beta}{r_D}\frac{\partial p_D}{\partial r_D} - \alpha_D\left(\frac{\partial p_D}{\partial r_D}\right)^2 = {r_D}^\theta \mathrm{e}^{\alpha_D p_D}\frac{\partial p_D}{\partial t_D}$$

$$p_D(r_D, 0) = 0$$

$$\lim_{r_D\to 0} p_D = 1$$

$$\lim_{r_D\to\infty} p_D = 0$$

By using transform (11), the above flow problem is simplified as

$$\frac{\partial^2\eta}{\partial r_D^2}+\frac{\beta}{r_D}\frac{\partial\eta}{\partial r_D}=\frac{r_D^\theta}{(1-\alpha_D\eta)}\frac{\partial\eta}{\partial t_D} \tag{31}$$

$$\eta(r_D,0)=0 \tag{32}$$

$$\lim_{r_D\to 0}\eta=\frac{1-e^{\alpha_D}}{\alpha_D} \tag{33}$$

$$\lim_{r_D\to\infty}\eta=0 \tag{34}$$

(a) Zeroth order:

The zeroth-order approximate equation is also Eq.(17), The initial and boundary value conditions are given by Eqs.(32) (33) and (34)

Making use of transformation expressed by Eq.(35)

$$y=\frac{r_D^{\theta+2}}{(\theta+2)^2 t_D} \tag{35}$$

reduces the initial-boundary value problem of partial differential equation to the boundary value problem of ordinary differential equation as follows:

$$\frac{d^2\eta_0}{dy^2}+(1+\frac{1-\nu}{y})\frac{d\eta_0}{dy}=0$$

$$\lim_{y\to 0}\eta_0=1$$

$$\lim_{y\to\infty}\eta_0=0$$

which has the solution

$$\eta_0=C_1\int_y^\infty y^{-(1-\nu)}e^{-y}dy+C_2$$

Using the initial and boundary value conditions, we get

$$C_2=0,\ C_1=\frac{1}{\Gamma(\nu)}$$

And the solution is given by

$$\eta_0=\frac{\Gamma(\nu,y)}{\Gamma(\nu)} \tag{36}$$

(b) First order:

$$\frac{\partial^2\eta_1}{\partial r_D^2}+\frac{\beta}{r_D}\frac{\partial\eta_1}{\partial r_D}=r_D^\theta(\frac{\partial\eta_1}{\partial t_D}+\eta_0\frac{\partial\eta_0}{\partial t_D})$$

$$\eta_1(r_D,0)=0$$

$$\lim_{r_D\to 0}\eta_1=-\frac{1}{2}$$

$$\lim_{r_D\to\infty}\eta_1=0$$

By using Eq.(35), the above equation is expressed as

$$\frac{d^2\eta_1}{dy^2}+(1+\frac{1-\nu}{y})\frac{d\eta_1}{dy}=-\eta_0\frac{d\eta_0}{dy} \tag{37}$$

where

$$\eta_0\frac{d\eta_0}{dy}=-\frac{1}{[\Gamma(\nu)]^2}y^{-(1-\nu)}e^{-y}\Gamma(\nu,y) \tag{38}$$

Substituting Eq.(38) into Eq.(37) yields

$$\frac{d^2\eta_1}{dy^2}+(1+\frac{1-\nu}{y})\frac{d\eta_1}{dy}=\frac{1}{[\Gamma(\nu)]^2}y^{-(1-\nu)}e^{-y}\Gamma(\nu,y) \tag{39}$$

Equation (39) can be solved by the method of variation of parameters. The homogeneous solutions are

$$u_1=-\Gamma(\nu,y),\ u_2=1$$

where u_1 and u_2 are intermediate solution values.

Let

$$h(y)=\frac{1}{[\Gamma(\nu)]^2}y^{-(1-\nu)}e^{-y}\Gamma(\nu,y)$$

The Wronskian of the homogeneous solutions is given by

$$W=\begin{vmatrix}u_1 & u_2\\ u_1' & u_2'\end{vmatrix}=-y^{-(1-\nu)}e^{-y}$$

The general solution to Eq. (37) is given by

$$\eta_1 = C_1(y)u_1(y) + C_2(y)u_2(y) \tag{40}$$

where

$$C_1(y) = \int^y C_1'(y)\mathrm{d}y = \int^y -\frac{hu_2}{W}\mathrm{d}y = \frac{1}{[\Gamma(\nu)]^2}\bullet$$

$$[y\Gamma(\nu, y) - \Gamma(1+\nu, y)] + C_3 \tag{41}$$

and

$$C_2(y) = \int^y C_2'(y)\mathrm{d}y = \int^y \frac{hu_1}{W}\mathrm{d}y = \frac{1}{[\Gamma(\nu)]^2}\bullet$$

$$\{(y-\nu)[\Gamma(\nu, y)]^2 - 2y^{\nu}\mathrm{e}^{-y}\Gamma(\nu, y) +$$

$$2^{1-2\nu}\Gamma(2\nu, 2y)\} + C_4 \tag{42}$$

Substituting Eqs.(41) and (42) into Eq.(40) and using boundary conditions lead to

$$C_4 = 0,\ C_3 = \frac{2^{1-2\nu}\Gamma(2\nu)}{[\Gamma(\nu)]^3} + \frac{1}{2\Gamma(\nu)}$$

Thus, on simplification, the first-order solution becomes

$$\eta_1 = \frac{1}{[\Gamma(\nu)]^2}[2^{1-2\nu}\Gamma(2\nu, 2y) - y^{\nu}\mathrm{e}^{-y}\Gamma(\nu, y) -$$

$$\frac{2^{2-2\nu}\Gamma(2\nu) + [\Gamma(\nu)]^2}{2\Gamma(\nu)}\Gamma(\nu, y)] \tag{43}$$

4. Discussion

The transformation given by Eq.(11) can be rewritten as

$$p_D = -\frac{1}{\alpha_D}\ln[1 - \alpha_D\eta_0 - \alpha_D^2\eta_1 + O(\alpha_D^3)]$$

Figure 1 demonstrates the variation of dimensionless pressure with time for different values of α_D, namely, 0.01, 0.1, 0.2 and 0.5. It can be seen that the pressure curves are not closely related to the magnitudes of α_D in the initial stage. With time increasing, the effect of α_D become larger and larger. With the lincrease of α_D, the dimensionless pressure decreases. Figure 2 shows the temporal pressure changes for the various value of d_s. A general trend is that pressure is increased faster for the smaller value of d_s. The effect of d_s is smaller in the initial stage, In the transitional stage, the pressure curves start diverging from each other depending on the relative magnitude of d_s, and the effect of d_s becomes the largest. In later stage, the effect of d_s becomes smaller and smaller.

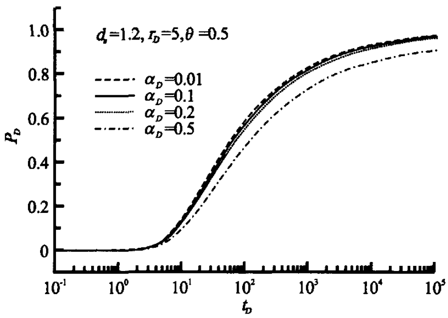

Fig.1 Semi-logarithm plots of pressure versus time depending on α_D

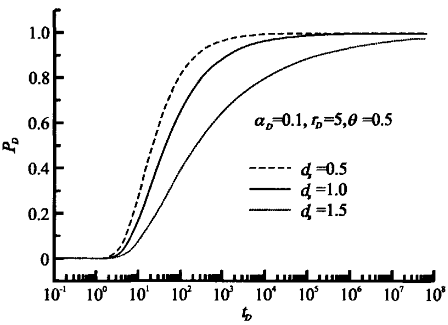

Fig.2 Semi-logarithm plots of pressure versus time at different d_s

Figure 3 exhibits the temporal variation of the pressure at different radii close to the well bore for two different values of α_D. In the initial stage, the variation of the pressure is smaller at different radii closer to the well bore. With time increasing, the differences between the pressure curves of fractal reservoir and the pressure curves of stress-sensitive fractal reservoir oncreases. Stress sensitivity in a variety of reservoir situations could be important and needs to be taken into account. Figure 4 shows that magnitude of the pressure curves at any radial distance would depend not only on the values of α_D, but also on time t_D. For smaller t_D (e.g., at $t_D = 10^2$), the difference between the pressure curves for the values α_D is smaller. For larger t_D (e.g., at $t_D = 10^4$), the difference between the pressure curves for the values α_D is larger. At any time, the difference between pressure curves would increase with increasing distance from the well bore. At large distances, however, pressure curves tend to uniformity., and the effect of the deformed parameter α_D died out.

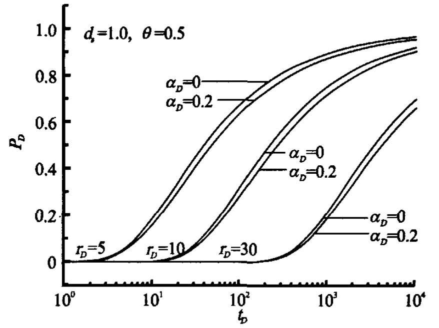

Fig.3 Semilogarithm plots of pressure versus time at different radii

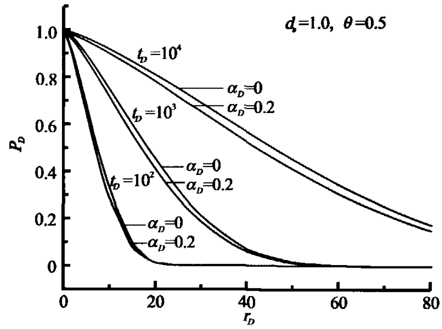

Fig.4 Semilogarithm plots of pressure versus radius at different times

5 Conclusion

(1) Fractal dimensions have been introduced to the flow equation of fluids in fractal reservoirs. The flow model has more extensive adaptability compared with the traditional ones.

(2)The similarity solutions for the flow models of fluid in fractal reservoir with both the constant rate production and the constant pressure production have been obtained by using similarity solution method.

(3) The perturbation solutions for a constant pressure production and a constant rate production of linear-source well have been obtained by using the regular perturbation method in an infinitely large system.

(4) With time increasing, the effect of α_D becomes remarkable. With increasing α_D, dimensionless pressure decreases.

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