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Pressure dynamic analysis of low permeability reservoirs with deformed media

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In the traditional well test models, the quadratic gradient term of nonlinear partial differential equation was neglected according to the assumption of slightly compressible fluid, which could lead to error when the well test time was too long. As time went by, the fluid flowing boundary of low permeability reservoirs extended outwards continuously. In order to study the flowing law of low permeability reservoirs with deformed media, the flow model of low permeability reservoirs of deformed media was built, which considered the influence of starting pressure gradient, moving boundary and quadratic gradient term. The numerical solution of the flow model was obtained by the fully implicit finite difference method. The pressure dynamic curves were drawn to analyse the seepage law of different starting pressure gradient, deformed media and moving boundary. The influence of the quadratic gradient term on the pressure dynamic curves was analyzed. The results could help people understand the seepage mechanism of low permeability reservoirs and provide the theoretical basis for exploring the low permeability reservoirs.

Key words: The quadratic gradient term, moving boundary, starting pressure gradient, deformed media, low permeability reservoirs.

INTRODUCTION

Along with the continuous development and utilization of petroleum resources, it was imperative to exploit the low permeability reservoirs on a large scale. In order to ensure the increasing growth of petroleum production and reserves, the low permeability reservoirs had been developed. Fully understanding the seepage law of low permeability reservoirs was essential for rational and efficient development of low permeability reserves. Years of research indicates that the fluid of low permeability reservoirs will have to surmount the starting pressure gradient to flow (Fuquan and Ciqun, 2000; Xiaodong and Xiaochun, 2011; Lijun et al., 2017). Besides, the influence of the deformed media should be considered in low permeability reserves (Jing et al., 2013; Manping, 2004; Odeh and Babu, 1998; Finjord and Adanoy, 1989; Hongxuan et al., 2015). The flow behavior of low permeability reserves did not follow Darcy's law, and the flow equation was strongly nonlinear. According to the assumption of slightly compressible fluid, the quadratic gradient term in nonlinear partial differential equation of

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the traditional models was usually neglected. However, this assumption was unconscionable for low permeability reservoirs. Neglecting the quadratic gradient term would lead to error and influence the analysis of actual production (Junjie et al., 2014; Wang and Dusseault, 1991; Dengke et al., 2002; Lili and Dengke, 2008; Yongheng et al., 2011; Fuxiang et al., 2010; Jun et al., 2011).

Starting with the characteristics of low permeability reserves, this thesis gave analyses to the influence of starting pressure gradient and the deformation of the media on flow. Based on that, starting from the principle of mass conservation, the nonlinear partial differential equation of low permeability reserves was deduced considering the influence of the quadratic gradient term. According to above-mentioned equation, mathematical model was built and solved by a finite difference method. Based on the proposed model, the pressure dynamic analysis of low permeability reservoirs along with propagation law of moving boundary was studied. The changing rule of the difference between the pressure solution of traditional model and the new model considering the quadratic gradient term was analyzed.

ESTABLISHMENT OF NONLINEAR SEEPAGE EQUATION WITH QUADRATIC GRADIENT

Assumptions

Considering the condition of a well in the single layer, we assume that:

(a) The output of the well is q;
(b) The isotropy of permeability was obtained;
(c) The influence of the wellbore storage and the skin effect was considered;
(d) The movement of formation fluid was isothermal process;
(e) The movement of formation fluid was non-Darcy flow;
(f) Formation fluid was single-phase compressible, while the compressibility was constant;
(g) The influence of gravity and capillary force was ignored;
(h) The medium was slightly compressible and the compressibility was constant. But the compression would cause the significant change of the permeability.

Continuity equation

The movement of formation fluid is single-phase flow, with the porosity being Φ. The continuity equation of radial flow was built through the principle of mass conservation:

$$-\frac{1}{r}\frac{\partial}{\partial r}\left(\rho r v_r\right)=\frac{\partial}{\partial t}(\phi\rho) \tag{1}$$

Momentum equation

The fluid of low permeability reservoirs will have to surmount the starting pressure gradient to flow. So in order to adequately describe the rule of starting pressure, we take the following methods to describe the fluid flow process:

$$\begin{cases} v=0, \dfrac{\Delta p}{L}\le G \\ v=\dfrac{K}{\mu}(\dfrac{\Delta p}{L}-G), \dfrac{\Delta p}{L}>G \end{cases} \tag{2}$$

Constitutive equation

The medium and the fluid were slightly compressible and the compressibility was constant. We can get state equation;

For compressible fluid:

$$\rho=\rho_0 e^{C_\rho(p-p_0)} \tag{3}$$

For compressible porous medium:

$$\phi=\phi_0 e^{C_\phi(p-p_0)} \tag{4}$$

$$K=K_0 e^{\gamma(p-p_0)} \tag{5}$$

With (1) to (5), the flow equation:

$$\frac{\partial^2 p}{\partial r^2}+(C_\rho+\gamma)\left(\frac{\partial p}{\partial r}\right)^2+\left(\frac{1}{r}-GC_\rho-G\gamma\right)\frac{\partial p}{\partial r}-\frac{G}{r}=\frac{\mu\varphi C_t}{K}\frac{\partial p}{\partial t} \tag{6}$$

Where: $Ct=C\rho+C_\Phi$, and C_t is total compressibility, MPa^{-1}.

Assuming that: $\gamma >> C_\rho$, Equation 6 reduced to:

$$\frac{\partial^2 p}{\partial r^2}+\gamma\left(\frac{\partial p}{\partial r}\right)^2+\left(\frac{1}{r}-GC_\rho-G\gamma\right)\frac{\partial p}{\partial r}-\frac{G}{r}=\frac{\mu\varphi C_t}{K}\frac{\partial p}{\partial t} \tag{7}$$

Definition of the following dimensionless quantities

Dimensionless pressure:

$$p_D=\frac{2\pi K_0 h}{\mu q}(p_0-p) \tag{8}$$

Dimensionless time:

$$t_D=\frac{K_0}{\mu\phi C_t r_w^2}t \tag{9}$$

Dimensionless starting pressure gradient:

$$G_{\mathrm{D}} = \frac{2\pi h K_0 r_w}{\mu q} G \tag{10}$$

Dimensionless permeability modulus:

$$\gamma_{\mathrm{D}} = \frac{\mu q}{2\pi h K_0} \gamma \tag{11}$$

Dimensionless distance:

$$r_{\mathrm{D}} = \frac{r}{r_w} \tag{12}$$

$$R = \frac{r_e}{r_w} \tag{13}$$

With Equations 8 to 13, we transform Equation 7 into the following form:

$$\frac{\partial^2 p_{\mathrm{D}}}{\partial r_{\mathrm{D}}^2} - \gamma_{\mathrm{D}} \left(\frac{\partial p_{\mathrm{D}}}{\partial r_{\mathrm{D}}} \right)^2 + \left(\frac{1}{r_{\mathrm{D}}} - \gamma_{\mathrm{D}} G_{\mathrm{D}} \right) \frac{\partial p_{\mathrm{D}}}{\partial r_{\mathrm{D}}} + \frac{G_{\mathrm{D}}}{r_{\mathrm{D}}} = \mathrm{e}^{\gamma_{\mathrm{D}} p_{\mathrm{D}}} \frac{\partial p_{\mathrm{D}}}{\partial t_{\mathrm{D}}} \tag{14}$$

Dimensionless initial conditions:

$$p_{\mathrm{D}} \Big|_{t_{\mathrm{D}}=0} = 0 \tag{15}$$

Dimensionless inner boundary conditions:

$$\frac{\partial p_{\mathrm{D}}}{\partial r_{\mathrm{D}}} \Big|_{r_{\mathrm{D}}=1} = -(\mathrm{e}^{\gamma_{\mathrm{D}} p_{\mathrm{D}}} + G_{\mathrm{D}}) \tag{16}$$

Dimensionless outer boundary conditions

Dimensionless infinite formation:

$$\lim_{r_{\mathrm{D}} \to \infty} p_{\mathrm{D}}(r_{\mathrm{D}}, t_{\mathrm{D}}) = 0 \tag{17}$$

Dimensionless closed outer boundary:

$$\frac{\partial p_{\mathrm{D}}}{\partial r_{\mathrm{D}}} \Big|_{r_{\mathrm{D}}=R} = 0 \tag{18}$$

Dimensionless pressure outer boundary:

$$p_{\mathrm{D}}(r_{\mathrm{D}}, t_{\mathrm{D}}) \Big|_{r_{\mathrm{D}}=R} = 0 \tag{19}$$

Because of the quadratic gradient term, Equation 14 exhibited nonlinear characteristics which cannot be solved unless the equation was linearized. We define the following variable:

$$p_{\mathrm{D}} = -\frac{1}{\gamma_{\mathrm{D}}} \ln(1 - \gamma_{\mathrm{D}} \eta(r_{\mathrm{D}}, t_{\mathrm{D}})) : x = \ln r_{\mathrm{D}} \tag{20}$$

we transform Equation 14 into the following form:

$$\frac{\partial^2 \eta}{\partial x^2} - G_{\mathrm{D}} \gamma_{\mathrm{D}} \mathrm{e}^x \frac{\partial \eta}{\partial x} + \mathrm{e}^x G_{\mathrm{D}} (1 - \alpha \eta) = \frac{\mathrm{e}^{2x}}{(1 - \gamma_{\mathrm{D}} \eta)} \frac{\partial \eta}{\partial t_{\mathrm{D}}} \tag{21}$$

Initial conditions:

$$\eta \Big|_{t_{\mathrm{D}}=0} = 0 \tag{22}$$

Internal boundary conditions:

$$\frac{\partial \eta}{\partial x} \Big|_{x=0} = 1 + G_{\mathrm{D}} (1 - \gamma_{\mathrm{D}} \eta) \tag{23}$$

Outer boundary conditions:

$$\lim_{r_{\mathrm{D}} \to \infty} \eta(x, t_{\mathrm{D}}) = 0 \tag{24}$$

$$\frac{\partial \eta}{\partial x} \Big|_{x=\ln R} = 0 \tag{25}$$

$$\eta(x, t_{\mathrm{D}}) \Big|_{x=\ln R} = 0 \tag{26}$$

SOLUTION OF THE FLOW MODEL

In this thesis, the implicit difference scheme was used to discretize the equation by which the numerical solution of the model was solved.

Difference scheme of flow equation:

$$\begin{aligned} &\frac{\eta_{i-1}^{n+1} - 2\eta_i^{n+1} + \eta_{i+1}^{n+1}}{\Delta x^2} - \mathrm{e}^{(i-1)\Delta x} \gamma_{\mathrm{D}} G_{\mathrm{D}} \frac{\eta_{i+1}^{n+1} - \eta_i^{n+1}}{\Delta x} \\ &+ G_{\mathrm{D}} \mathrm{e}^{(i-1)\Delta x} (1 - \gamma_{\mathrm{D}} \eta_i^{n+1}) = \frac{\mathrm{e}^{2(i-1)\Delta x}}{1 - \gamma_{\mathrm{D}} \eta_i^n} \frac{\eta_i^{n+1} - \eta_i^n}{\Delta t} \end{aligned} \tag{27}$$

We assume $\omega = \mathrm{e}^{(i-1)\Delta x}$; combining similar terms, the equation was simplified into the following form:

$$\begin{aligned} &\eta_{i-1}^{n+1} + \left(\Delta x \omega \gamma_{\mathrm{D}} G_{\mathrm{D}} - 2 - \omega \gamma_{\mathrm{D}} G_{\mathrm{D}} \Delta x^2 - \frac{\omega^2 \Delta x^2}{(1 - \gamma_{\mathrm{D}} \eta_i^n) \Delta t} \right) \eta_i^{n+1} \\ &+ (1 - \omega \gamma_{\mathrm{D}} G_{\mathrm{D}} \Delta x^2) \eta_{i+1}^{n+1} = -\frac{\omega^2 \Delta x^2}{(1 - \gamma_{\mathrm{D}} \eta_i^n) \Delta t} \eta_i^n - G_{\mathrm{D}} \omega \Delta x^2 \end{aligned} \tag{28}$$

$$\eta_{i-1}^{n+1} + a(i)\eta_i^{n+1} + b(i)\eta_{i+1}^{n+1} = d(i) \tag{29}$$

Where:

$a(i) = \Delta x \omega \gamma_D G_D - 2 - \omega \gamma_D G_D \Delta x^2 - \dfrac{\omega^2 \Delta x^2}{(1-\gamma_D \eta_i^n)\Delta t}$;

$b(i) = 1 - \omega \gamma_D G_D \Delta x^2$;

$d(i) = -\dfrac{\omega^2 \Delta x^2}{(1-\gamma_D \eta_i^n)\ \Delta t}\eta_i^n - G_D \omega \Delta x^2$;

i=1,…,*N* (*N* as the number of nodes in the spatial direction).

Difference scheme of initial conditions:

$$\eta_j^0 = 0(j = 1,2,3\ldots) \tag{30}$$

Difference scheme of inner boundary conditions:

$$\frac{\partial \eta}{\partial x}\Big|_{x=0} = 1 + G_D(1-\gamma_D \eta)$$

$$\left[G_D \gamma_D - \frac{1}{\Delta x}\right]\eta_0^{n+1} + \frac{1}{\Delta x}\eta_1^{n+1} = 1 + G_D \tag{31}$$

Difference scheme of closed outer boundary conditions:

$$\eta_{N+1} = \eta_N \tag{32}$$

When the difference scheme of initial conditions is adapted to the difference scheme of the flow equation, we can obtain tridiagonal systems of order N, which can be solved by Thomas Algorithm.

The fluid flowing boundary extending outwards continuously with time are the remarkable feature of low permeability reservoirs. The pressure cannot spread instantaneously to infinity as there is a moving boundary, which is a function of time, and expands with time. So, at any moment, the moving boundary put the reservoir into two regions: the dynamic zone affected by pressure waves and the silent area outside. We also believe that the outer boundary of dynamic area is the supply boundary at the moment. On the one side of the moving boundary, the fluid flows. On the other side, the fluid remains static. The moving boundary spreads outward gradually with time. We generally use the finite difference method or finite element method to solve the low permeability numerical simulation. Because of the dynamic characteristic, we need to divide grid each step in the calculation.

Assuming that the location of the moving boundary is r_{fD}^j, at t_j moment, we can get the moving boundary condition:

$$\begin{cases} \dfrac{\partial p_D}{\partial r_D}\Big|_{r_D = r_{fD}} = -G_D \\ p_D\Big|_{r_D >= r_{fD}} = 0 \end{cases} \tag{33}$$

From that we can know the location of moving boundary at t_{j+1} moment:

$$r_{fD}^{j+1}(t) = \begin{cases} r_{fD}^j + \Delta r, \Delta r \geq 0 \\ r_{fD}^j, \Delta r < 0 \end{cases} \tag{34}$$

where $\Delta r = \left[\dfrac{p_{N-3}^j}{G_D} - (r_{fD}^j - r_{N-3}^j)\right]$, and p_{N-3}^j, r_{N-3}^j represent pressure and location at node *N*-3, at t_j moment. p is short for p_D. We can use this formula to determine the next moment moving boundary location.

RESULTS ANALYSIS

The simulation result was obtained by the flow model of low permeability reservoirs. With the results, the movement rule of the moving boundary was studied. The pressure dynamic curves of low permeability reservoirs were drawn to analyze the seepage law of different starting pressure gradient, deformed media and moving boundary. The influence of the quadratic gradient term on the pressure dynamic curves was analyzed.

Pressure dynamic analysis of low permeability reservoir

Basic parameters of a low permeability reservoir are all in Table 1. From the above parameters, we can obtain the typical pressure dynamic curve (Figure 1). From the typical pressure dynamic curve, we can see that the log-log graph can be divided into four different stages. The first stage is the wellbore storage stage, in which the pressure curve and the derivative curve present a straight line with the slope of 45°. The second stage is the transitional stage, where the derivative curve presents a hump. It reflects the situation of the near wellbore reservoir affected by the skin effect. The third stage is the radial flow stage. Here the permeability declined with increase of the pressure in the low permeability reservoirs with deformed media. As a result, the curve of the third stage is no longer a parallel straight line. The fourth stage is the later period of flow. The curve with different boundary value shows different trend. In the case of closed boundary, the later stage of the curve appears upturned.

Table 1. Basic parameters of a low permeability reservoir.

K(μm^2)	28.5×10^{-3}	Φ	0.15	q(m^3/day)	3
ρ(g/cm^3)	0.78	G(MPa/m)	0.05	C_D	2
γ(1/MPa)	0.03	C_ρ(1/MPa)	3.09×10^{-3}	μ(mPa•s)	6.5
h(m)	2	C_Φ(1/MPa)	3.28×10^{-4}	p_i(MPa)	0.15
R(m)	100	r_w(m)	0.1	S	5

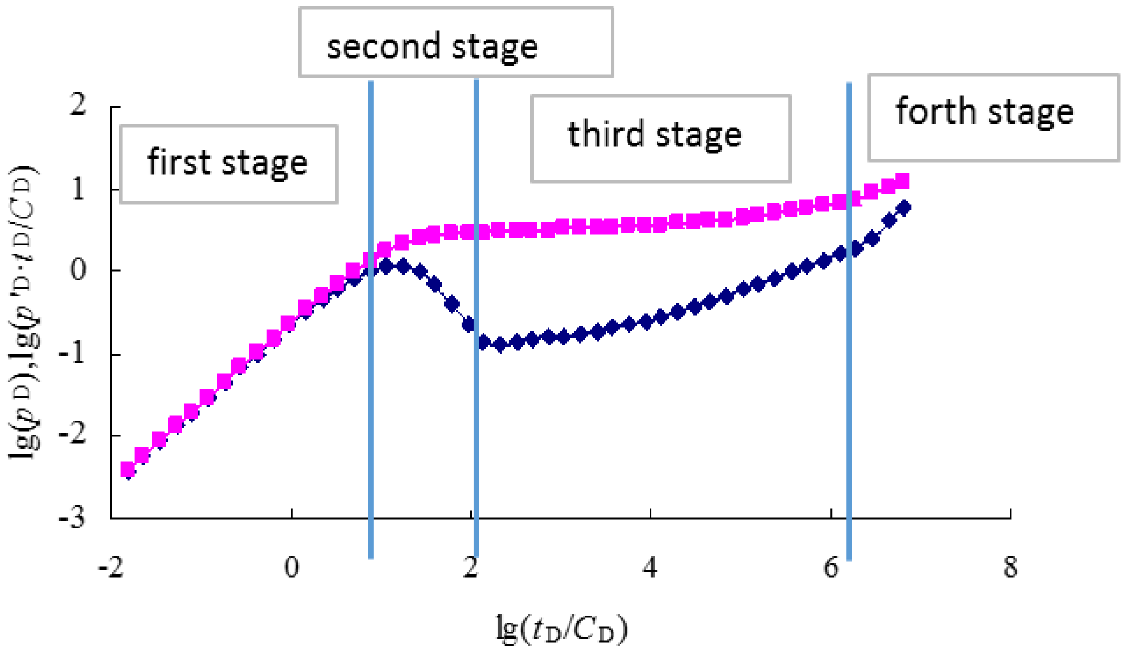


Figure 1. The typical pressure dynamic curve.

Effects of medium deformation on the pressure dynamic curve

In the low permeability reservoir, with the decrease of pore pressure, the effective stress of rocks increases, after which the skeleton of reservoir will be deformed. Therefore, the permeability and the porosity will decrease. Permeability modulus γ is induced as parameters to express effects of medium deformation. Dimensionless permeability modulus is expressed by γ_D.

Figure 2 indicates the effect of dimensionless permeability modulus γ_D on the pressure dynamic curve. Permeability modulus has main effect on the later period of flow.

At the initial stage, there is a slow rise in pressure. The value of γ_D has little effect on the progress. After the initial stage, with the increase of time, pressure curves are divergent. The influence of γ_D on pressure is increasing, and dimensionless pressure increases with the value of γ_D reduces. Along with the increasing of the deformation medium elasticity, the pressure declines more rapidly.

Effects of starting gradient on the pressure dynamic curve

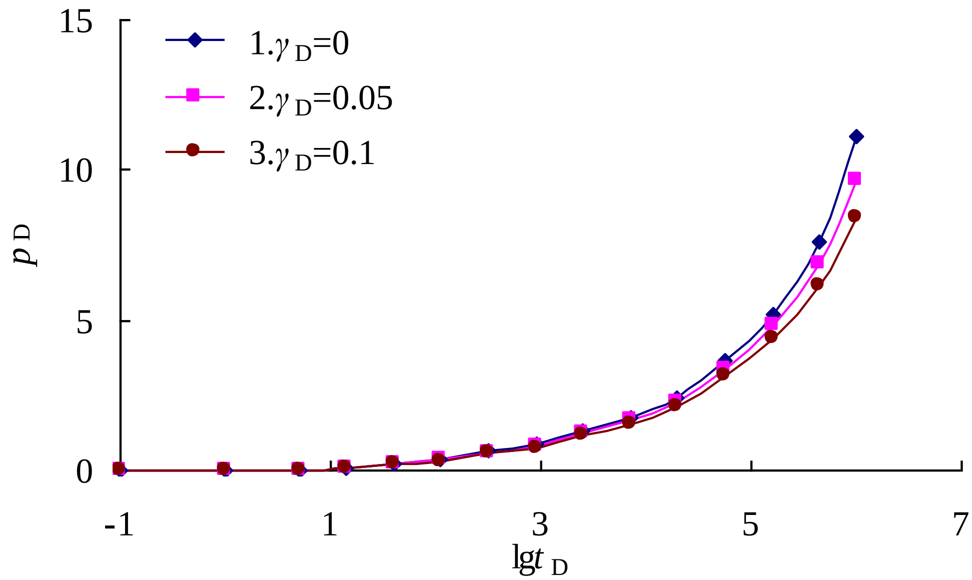
The fluid of low permeability reservoirs will have to surmount the starting pressure gradient to flow. G is defined as the starting pressure gradient. Dimensionless starting pressure gradient is expressed by G_D.

Figure 3 indicates the effect of dimensionless starting pressure gradient on the pressure dynamic curve. Dimensionless starting pressure gradient has main effect on the radial flow stage and the later period of flow.

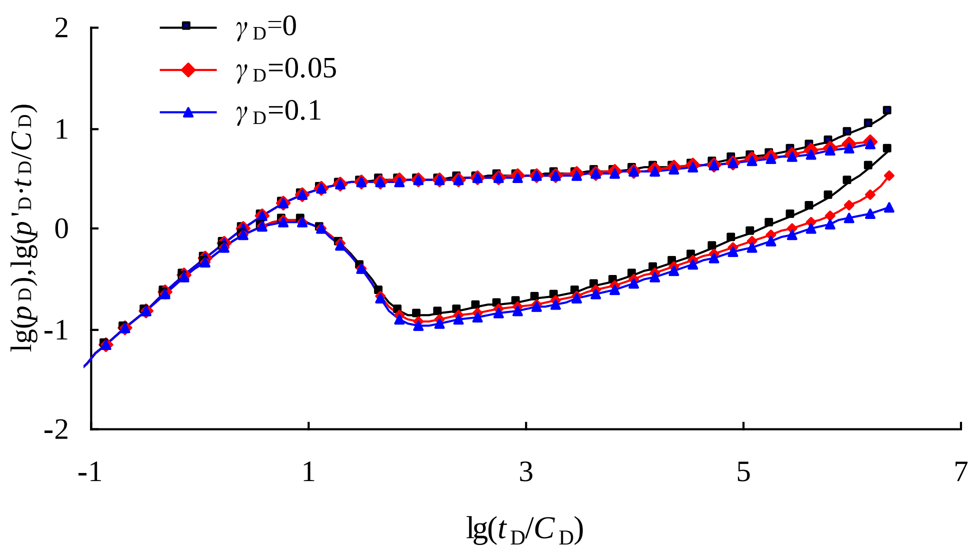
Along with the increase of the dimensionless starting pressure gradient, the seepage resistance will grow to becoming overcome by fluid to flow; the pressure descending rate will become slower, and the warping of the curve will reduce.

Analysis on effects of the quadratic gradient

In the traditional well test models, the quadratic gradient



(a)



(b)

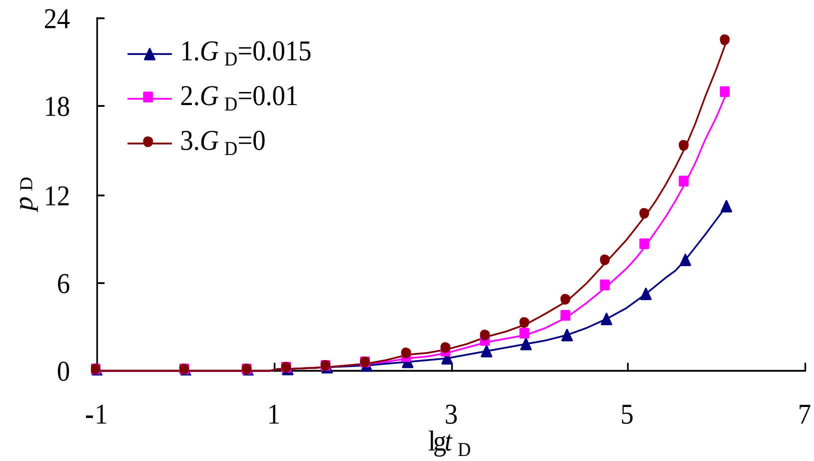
Figure 2. Influence of γ_D on pressure dynamic curve (a) Semi-log graph (b) Log-log graph.

term of nonlinear partial differential equation was neglected according to the assumption of slightly compressible fluid, which could lead to error when the well test time was too long. Figure 4 indicates two pressure dynamic curves, one of which is obtained by the model considering the quadratic gradient term; and the other of which is obtained by the model neglecting the quadratic gradient term.

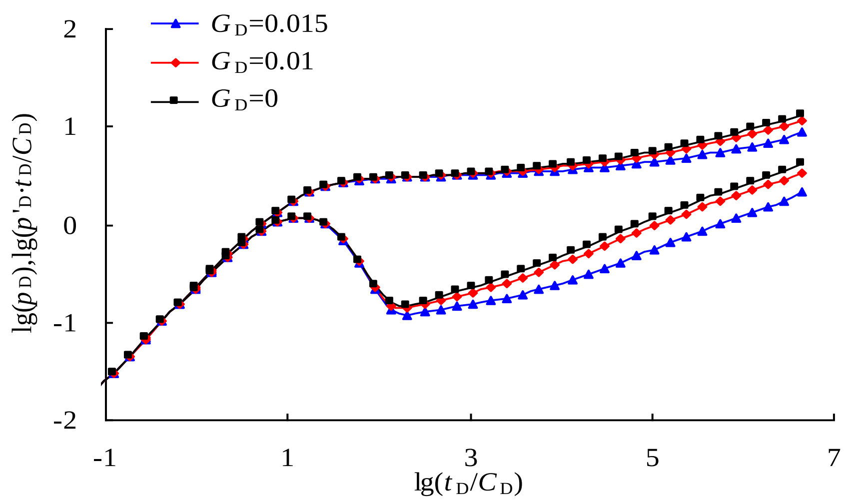
In order to describe the effect of the quadratic gradient, we define:

$$\varepsilon = \frac{p_{\mathrm{Df}} - p_{\mathrm{Dnf}}}{p_{\mathrm{Dnf}}} \tag{28}$$

ε indicates the difference of the pressure numerical solution between two models. p_{Df} and p_{Dnf} respectively express the dimensionless pressure numerical solution of the model considering and neglecting the quadric gradient effect. From the definition, we know that the



(a)



(b)

Figure 3. Influence of G_D on pressure dynamic curve (a) Semi-log graph (b) Log-log graph.

bigger the deviation between ε and 0 is, the greater the difference between the two solutions becomes.

Figure 5 indicates the change regulation of ε with the dimensionless radius. When other parameters are constant, along with the increasing radius, the pressure solution difference increases first and then decreases, finally tending to zero. It means that the effect of the quadratic gradient term on the calculation increases first and then decreases, finally tending to disappear when pressure wave is moving away from the wellbore.

Figure 6 indicates the change regulation of ε with the time when G_D=0.008, r_D=6.3164. α indicates the factor of the quadratic gradient term. At the initial stage, curve is near the horizontal line. Along with the time increases, the curve gradually diverges up and then tend to be horizontal. When the time is 10^4, the difference goes up to 3%. Besides, when time is fixed, with α deciding, the pressure solution difference increases. The value of α has little effect on the initial stage. Along with the time increases, the influence of α on pressure solution difference increases. The bigger the value of α, the greater the influence becomes.

Analysis on moving boundary

By numerical simulation computing, we can obtain the location of moving boundary r_{fD} of different regions at

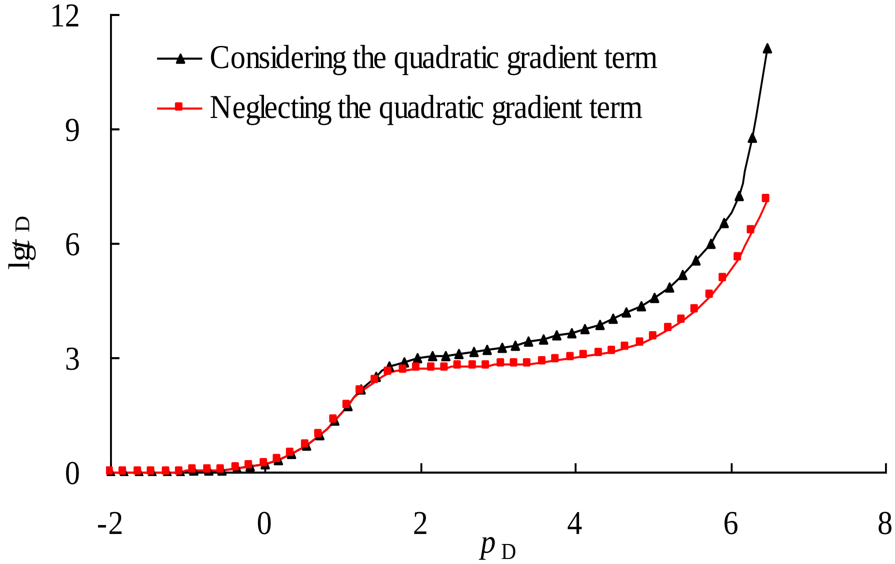


Figure 4. Contrast on considering and neglecting the quadratic gradient term.

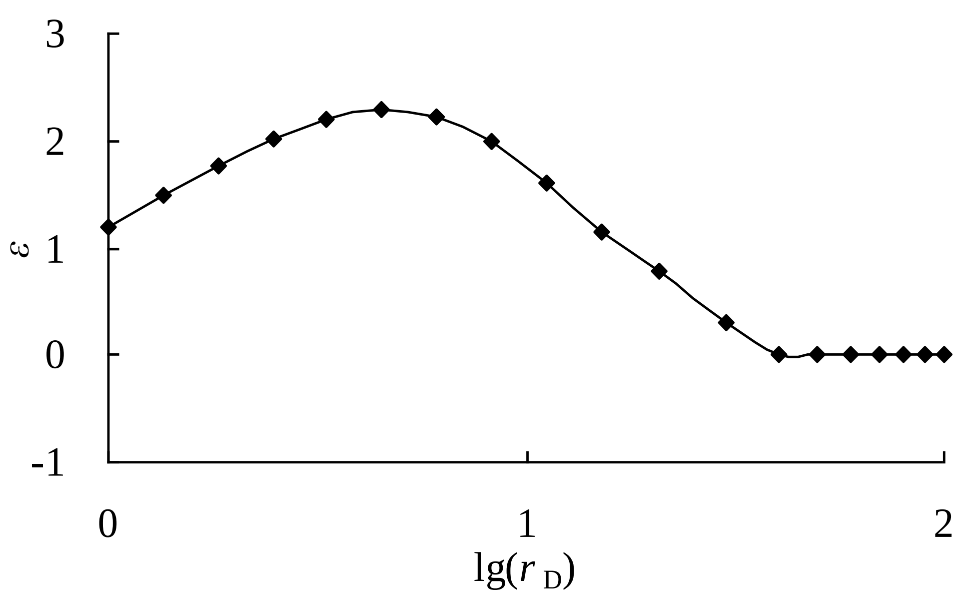


Figure 5. Change regulation of ε with the dimensionless radius.

different moments. We can draw the curves of moving boundary r_{fD} changing with time (Figure 7).

Figure 7 indicates the change regulation of r_{fD} with time. When other parameters are constant, moving boundary is affected by various values of G_D. Along with the time increases, the moving boundary is expanding, but the speed of expansion becomes slower. In the later period of flow, we can believe that moving boundary extends to a certain distance after a longer extension. The greater the reservoir starting pressure gradient is, the smaller the region boundary is. Thereafter, the affected scope of the pressure becomes smaller and the speed of moving boundary becomes slower.

Conclusion

(1) The flow model of low permeability reservoirs of deformed media was built, which considered the influence of starting pressure gradient, moving boundary,

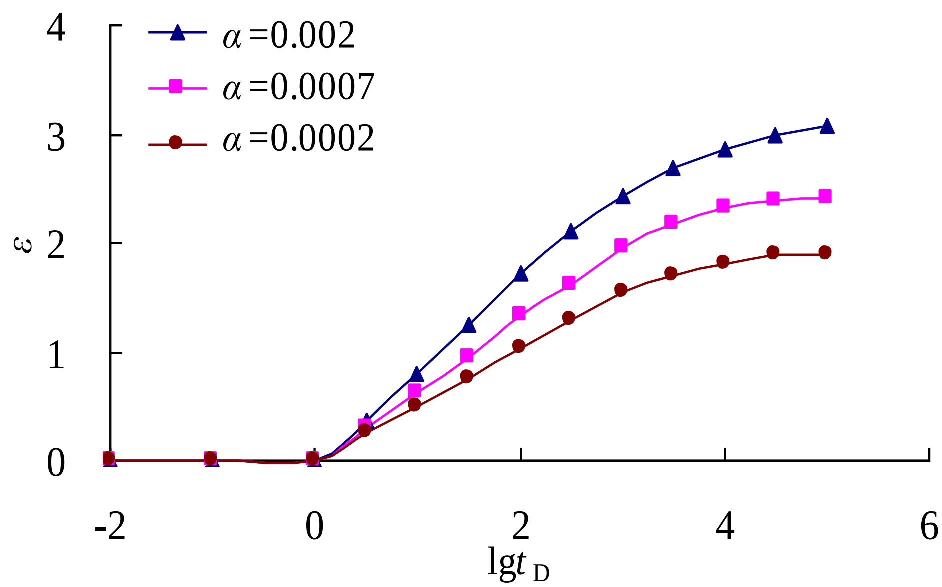


Figure 6. Influence of *α* on *ε*.

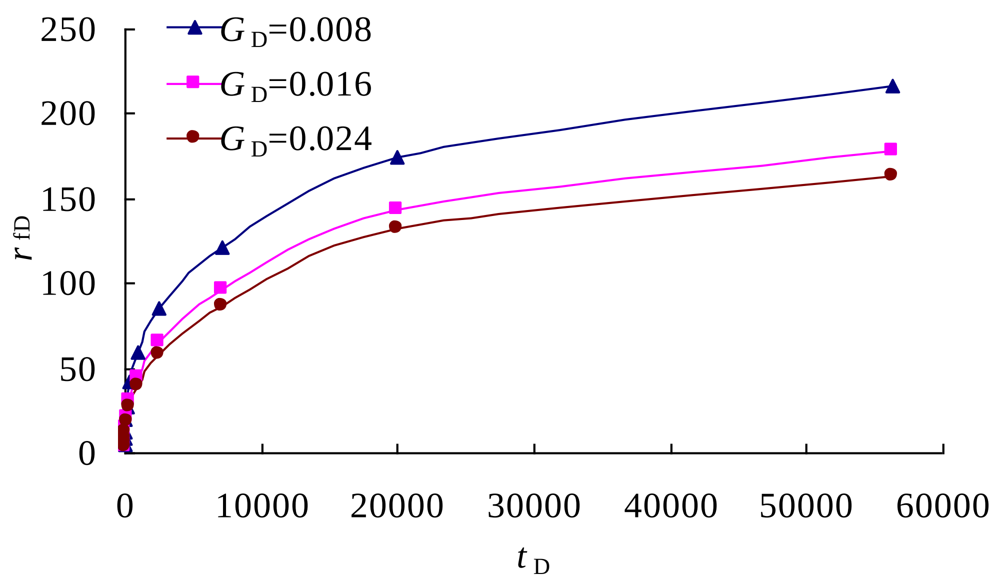


Figure 7. Influence of G_D on r_{fD} curve.

and quadratic gradient term. The numerical solution of the flow model was obtained by the fully implicit finite difference method;

(2) Analysis on the flow model of low permeability reservoir indicates that the starting pressure gradient and the deformation of the media mainly influences on the pressure characteristic curve in the middle and later period. The smaller the value is, the bigger the descending rate of the dimensionless pressure;

(3) The factor of the quadratic gradient term affects the middle and later period. The greater the value of *α* is, the greater the difference of the pressure numerical solution between two models. With the radius increasing, pressure solution difference increases first, then decreases, and finally tends to zero. With the increase of time, the pressure curves are divergent;

(4) In the low permeability reservoir, due to the existence of the starting pressure gradient, the pressure is not instantaneously spread to infinity, but spreads gradually over time. And the greater the starting pressure gradient

is, the slower the speed of moving boundary becomes. Thus, in the low permeability reservoir development process, we should consider the impact of the moving boundary.

(5) The results could help people understand the seepage mechanism of low permeability reservoirs and provide the theoretical basis for exploring the low permeability reservoirs.

SIGN ANNOTATION

***v*,** Seepage velocity (cm/s); ***K*,** permeability ($10^{-3}\mu m^2$); ***L*,** length of model (cm); **Δp,** pressure difference (MPa); ***μ*,** viscosity (mPa·s); ***G*,** starting pressure gradient (MPa/m); **p_i,** infinite-acting initial pressure (MPa); ***h*,** reservoir thickness (m); ***r*,** distance from the well (m); **r_w,** radius of the well (m); **r_e,** drainage radius (m); ***t*,** production time (h); ***K*,** permeability (μm^2); ***q*,** surface output (m^3/day); ***μ*,** Viscosity, mPa·s); ϕ, porosity (f); ***ρ*,** density (g/cm^3); **γ,** permeability modulus (MPa^{-1}); **C_ρ,** liquid compressibility (MPa^{-1}); **C_Φ,** rock compressibility (MPa^{-1}); **C_t,** total compressibility, MPa^{-1}); ***η*,** pseudo pressure (f); **r_{fD},** moving boundary (m).

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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