分形油藏中有限导流垂直裂缝井的非牛顿流渗流规律

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摘　要　提出了分形油藏中有限导流垂直裂缝井的非牛顿流的数学模型, 用影响椭圆和平均值的方法求其近似解,分析计算了改变分维参数、幂律指数、弹性储量比、窜流系数、无量纲导流参数时的压力变化规律, 其流态可分为 4 个阶段: 开始时的裂缝内线性流; 早期的双线性流; 中期的质量交换压力平缓过渡阶段; 晚期的平均双重介质径向流阶段。另外, 得到了单重分形油藏中非牛顿幂律流的点源函数和有限导流垂直裂缝井的等流量解。

主题词　油气藏　近井地带　垂直裂缝　裂缝导流能力　试井解释　渗流力学

1990 年 Chang J[1]首次用分形油藏的概念来描述复杂的自然裂缝油藏, 建立了一种研究横向非均质油藏的试井分析方法。所谓分形油藏, 其特征表现在孔隙度和渗透率的描述上, 刘慈群[2]用谱指数 θ_φ、θ_k 来描述孔隙度和渗透率的分布, 即 $\varphi(r)=\varphi_0(r_d)^{\theta_\varphi}$, $k(r)=k_0(r_d)^{\theta_k}$。其中 φ_0 和 k_0 表示 $r_d=1$ 处的特征孔隙度和渗透率; 在 $\theta_\varphi=D-d$ 和 $\theta_k=D-d-\theta$ 中, D 是油藏的分维, d 是分形所嵌入的欧氏空间维数, $\theta=\theta_\varphi-\theta_k$ 为谱指数。Aprilian S[3]和 Acuna J A[4]利用基于分形油藏的试井分析方法解释了油田中用以往方法难以解释的复杂油藏的试井结果, 得到了和现场实验一致的结论, 这说明用分形来描述这一类横向非均质油藏是合理的。可以根据试井资料反求谱指数, 进而了解油藏的非均质性。

本文讨论双孔分形油气藏中幂指数为 n 的非牛顿流体和具有有限导流能力的垂直裂缝井的渗流规律。弹性储量比 $\omega=1$ 即为单重分形油藏的结果, $n=1$ 的特殊情况即为牛顿流体渗流的规律, 此时的结果可用于气藏的渗流理论研究。刘慈群[5]研究了均质油藏中非牛顿流的渗流规律, 即 $D=2$, $\theta=0$时的结果。另外, 文中给出了无限大分形油藏的点源解, 用面源积分的方法求得了单重分形油藏中有限导流垂直裂缝井的等流量解。

双孔分形油藏中数学模型

有限导流垂直裂缝井的渗流可分为两个主要阶段: 裂缝面的线性流和地层中的椭圆状渗流。

垂直裂缝面内的渗流区很小, 如不考虑液体压缩性和粘度变化影响, 则幂律流在裂缝内的流动规律为:

$$\frac{\partial^2 p_{Df}}{\partial \eta^2}+\frac{2}{F}\left.\frac{\partial p_{D1}}{\partial \xi}\right|_{\xi=0}=0 \quad 0<\eta<\frac{\pi}{2} \tag{1}$$

裂缝井等产量条件: $$\left.\frac{\partial p_{Df}}{\partial \eta}\right|_{\eta=\frac{\pi}{2}}=\frac{\pi}{F} \tag{2}$$

裂缝端部封闭条件: $$\left.\frac{\partial p_{Df}}{\partial \eta}\right|_{\eta=0}=0 \tag{3}$$

式中: $p_{Di}=\dfrac{2\pi K_{01}h(p_0-p_i)}{\mu_0 Q}$　$(i=1,2,f)$,

$$F=\frac{K_f y_f}{K_{01}x_f}$$

假定双孔介质(裂缝和基质)有相同的分维 D 和谱指数θ, 根据分形油藏的定义则可近似地认为双孔分形油藏中渗透率和孔隙度有如下的分布规律:

$$K_1(\xi)=K_{01}e^{\theta_K\xi}\text{和}\ \varphi_{1,2}(\xi)=\varphi_{01,2}e^{\theta\varphi\xi}$$

其中, K_{01}, $\varphi_{01,2}$分别是 $K_1(\xi)$, $\varphi_{1,2}(\xi)$ 在 $\xi=0$ 时的值。

非牛顿幂律流体粘度的椭圆分布为 $\mu(\xi)=$

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$\mu_0 e^{(1-n)\xi}$。根据质量守恒原理,可知平均压力满足如下的方程组:

$$\omega e^{\theta\varphi\xi}\frac{d\bar p_{D1}}{dt_D}+(1-\omega)e^{\theta\varphi\xi}\frac{d\bar p_{D2}}{dt_D}=2\pi \qquad (4)$$

$$(1-\omega)e^{\theta\varphi\xi}\frac{d\bar p_{D2}}{dt_D}=\lambda(\bar p_{D1}-\bar p_{D2}) \qquad (5)$$

其中, $t_D=\frac{K_{01}t}{\mu_0(\varphi_{01}C_1+\varphi_{02}C_2)x_f^2}$,

$\omega=\frac{\varphi_{01}C_1}{\varphi_{01}C_1+\varphi_{02}C_2}$

初始条件: $\bar p_{D1(2)}=0$ $(t_D=0)$ (6)

边界条件: $\bar p_{D1(2)}=0$ $(\xi=\xi_D)$

$p_{Df}(\eta)=p_{D1}(0,\eta)$ (7)

这里 $\bar p_{Di}=\frac{2}{\pi}\int_0^{\frac{\pi}{2}}p_{Di}(\xi,\eta)d\eta$ $(i=1,2,f)$ (8)

$\bar p_{Di}=w\int_0^{\xi_R}\pi\bar p_{Di}e^{\theta\varphi\xi}\mathrm{ch}2\xi d\xi$ $(i=1,2)$ (9)

近 似 解

从方程(4)、(5)可得:

$$\bar p_{D1}=\frac{2\pi}{e^{\theta\varphi\xi}}\left\{t_D+\frac{(1-\omega)^2e^{\theta\varphi\xi}}{\lambda}\left[1-e^{-\frac{\lambda t_D}{\omega(1-\omega)e^{\theta\varphi\xi}}}\right]\right\} \qquad (10)$$

根据式(6)、(7)可设双孔分形介质中渗流压力试探解为:

$$p_{D1}=p_{Df}\frac{e^{(1-n-\theta_k)\xi_R}-e^{(1-n-\theta_k)\xi}}{1-n-\theta_k} \qquad (11)$$

把式(11)代入式(1)得:

$$\frac{d^2p_{Df}}{d\eta^2}-\frac{2}{F}\frac{p_{Df}}{g(\xi_R)}=0 \qquad (12)$$

其中, $g(\xi)=\frac{e^{(1-n-\theta_k)\xi_R}}{1-n-\theta_k}$

考虑边界条件(2)、(3),由式(12)解得:

$$p_{Df}=\frac{\pi}{F}\frac{\mathrm{ch}(\beta\eta)}{\beta\mathrm{sh}\left(\frac{\pi}{2}\beta\right)} \qquad (13)$$

其中, $\beta^2=\frac{2}{Fg(\xi_R)}$。

则有: $p_{wD}=p_{Df}\left(\frac{\pi}{2}\right)=\frac{\pi}{F\beta}\mathrm{cth}\left(\frac{\pi}{2}\beta\right)$ (14)

由式(9)得:

$$\bar p_{D1}=\frac{w\pi}{2}\left[\frac{e^{(3-n+\theta)\xi_R}}{(\theta_\varphi+2)(3-n+\theta)}+\frac{e^{(\theta-1-n)\xi_R}}{(\theta_\varphi-2)(\theta-1-n)}\right]+\frac{w\pi}{1-n-\theta_k}\times\left[\frac{1-n+\theta}{(3-n+\theta)(\theta-1-n)}-\frac{\theta_\varphi e^{(1-n-\theta_k)\xi_R}}{\theta_\varphi^2-4}\right] \qquad (15)$$

由$\bar p_{D1}$和式(10)相等,整理后得影响椭圆传播公式:

$$\frac{1}{e^{\theta\varphi\xi_k}}\left\{t_D+\frac{(1-\omega)^2e^{\theta\varphi\xi_R}}{\lambda}\left[1-e^{-\frac{\lambda_D t_D}{\omega(1-\omega)e^{\theta\varphi\xi_R}}}\right]\right\}=\frac{w}{4}\left[\frac{e^{(3-n+\theta)\xi_R}}{(\theta_\varphi+2)(3-n+\theta)}+\frac{e^{(\theta-1-n)\xi_R}}{(\theta_\varphi-2)(\theta-1-n)}\right]+\frac{w}{2(1-n-\theta_k)}\times\left[\frac{1-n+\theta}{(3-n+\theta)(\theta-1-n)}-\frac{\theta_\varphi e^{(1-n-\theta_k)\xi_R}}{\theta_\varphi^2-4}\right] \qquad (16)$$

在式(16)中求出ξ_R,代入式(14)得有限导流垂直裂缝井瞬时压力p_{wD}。

单重分形油藏中的数学模型和源函数解

幂律指数为 n 的非牛顿弱压缩流体的粘度径向分布公式为[6] $\mu=\mu_0 r_D^{1-n}$。式中的μ_0为非牛顿液体在$r_D=1$时的粘度,据它得到分形油藏中直井渗流的连续性方程:

$$\frac{\partial}{\partial r_D}\left(r_D^{n+\theta_k}\frac{\partial p_D}{\partial r_D}\right)=r_D^{1+\theta_\varphi}\frac{\partial p_D}{\partial t_D} \qquad (17)$$

其中, $p_D=\frac{2\pi K_0h(p_i-p)}{Q\mu_0}$, $t_d=\frac{K_0t}{\mu_0C_t\varphi_0r_w^2}$, $r_D=\frac{r}{r_w}$

可以求得满足方程(1)的点源的源函数为:

$$S(r_D,t_D)=\frac{\frac{\alpha}{2}e^{-\frac{r_D^\alpha}{\alpha^2t_D}}}{\pi\Gamma(\delta)(\alpha^2t_D)^\delta} \qquad (18)$$

其中, $\alpha=3+\theta_\varphi-\theta_k-n$, $\delta=\frac{D}{3+\theta_\varphi-\theta_k-n}$。

下面利用这个点源函数研究如图 1 所示的有限导流垂直裂缝井,半长为 x_f、半宽为 y_f 的裂缝被分成 $M\times N$ 块,每块产率为 $q_{ij}(t_D)$满足如下条件:

$$2\sum_{i=1}^{M}\sum_{j=1}^{N}q_{ij}\left(\frac{x_fy_fh}{MN}\right)=q_f \qquad (19)$$

令 $p_D=\frac{\alpha}{2}\frac{2\pi K_0h(p_i-p)}{q_f\mu_0}$,

$t_D=\left(\frac{\alpha}{2}\right)^2\frac{K_0t}{\mu_0C_t\varphi_0x_f^2}$, $x_D=\frac{x}{x_f}$, $y_D=\frac{y}{x_f}$

根据式(18),利用面源积分的方法可得有限导流垂直裂缝井在地层中的无因次压力分布公式:

$$p_D(x_D,y_D,t_D)=\frac{2hx_fy_f}{\Gamma(\delta)q_f}\int_0^{t_D}\left\{\sum_{i=1}^{M}\sum_{j=1}^{N}q_{ij}(\tau)\int_{\frac{i-1}{M}}^{\frac{i}{M}}\int_{\frac{j-1}{N}\frac{y_f}{x_f}}^{\frac{j}{N}\frac{y_f}{x_f}}\exp\left\{-\frac{[(x_D-x')^2+(y_D-y')^2]^{\frac{\alpha}{2}}}{4(t_D-\tau)}\right\}dy'dx'\right.$$
$$-\sum_{i=1}^{M}\sum_{j=1}^{N}q_{ij}(\tau)\int_{-\frac{i-1}{M}}^{\frac{i}{M}}\int_{\frac{j-1}{N}\frac{y_f}{x_f}}^{\frac{j}{N}\frac{y_f}{x_f}} \qquad ($$

$$\exp\left\{-\frac{\left[(x_D-x')^2+(y_D-y')^2\right]^{\frac{a}{2}}}{4(t_D-\tau)}\right\}$$

$$dy'\,dx'\left\{\frac{d\tau}{[4(t_D-\tau)]^{\delta}}\right. \qquad (20)$$

由此可得等流量裂缝中心的压力公式为:

$$p_{wD}(0,0,t_D)=\frac{1}{\Gamma(\delta)}\int_0^{t_D}\int_{-1}^{1}\int_{-\frac{y_f}{x_f}}^{\frac{y_f}{x_f}}$$

$$\exp\left[-\frac{(x'^2+y'^2)^{\frac{a}{2}}}{4(t_D-\tau)}\right]dx'\,dy'\,\frac{d\tau}{[4(t_D-\tau)]^{\delta}} \qquad (21)$$

分析和计算

1. 双孔分形油藏

(1) δ变化时的情况

$\delta=D/(3+\theta_\varphi-\theta_k-n)$是综合反映分维和谱指数θ的参数,图 1 是 δ变化时的无因次压力变化示意图。$D=2$, $\theta=0$时, $\delta=1$即为非牛顿流体在均质油藏中的渗流规律。当 $t_D\to 0$, $n=1$, $\omega=1$时,式(16)变为:

$$\frac{t_D}{\omega}=\frac{w}{4}\xi_R^2 \qquad (22)$$

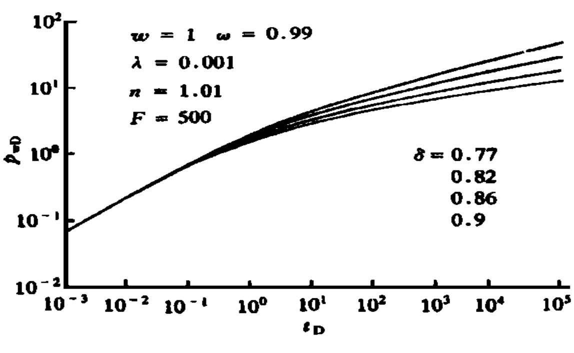

图 1　δ改变时无因次压力变化示意图

Fig. 1. Non-dimensional pressure change in accordance with the alteration of δ.

于是式(14)变为: $p_{wD}=\sqrt{\frac{\pi}{F}}\left(\frac{4}{w}\right)^{1/4}t_D^{1/4}$ (23)

如令 $w=1.05$,则式(23)和已知的均质介质牛顿流体双线性流公式 $p_{wD}=\frac{2.45}{\sqrt{F}}t_D$ 是一样的。

当 $t_D\to\infty$时, $p_{wD}=\frac{1}{2}\ln\left(\frac{16}{w}t_D\right)$ $(n=1,\ \omega=1)$ (24)

如令 $w=2.45$,则式(24)和已知的均质介质牛顿流体径向流公式 $p_{wD}=\frac{1}{2}(\ln t_D+2.2)$ 是一样的。

(2) n 变化时的情况

幂律指数 $n=1$,即为牛顿流体在双孔分形油藏中的渗流规律,此时的结果可用于描述气藏的渗流规律,图 2 是 n 取不同的值时无因次压力变化示意图。另外还计算了弹性储量比(ω)、窜流系数(λ)、无量纲导流参数(F)、裂缝宽长比(y_f/x_f)改变时无因次压力与时间的变化规律。

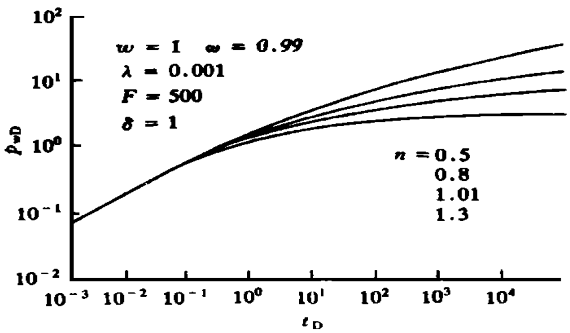

图 2　n 改变时无因次压力变化示意图

Fig. 2. Non-dimensional pressure change in accordance with the alteration of n.

2. 单重分形油藏 δ变化时的情况

图 3 是由式(21)计算的 δ改变时单重分形油藏中裂缝中心的无因次压力变化示意图。在同一时刻,时间比较大时, δ越大, p_{wD}越小;时间比较小时, δ越大, p_{wD}越大。

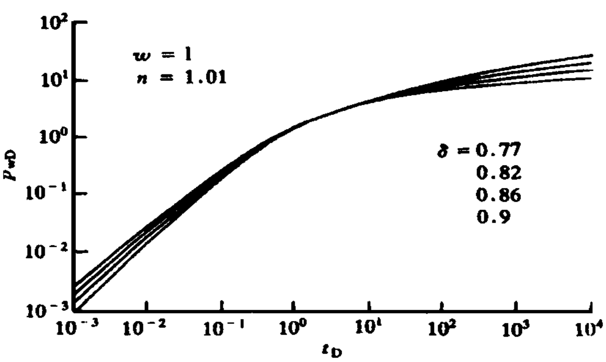

图 3　单重分形油藏中 δ改变的示意图

Fig. 3. Alteration of δ in the single fractal oil reservoir.

结　　论

(1) 提出了双孔分形油藏中有限导流垂直裂缝井的非牛顿流的数学模型,并用影响椭圆和平均值的方法求得了近似解。此模型概括了以下模型: $\omega=1$为单重分形油藏的情况; $n=1$为牛顿流体的结果,可用于气藏; $D=2$, $\theta=0$为双孔油藏的情况。

(2) 双孔分形油藏中有限导流垂直裂缝井的压力动态行为大致可分为: 开始时的裂缝内线性流; 早期的双线性流阶段; 中期的质量交换压力平缓阶段; 晚期的平均双重介质径向流 4 个阶段。

(3) 得到了单重分形油藏中非牛顿流的点源函数和有限导流垂直裂缝井的等流量解。

符　号　说　明

C_t 为总的压缩系数, 1/atm, 1MPa= 9.8 atm;
h 为油藏厚度, cm;
p_D 为无因次压力;
r 为某点距井中心的距离, cm;
t_D 为无因次时间;
w 为权重;
θ_k 为渗透率谱指数;
ξ 为椭圆坐标;
μ 为粘度, mPa·s;
ξ_R 为影响椭圆的椭圆坐标;
λ 为窜流系数;
下标f, 1, 2分别表示井裂缝、裂缝、基质;
$C_{1(2)}$ 为裂缝(基质)的压缩数;
K 为渗透率, μm^2;
q_f 为裂缝总的流率, cm^3/s;
r_w 为井筒半径;
x_f, y_f 为裂缝半长, cm;
θ_φ 为孔隙度谱指数;
θ 为谱指数;
η 为椭圆坐标;
Γ 为伽马函数;
φ 为孔隙度;
ω 为弹性储量比。

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changed into the non-reservoir one. The storage property and permeability are mainly affected by the calcite content and clay mineral occurrence.

SUBJECT HEADINGS: Sichuan Basin, West, Upper Jurassic, Low permeability reservoir, Reservoir characteristic, Pore structure.

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APPLICATION OF NERVE NETWORK TO LOG INTERPRETATION

Luo Li (Logging Company of Sichuan Petroleum Administration). *NATUR. GAS IND.* v. 17, no. 5, pp. 23~ 26, 9/25/97. (ISSN 1000-0976; **In Chinese**)

ABSTRACT: After the essential pretreatment and reasonable choice of the logging data have been done, a correct sample set may be established by combining the logging data with geological parameters. For designing the BP neural network, it is necessary to correct neuron action function, to adjust the weighted value recursion formula of neurons and to carry out the network training for the samples. When the system error of the network is smaller than the allowable error, the network training will be ended. By use of the network model parameters obtained, the result needed will be got. Reservoir parameters can be calculated through inputting log data and by comparing the calculated result with core analysis result, the error of the former is very small. When the parameters calculated by logging are badly related with reservoir productivity, it is necessary to link the reservoir parameters with reservoir productivity to design BP network to carry out sample training. After the model parameters have been got through correcting step width adjustment factor and smoothing factor in the process of training, the effect of evaluating reservoir productivity is very good with high accuracy. The structure, neuron's weighted value, domain value and output function of Hamming network were improved to suit for the pattern recognition with successive input values. It is proved by treating practical data that such a network has stronger pattern recognition ability, a good result being obtained.

SUBJECT HEADINGS: Nerve network, Log interpretation, Reservoir, Production calculation, Error, Comprehensive evaluation.

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FLOW RULE OF NON-NEWTONIAN FLUIDS IN A FRACTAL OIL RESERVOIR WITH FINITE CONDUCTIVITY VERTICAL FRACTURE WELL

Li Fanhua and Liu Ciqun (China National Petroleum Corporation / Institute of Porous Flow and Fluid Mechanics, Academia Sinica). *NATUR. GAS IND.* v. 17, no. 5, pp. 27~ 30, 9/25/97. (ISSN 1000-0976; **In Chinese**)

ABSTRACT: A mathematic model of non-Newtonian fluid flow in a fractal oil reservoir with finite conductivity vertical fracture well is proposed and its approximate solution is acquired by the influence ellipse and mean value method. The pressure-changing rule is analyzed and calculated while the fractional dimension parameter (δ), power law exponent (n), elastic reserve ratio (ω), interporosity flow coefficient (λ) and non-dimensional conductivity parameter (F) are altered. Its flow state may be divided into 4 stages: linear flow within fractures at the beginning; bilinear flow at early time; mass exchange and pressure gentle transition period at middle time and average dual-porosity media radial flow period at later time. In addition, the point-source function of non-Newtonian exponential flow in single fractal reservoir and the uniform flux solution of the finite conductivity vertical fracture well are obtained.

SUBJECT HEADINGS: Oil and gas reservoir, Near wellbore area, Vertical fracture, Fracture conductivity, Well test interpretation, Percolation mechanics.

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A MODEL INVESTIGATION ON FORECASTING THE PRODUCTION OF OIL AND GAS FIELD

Hu Jianguo and Zhang Dongjie (Changqing Petroleum Exploration Bureau) and Chen Yuangqian (Research Institute of Petroleum Exploration and De-