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近井带有机伤害解除的数值模拟

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摘要:近井带温度、压力和组分等条件的变化会导致原油中的胶质、沥青质等有机物在油层孔隙内部沉积,降低渗透率,造成近井带油层伤害,而利用注入有机溶剂浸泡来解除近井带有机污染是一种有效的方法。文中建立了一个利用有机溶剂吞吐解除油层有机伤害的数学模型,并进行了数值求解。同时,针对一个实例,模拟了溶剂注入速度、注入量、闷井时间对渗透率改善效果的影响,并对改善效果进行了预测。矿场应用结果表明,该方法效果较好。

关键词:沥青质;油层伤害;溶剂浸泡;数值模拟

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引 言

油井在生产过程中,由于温度、压力和组分的改变会导致原油中的沥青质发生絮凝、沉积,伤害油层。近井带的温度、压力和组分的变化是最剧烈的,因此最可能出现伤害的油层部位首先是近井带。如果采用CO_2驱时,也可导致沥青质在油层深部沉积。Kosta. J. Leontaritis[1]将沥青质等重有机组分对油层造成的伤害归结为:(1)沥青质微粒堵塞孔道,降低油层岩石的渗透率,这一点也是最主要的伤害;(2)吸附在岩石孔隙表面上导致矿物表面的水润湿特性变为油润湿特性,降低油相的有效渗透率;(3)沥青质微粒起核心作用,形成乳状液,增加流动阻力。各种研究表明,近井带沥青质导致的油层伤害问题的解除是比较困难和复杂的[1,2]。近年来研究表明[3-5],采用向近井带注入化学溶剂的方法来解除沥青质等有机垢堵塞油层问题是行之有效的。国外有人[6,7]曾对用溶剂法开采沥青进行过油藏数值模拟研究。本文在前人研究的基础上,建立了一个适合模拟用有机溶剂解除近井带有机油层伤害的数学模型,并采用有限差分法进行了求解。同时对一个油田实例进行了模拟。实践表明该模型能够成功地模拟注入量、注入速度、闷井时间对解堵效果的影响,以及解堵有效期,为矿场施工参数的确定提供依据。

1 模型的建立

1.1 模型建立的假设条件

该数学模型的假设条件为:

(1)近似认为胶质、沥青质不流动,其流动部分是被溶剂溶解的部分。

(2)地层孔隙完全被胶质、沥青质颗粒和流体所占。

(3)胶质、沥青质颗粒被束缚在孔隙中,其组分的传播仅靠分子扩散,流体组分的传播靠对流—扩散两种方式。

(4)考虑油层孔隙度、渗透率和流体粘度的非均质性。

(5)假设存在一个临界溶剂浓度,当溶剂浓度高于此浓度时对胶质、沥青质颗粒进行溶解。

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(6) 假定注入溶剂与原油瞬时溶解，而且油层温度保持不变。

1.2 数学模型

1.2.1 流体瞬时饱和度、沥青质颗粒与溶剂关系模型

将地层孔隙看作由沥青质颗粒和流体(流体成分为溶剂和溶解的沥青)完全充填，则流体的瞬时饱和度和沥青质颗粒的关系[8]为

$$S = \frac{\phi}{\phi_m} = 1 - \frac{4\pi n_p r_p^3}{3\phi_m} \tag{1}$$

式中　ϕ_m 为单位体积岩石中流体和有机沉积物颗粒共同占有的孔隙体积，ϕ 为单位体积岩石中流体占有的孔隙体积，n_p 为有机沉积物颗粒密度，r_p 为有机沉积物颗粒半径。

实际上，沥青质颗粒并非规则球形，引入有机颗粒的体积形状系数 ω，因而方程(1)改写为

$$S = \frac{\phi}{\phi_m} = 1 - \frac{4\pi}{3}\frac{\omega n_p r_p^3}{\phi_m} \tag{2}$$

颗粒的溶解速度可表示为

$$r_{pv} = \frac{dr_p}{dt} \tag{3}$$

颗粒的半径 r 是溶剂浓度的函数，它们的关系由以下积—微分方程[8]表示

$$\frac{\partial}{\partial t}\left(\int_0^{r_p} C_s r^2 dr\right) = C^* \frac{\partial}{\partial t}\left[r_0 F(t) + \int_0^t r_{pv}(\tau)F(t-\tau)d\tau\right] = r_p^2[C \times r_{pv} + \alpha(C - C^*)] \tag{4}$$

$$F(t) = r_p^2\left[\frac{1}{3} - \frac{2}{\pi}\sum_{i=1}^{\infty}\frac{e^{i^2\pi^2 D_s/r_p^2}}{i^2}\right] \tag{5}$$

式中　C 为溶剂体积浓度；C_s 为有机沉积颗粒内溶剂浓度，该浓度沿颗粒径向变化，在中心处最小；C^* 为临界溶剂浓度，决定了颗粒与周围流体间界面的动态变化；α 为吸附系数；D_s 为沥青质颗粒分子扩散系数。该模型是将孔隙内充填物分为两相，即有一定尺寸的不能流动的沥青质颗粒和流体相，其中的流体组成除了含有溶剂和溶解的沥青外，还有油层原油，不同于前人模型。方程(4)的左端项表示单位时间一个颗粒内溶剂量的变化，右端项表示通过一个颗粒表面层的溶剂量。

1.2.2 对流—扩散—吸附模型

溶剂在地层内的流动规律符合对流—扩散—吸附定律[8]，对一个单元体而言，单位时间内单元体内溶剂的变化量等于流入该单元体的溶剂量与流出溶剂量之差；单元体内溶剂与外界的交换是通过对流—扩散的方式实现的。描述这一过程的数学模型为

$$\frac{\partial}{\partial x}\left[D_x\frac{\partial C}{\partial x} - v_x C\right] + \frac{\partial}{\partial y}\left[D_y\frac{\partial C}{\partial y} - v_y C\right] = \left[\phi_m - \frac{4\pi}{3}\omega n_p r_p^3\right]\frac{\partial C}{\partial t} + 4\pi\zeta n_p r_p^2[\alpha(C - C^*)] \tag{6}$$

式中　D_x、D_y 分别表示溶剂在 X 和 Y 方向的分子扩散系数；ζ 为有机微粒表面形状系数。方程 6 的左端项是对流扩散项；右端的第 1 项表示单元体内流体内溶剂的变化量，第 2 项表示单元体内所有颗粒单位时间内吸附的溶剂量。这就是说溶剂在单元体内的存在形式一部分存在于流体中，另一部分存在于半固体胶质、沥青质颗粒中。

1.2.3 质量守恒模型

假设流体在地层孔隙介质内的流动符合达西渗流，并忽略重力和毛管力，则连续性方程可表示为

$$\frac{\partial}{\partial x}\left(\frac{\rho K_x}{\mu}\frac{\partial p}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{\rho K_y}{\mu}\frac{\partial p}{\partial y}\right) = \rho\phi_m C_t\left[1 - \frac{4\pi}{3}\omega n_p r_p^3\right]\frac{\partial p}{\partial t} \tag{7}$$

式中　K_x、K_y 分别为 X、Y 方向的渗透率；C_t 为综合压缩系数。方程 7 的左端项表示单位时间内单元体与外界的质量交换量；右端项表示单元体内单位时间内流体的质量变化量。其中的 μ 是溶剂与原油组成的混合体系的粘度，是溶剂浓度 C、溶剂粘度 μ_s 和原油粘度 μ_o 的函数。假定这些参数符合下列关系

$$\mu = C\mu_s + (1-C)\mu_o \tag{8}$$

1.2.4 胶质、沥青质引起的地层伤害模型

油层的污染伤害主要体现为油层的渗透性降低。在该模型中，假设油层渗透性的变化是由于胶质、沥青质颗粒的体积变化导致地层孔隙的变化；如果颗粒的尺寸增加，则导致油藏岩石的孔隙度、渗透率减小。地层渗透率的降低可以由以下模型表示

$$K = K_o\phi^\beta/\phi_o \tag{9}$$

$$\beta = 1 + [C_1 - e^{\lg(C_2T)}] \tag{10}$$

式中 K，K_o 分别表示目前和原始渗透率；T 为时间，C_1，C_2 分别为拟合常数。

1.2.5 溶剂注入下的胶质、沥青质解堵模型

胶质、沥青质污染后的地层，在注入溶剂的溶解作用下，地层的有效孔隙度增加，从而使得地层的渗透率增加。当然在溶剂作用下，地层原油的流动性也会增强。溶剂作用下的渗透率变化由下列方程描述

$$K = K_o\frac{(1-\phi_o)^2\phi^3}{\phi_o^3(1-\phi)^2}\eta \tag{11}$$

$$\eta = 1 + me^{\left(1-\lg\frac{n}{T}\right)} \tag{12}$$

式中 η 为拟和参数，是原模型[8]的修正项；m，n 为经验常数；T 为时间。

方程(1)～(12)组成了模拟胶质、沥青质等有机垢导致的地层伤害及污染后的解堵数学模型，通过求解方程(1)～(12)组成的封闭方程组，即可对我们研究的问题进行数值模拟。

2 地质模型

2.1 网格划分

采用溶剂的注入来解堵胶质、沥青质造成的油层污染的数值模拟是一个典型的单井模拟问题。由于解堵的目的层位是油井近井地带，而且注入几十方溶剂，溶剂的作用范围也仅限于近井带 10m 以内。为了精细模拟，将网格的尺寸定为 2m，模拟区为 $22\times22m^2$，网格数为 11×11，并假定油井位于模拟区中央。

2.2 边界处理

对于压力方程的求解，在溶剂注入过程中，内边界采用定速度注入。由于外边界压力变化很小，所以外边界采用定压外边界。在污染过程的模拟过程中，内边界条件为定产量生产。

对于浓度方程，内、外边界均采用定浓度，其中外边界浓度为临界浓度。

2.3 模拟参数

所采用的模拟参数详见表 1。

表 1 模拟参数

Table 1 Simulation parameters

参数	取值	参数	取值
原始地层孔隙度(%)	30.0	胶质、沥青质颗粒密度(个/m^3)	2×10^{14}
地层有效厚度(m)	22.0	初始颗粒半径(m)	2×10^{-8}
原始渗透率(μm^2)	1.6	原油粘度(mPa·s)	57
伤害后地层平均渗透率(μm^2)	0.774	溶剂粘度(mPa·s)	3
井筒半径(m)	0.1	临界浓度(m^3/m^3)	0.01
原始地层压力(MPa)	15	综合压缩系数(1/MPa)	5×10^{-4}

3 求解方法

本模型的 3 个主要方程，即连续性方程、对流—扩散—吸附方程和胶质、沥青质颗粒溶解方程都是非线性方程，无法直接得到其解析解，这里采用有限差分法。求解的顺序是：(1)解连续性方程，得到压力场，再由达西定律获得流体的流动速度场；(2)求解对流—扩散—吸附方程，获得溶剂的浓度分布；(3)求解胶质、沥青质颗粒溶解方程，获得颗粒的半径。利用新的颗粒半径，再回到第一步，这样反复循环，直到模拟时间结束。

4 模拟结果及分析

4.1 溶剂浓度和渗透率分布

图 1 是向地层中注入 $20m^3$ 溶剂，在 1d 内连续注入，然后闷井，溶剂浓度分别在 0.5d 和 1d 时的浓度分布图，可以看出溶剂浓度前缘随时间增长而不断向外扩展。若以溶剂浓度 0.1 为前缘，在闷井时间为 0.5d 和 1d 时，扩散半径分别是 3m 和 4m，高浓度区集中在近井带几米之内。图 2 是初始时刻和注溶剂结束后的渗透率分布图。在初始时刻是有机伤害后的渗透率分布，距离井越近，渗透率伤害越严重；注溶剂结束后，由于溶剂对孔隙内的有机垢的溶解作用，使得井筒附近的渗透率升高幅度较远离井筒的油层的渗透率大。

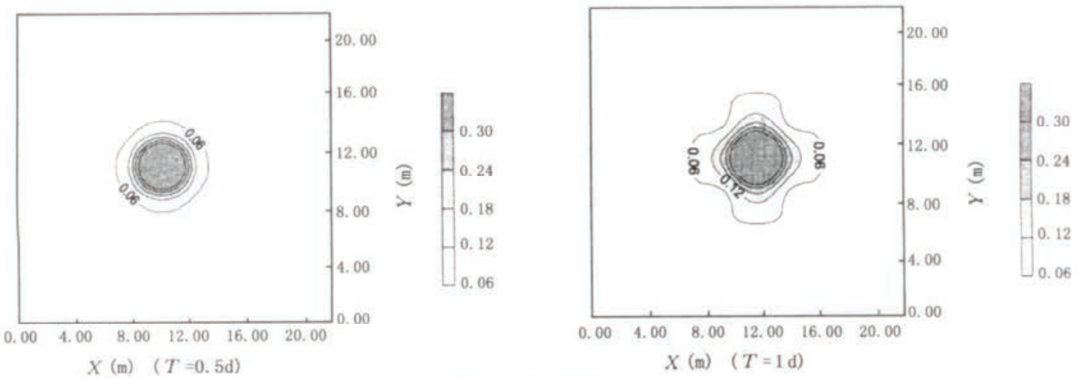

图 1　溶剂浓度分布

Fig. 1　Distribution of solvent concentration

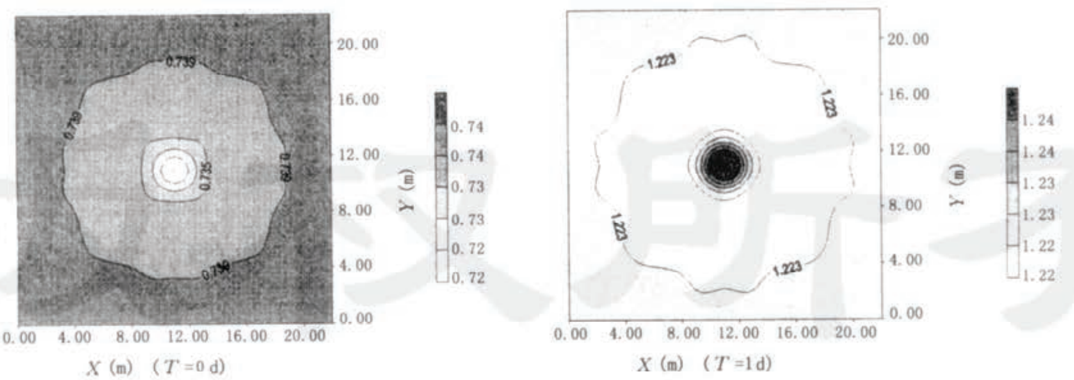

图 2　渗透率分布

Fig. 2　Distribution of permeability

4.2 溶剂注入量与改善流度关系

向地层内分别注入 10、15、20、25、$30m^3$ 的溶剂，在模拟中假设均在一天内连续注入，从第二天起闷井 4d，

得到不同量的注入量下近井带(半径 5m)内溶剂和油层原油组成的体系的流度改善百分数对比图(图 3)。因为溶剂在地层内不仅对孔隙介质起作用,同时也对地层原油起到降粘作用,为综合进行评价,用流度来评价改善效果。从图 3 中看出,从 $10m^3$ 到 $30m^3$,改善效果不断增强,但是增长的趋势是不断递减的,也就是说改善效果与溶剂注入量并不是线性关系。

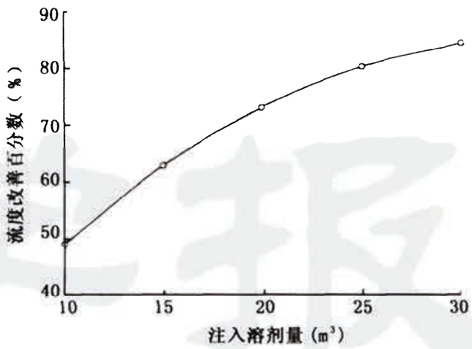

图 3　流度改善图

Fig. 3　Improvement of mobility

4.3　闷井时间与解堵效果关系

图 4 中的 3 条曲线 a、b、c 分别是 10、15、$20m^3$ 3 个溶剂量下流度随时间变化曲线,从图中可以看出,进入闷井阶段(1d 后),流度增长趋势逐步变缓,建议闷井时间为 1～2d。

4.4　注入速度对流度改善效果的影响

图 5 是以不同的注入速度注入油层,在两天后流度改善对比图。从图中可以看出,总注入溶剂量一定时,以较缓慢的速度注入,改善效果较好。

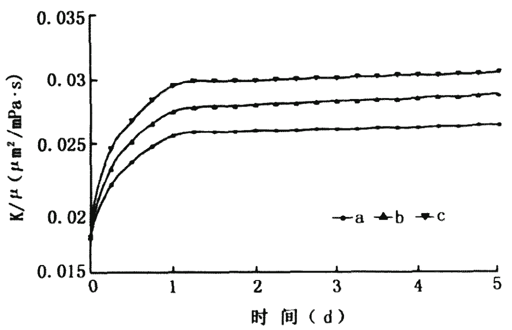

图 4　流度与闷井时间关系

Fig. 4　Relationships between mobility and soak time

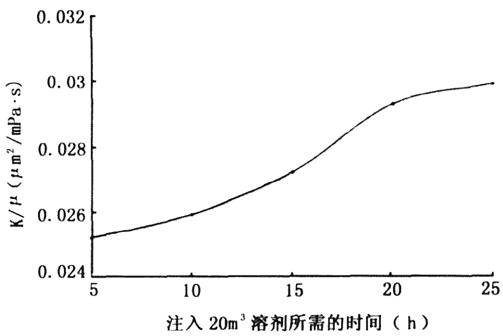

图 5　流度与注入速度关系

Fig. 5　Relationships between mobility and injection rates

4.5　流度变化

图 6 是近井地带地层原油流度的变化曲线。在这条曲线上,分 3 个阶段,第 1d 为溶剂注入阶段,然后闷井 4d,从第 5d 开始进入生产阶段。从图中看出,在注入阶段,原油流度迅速提高;在闷井阶段,流度缓慢增加;在生产阶段,流度先经历了一个迅速下降阶段,然后进入平稳下降阶段。这主要是因为,刚进入生产阶段,近井带内含有较高浓度溶剂且粘度较低的原油很快地被采出,几天之后就会进入平稳下降阶段。

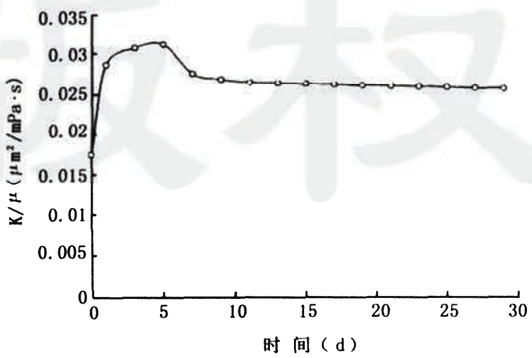

图 6　流度与时间关系

Fig. 6　Relationships between mobility and time

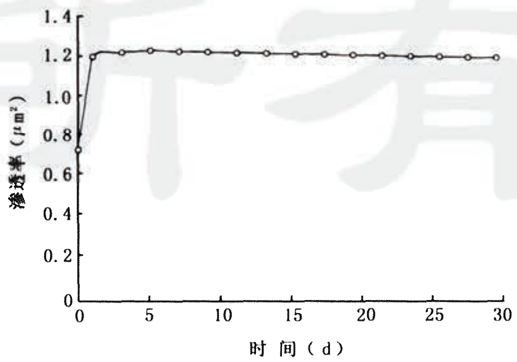

图 7　渗透率与时间关系

Fig. 7　Relationships between permeability and time

4.6 近井带渗透率变化

图 7 是解堵后的渗透率变化曲线,同前面的流度变化曲线相比,恢复生产后渗透率的变化没有流度变化剧烈。由此也可以看出,在解堵后投产的初期,日产油量的增加是由地层渗透性的改善和溶剂对地层原油的降粘共同作用的结果,但随着近井带溶剂降粘后的原油的采出,产能的增加主要靠地层渗透率的改善。

5 结 论

1. 本模型既能成功地模拟采用溶剂吞吐方法解除有机垢造成的渗透率伤害问题,也能够模拟有机垢对油层造成的伤害过程。

2. 通过单井溶剂吞吐模拟,可方便地为矿场施工参数提供依据,并可以预测施工后的生产动态。

3. 模拟实例结果表明,溶剂的注入速度是影响改善效果的重要因素之一,一定的溶剂量,缓慢地注入较急速地注入效果要好。

4. 注入量对解堵的范围和效果影响较大,对于近井带范围来说,渗透率的提高与溶剂量增加并不成直线关系,超过了一定的量,增加趋势会逐步变缓。闷井时间不必太长,超过一定时间(约 1d)后,改善效果随闷井时间延续而增强的非常缓慢,最佳闷井时间为 1～2d。

5. 产能的增加是溶剂对油层的渗透性改善和地层原油降粘共同作用的结果,前者的改善效果较后者更持久。从模拟结果看,两个月后同解堵前相比,仍然增产 35%,解堵有效期至少在半年以上。

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characterized with complex, a mass of work, difficult to manage and high cost. It was difficult to develop remaining oil fully by the mode of division of injection-production wells, so the author put forward a new idea about developing remaining oil and improve water flood EOR in heterogeneous medium and low permeability oil field—separate-layer injection-production development mode in the same well, and water flood EOR can improve 3. 7 percent over standard value by use of this mode through effect prediction in the south of Putaohua oil field in Daqing.

Key words: remaining oil; separate-layer injection-production in the same well; improve EOR, new mode

STUDY ON THE MECHANISM OF POLYMER SOLUTION WITH VISCO-ELASTIC BEHAVIOR INCREASING MICROSCOPIC OIL DISPLACEMENT EFFICIENCY

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Abstract: In this paper, the visco-elastic characteristics of polyacrylamide solution have been studied experimentally. Based on the forms of residual oil after water flooding in porous media and flowing behavior of polymer solution, the mechanisms of the effect of polymer solution with visco-elastic characteristic on each type of residual oil after water flooding had been analyzed and the mechanisms of polymer solution with visco-elastic characteristic increasing microscopic oil displacement efficiency were studied. By the analysis of microscopic experiments of percolating flow, relevant relationships between the characteristic parameter describing the visco-elastic behavior of polymer solution and displacement efficiency of residual oil in "dead ends" were given. It is shown that the larger the visco-elastic behavior of polymer solution, the higher the displacement efficiency of residual oil in "dead ends". The residual oil can be pulled into "oil threads" by the polyacrylamide solution, and a new type of oil flow channel, i. e. "oil thread" channel, can be formed and residual oil flows downstream through the "oil thread" channel. The probability of forming a steady "oil thread" flow channel in polymer flooding was also analyzed theoretically and proved. The research result indicates that the mechanism of polymer solution microscopically increasing oil recovery is due to the visco-elastic characteristic of the polymer solution, the sweeping force acting on the residual oil by the visco-elastic polymer solution is larger than that of water. The residual oil was not pushed out by the polymer solution but pulled out by the polymer solution. It is also found that every type of residual oil after water flooding can be decreased by visco-elastic polymer solution, and the larger the visco-elastic property, the stronger the capability of the polymer solution to "sweep out" the residual oil.

Key words: polyacrylamide solution; rheological characteristic; viscous-elastic behavior; oil displacement efficiency; mechanism

THE NUMERICAL SIMULATION OF REMOVAL OF ORGANIC FORMATION DAMAGE NEAR THE WELL-BORE

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Abstract: The precipitation or block of asphalts, asphaltenes and other organics in the porous media near the well-bore will reduce permeability due to changes of temperature, pressure and compositions of reservoir oil.

Injection of organic aromatic solvents and soaking is one efficient method to remove the precipitates. A mathematical model to remove the formation damages caused by organic precipates by soaking of aromatic solvents is presented and solved by numerical method. The influences of different injected rate, volume and soak time of solvent had been simulated to improve the permeability of the damaged region. And the permeability is also predicted after soak. The simulated results coincide with the data from oil field.

Key words: asphaltene; formation damage; solvent soak; numerical simulation

MATHEMATICAL MODEL OF NONLINEAR FLOW LAW IN LOW PERMEABILITY POROUS MEDIA AND ITS APPLICATION

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Abstract: Two thousand and four hundred millions tons of proved and undeveloped low-permeability reserves are a great potentiality for Chinese petroleum industry to develop. A problem on nonlinear flow in low-permeability porous media is a basic one in exploiting low-permeability oil and gas fields. It is also one of up-to-date research fields of modern mechanics of fluids in porous media. It is the first time that a mathematical model expressed in a continuous function for the nonlinear flow was established based on experiments. It lays a foundation of studying the nonlinear flow from qualitative analysis to quantitative one. Nonlinear mathematical models for steady and unsteady flow are given according to the model. Formulas of pressure distributions are presented. A formula of pressure disturbance radius of the unsteady flow is derived by means of average conservation of mass. An example is discussed on the authority of experiments. Pressure distributions and a movement law of the radius for the nonlinear flow, and their comparisons with those for the linear flow are obtained. It is shown that there is much difference between results based on nonlinear flow law and linear flow law. Thus, it is necessary that influence of nonlinear flow on development indexes of the fields be taken into account.

Key words: low permeability reservoir; nonlinear flow; mathematical model; pressure disturbance radius; average conservation of mass

THE CHANGE OF THE VARIOGRAM FUNCTION AND THE VARYING RULE OF THE POROSITY IN THE COURSE OF WATER FLOODING

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Abstract: The variation of the porosity in different microfacies during the development of hydrocarbon is different. In the clustered channel facies, the distribution of porosity is controlled obviously by the width and shape of the single channel during the early production stage. The perpendicular variogram range of the porosity during the later production stage becomes greater, the distribution of the porosity becomes wider and more even, and the vertical heterogeneity becomes more intensive, because the clay minerals between grains were taken away by the fluids in water flooding performance, and the high mud content barrier between