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介质变形引起地层孔渗变化条件下的试井分析

Well test analysis under the variation of porosity and permeability caused by formation deformation

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摘要: 储层介质变形分为弹性变形、塑性变形和弹塑性变形 3 种类型. 重点研究了介质塑性变形后地层孔隙度和渗透率变化条件下的不稳定渗流问题. 建立了孔隙度、渗透率指数变化规律的试井分析模型, 通过有限元方法得到了井底压力随时间变化的双对数理论曲线, 并对理论曲线的特征进行了分析. 通过实际井例分析, 说明变孔渗试井模型具有较好的应用效果.

关键词: 变形介质; 不稳定渗流; 试井分析
中图分类号: TE312　　文献标识码: A

变形介质油藏可分为 3 种类型: 弹性变形介质油藏、塑性变形介质油藏和弹塑性变形介质油藏[1]. 过去的研究主要集中在弹性变形介质油藏, 主要理论依据是孔隙度和渗透率随孔隙压力变化. 这一理论的主要来源是 Raghavan[2]1972 年提出的理论和葛家理[3]1982 年的分析理论. 对于塑性变形介质油藏和弹塑性变形介质油藏国内外研究较少. 本文重点研究介质塑性变形后对渗流的影响.

介质变形的油藏中有两类是非常明显的, 一类是深层高温高压油藏, 另一类是低渗透油藏. 容易产生塑性变形的油藏主要是胶结砂岩油藏、泥质砂岩油藏和低压低渗油藏. 关于变形介质油藏的渗流理论, 国内外曾进行过大量的研究[4-7]. 这些研究大多是以渗透率随压力呈单段指数变化规律为基础的. 由于孔隙度变化相对渗透率变化较小, 忽略孔隙度变化的影响.

笔者给出了孔隙度、渗透率变化的指数变化模式, 建立了介质变形后变孔渗试井分析模型. 应用文献[8, 9]介绍的数值计算方法对数学模型进行求解, 并分析了理论压力曲线的特征.

1　变形介质试井理论模型

1.1　物理模型

①储层为水平、等厚、各向同性的均质孔隙介质, 发生塑性变形后, 孔渗沿径向发生变化; ②储层内流体为微可压缩的牛顿流体; ③忽略重力和毛管力的影响; ④存在井储和表皮效应的影响.

假定所有的变形都是完全不可逆的, 那么根据文献[1]的研究可以假定地层参数随地层距离呈指数变化, 即

$$k(r) = k_{avg} e^{-\frac{r_w}{r}\ln(k_{min}/k_{avg})},$$

$$\varphi(r) = \varphi_{avg} e^{-\frac{r_w}{r}\ln(\varphi_{min}/\varphi_{avg})}.$$

如果 $r = r_w$, 那么由 $k(r_w) = k_{avg} e^{-\frac{r_w}{r}\ln(\varphi_{min}/\varphi_{avg})}$ 可知, $k = k_{min}$; 如果 $r \to \infty$, $k = k_{avg}$. 同上可知, $r = r_w$, $\varphi = \varphi_{min}$; $r \to \infty$, $\varphi = \varphi_{avg}$.

定义油藏无因次渗透率变化 $k_D(r_D) = e^{-\frac{1}{r_D}\ln k_{0D}}$, 无因次孔隙度变化 $\varphi_D(r_D) = e^{-\frac{1}{r_D}\ln\varphi_{0D}}$. 式中, $r_D = \frac{r}{r_w}$, $k_{0D} = \frac{k_{min}}{k_{avg}}$, $\varphi_{0D} = \frac{\varphi_{min}}{\varphi_{avg}}$.

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令 $\alpha_D = -\ln\varphi_{0D}$, $\beta_D = -\ln k_{0D}$, 由 $\varphi_{min} \le \varphi_{avg}$, $k_{min} \le k_{avg}$, 可知 $\alpha_D \ge 0$, $\beta_D \ge 0$.

对于孔隙度和渗透率沿径向由大变小的情况, 以上各式中的 φ_{min} 和 k_{min} 变为 φ_{max} 和 k_{max}, $\alpha_D \le 0$, $\beta_D \le 0$.

1.2　数学模型

根据物理模型的描述, 由流体在地层中流动的连续性方程和运动方程, 可以得到如下的数学模型:

总的控制方程

$$\frac{1}{r}\frac{\partial}{\partial r}\left[rk(r)\frac{\partial p(r,t)}{\partial r}\right] = \varphi(r)\mu C_t \times \frac{\partial p(r,t)}{\partial t}. \tag{1}$$

初始条件 $p|_{t=0} = p_i$, (2)

内边界条件 $r\frac{\partial p}{\partial r}\Big|_{r=r_w} = \frac{1.842\times10^{-3}q\mu B}{kh} - C\frac{\mathrm{d}p_w}{\mathrm{d}t}$, (3)

外边界条件中, 无限大边界 $p|_{r\to\infty} = p_i$, (4)

定压边界 $p|_{r=r_e} = p_i$, (5)

封闭边界 $r\frac{\partial p}{\partial r}\Big|_{r=r_e} = 0$. (6)

定义以下无因次变量:

无因次压力 $p_D = \frac{k_{avg}h}{1.842\times10^{-3}qB\mu}(p_i - p)$,

无因次距离 $R_D = \frac{r}{r_w e^{-S}}$,

无因次井筒储存系数 $C_D = \frac{C}{2\pi h\varphi C_t r_w^2}$,

无因次时间 $t_D = \frac{3.6k_{avg}}{\varphi\mu C_t r_w^2}$.

令 $T_D = t_D/C_D$. 将以上模型进行无量纲化处理, 可以得到如下具有一定普适性的无量纲方程:

控制方程

$$k_D(R_D)\frac{\partial^2 p_D}{\partial R_D^2} + \frac{1}{R_D}k_D(R_D)\frac{\partial p_D}{\partial R_D} + \frac{\partial k_D(R_D)}{\partial R_D}\cdot\frac{\partial p_D}{\partial R_D} = \frac{\varphi_D(R_D)}{C_D e^{2S}}\cdot\frac{\partial p_D}{\partial T_D}. \tag{7}$$

初始条件 $p_D|_{T_D=0} = 0$, (8)

内边界条件 $R_D\frac{\partial p_D}{\partial R_D}\Big|_{R_D=1} = -1 + \frac{\partial p_{wD}}{\partial T_D}$, (9)

外边界条件中, 无限大边界 $p_D|_{R_D\to\infty} = 0$, (10)

定压边界 $p_D|_{R_D=R_{eD}} = 0$, (11)

封闭边界 $R_D\frac{\partial p_D}{\partial R_D}\Big|_{R_D=R_{eD}} = 0$. (12)

式中, B 为地层体积系数, m^3/m^3; C 为井筒存储系数, m^3/MPa; C_t 为总压缩系数, MPa^{-1}; h 为地层有效厚度, m; k 为油藏渗透率, $10^{-3}\mu m^2$; k_{min} 为油藏最小渗透率, $10^{-3}\mu m^2$; k_{max} 为油藏最大渗透率, $10^{-3}\mu m^2$; k_{avg} 为油藏平均渗透率, $10^{-3}\mu m^2$; p 为地层压力, MPa; p_i 为地层原始压力, MPa; p_w 为井筒压力, MPa; q 为井的产量, m^3/d; r 为距井点的距离, m; r_w 为油井半径, m; r_e 为油藏半径, m; φ 为油藏孔隙度; φ_{min} 为油藏最小孔隙度; φ_{max} 为油藏最大孔隙度; φ_{avg} 为油藏平均孔隙度; μ 为地层中流体的黏度, mPa·s.

2　数学模型的求解及理论曲线特征分析

由于模型的复杂性, 很难求得该试井模型的解析解, 因此选择有限元方法对这一问题求数值解. 首先, 对所研究的油藏进行非结构化网格划分, 类似文献[4, 5]所提供的方法, 对所研究的油藏绘制成如图 1 所示的网格, 近井区域的网格如图 2 所示.

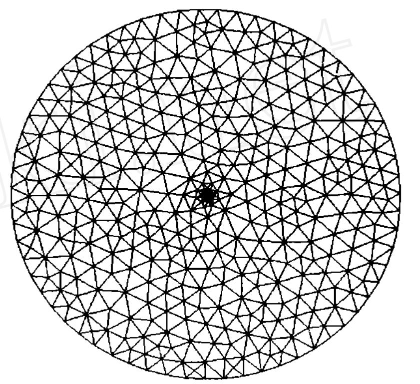

图 1　所研究油藏的三角形网格图

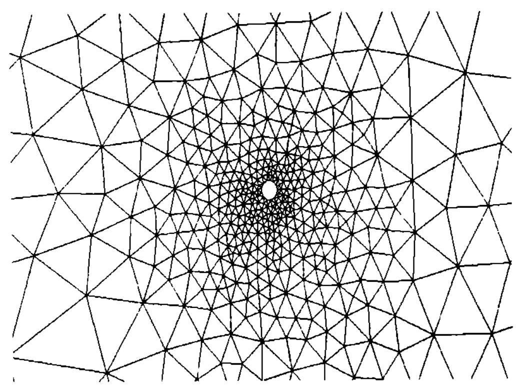

图 2　近井区域的网格图

利用伽辽金法, 取权函数等于插值函数 φ_i, 并令在单元整个区域上加权余量的积分为零, 将模型变为有限元方程

$$\iint_A \varphi_i\left[k_D(R_D)\frac{\partial^2 p_D}{\partial R_D^2} + \frac{1}{R_D}k_D(R_D)\frac{\partial p_D}{\partial R_D} + \frac{\partial k_D(R_D)}{\partial R_D}\cdot\frac{\partial p_D}{\partial R_D} - \frac{\varphi_D(R_D)}{C_D e^{2S}}\frac{\partial p_D}{\partial T_D}\right]\mathrm{d}A = 0, \tag{13}$$

式中, φ_i 为单元插值函数, 取线性插值 $\varphi_i = a_i +$

$b_i x + c_i y$, $i = 1, 2, 3$. 其中, $\frac{\partial \varphi_i^e}{\partial x} = b_i$; $\frac{\partial \varphi_i^e}{\partial y} = c_i$;

$$a_1 = \frac{1}{2A}(x_2 y_3 - x_3 y_2),\ a_2 = \frac{1}{2A}(x_3 y_1 - x_1 y_3),$$

$$a_3 = \frac{1}{2A}(x_1 y_2 - x_2 y_1);$$

$$b_1 = \frac{1}{2A}(y_2 - y_3),\ b_2 = \frac{1}{2A}(y_3 - y_1),$$

$$b_3 = \frac{1}{2A}(y_1 - y_2);$$

$$c_1 = \frac{1}{2A}(x_3 - x_2),\ c_2 = \frac{1}{2A}(x_1 - x_3),$$

$$c_3 = \frac{1}{2A}(x_2 - x_1);$$

A 为三角形的面积, 即

$$A_1 = \frac{1}{2}\begin{vmatrix} 1 & 1 & 1 \\ x_1 & x_2 & x_3 \\ y_1 & y_2 & y_3 \end{vmatrix}$$

$$= \frac{1}{2}(x_2 y_3 + x_1 y_2 + x_3 y_1 - x_2 y_1 - x_3 y_2 - x_1 y_3).$$

根据图 3 所列的计算机框图编制了相应的有限元计算程序. 通过有限元计算, 可以得到井底压力随时间变化的双对数理论曲线, 如图 4 所示.

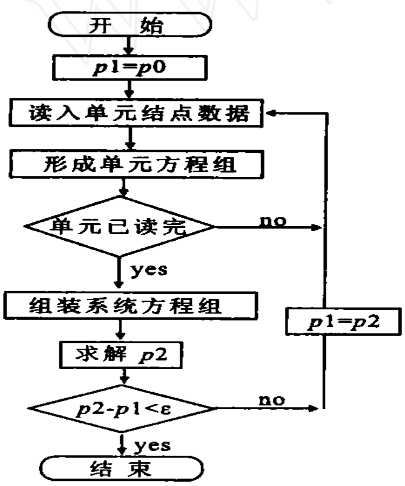

图 3　有限元程序计算框图

从图 4 可以看出: 由于考虑了介质变形后孔隙度和渗透率的变化, 因此在中、后期, 压力导数值不再象常规无限大油藏那样恒等于 0.5, 而是导数曲线上翘, 孔隙介质变形越严重, 上翘程度越大. 介质变形主要影响曲线的中、后期形态, 而对早期纯井储段曲线的特征影响不大. 在早期纯井储段, 曲线特征与常规油藏的相同, 是一条斜率为 45° 的直线.

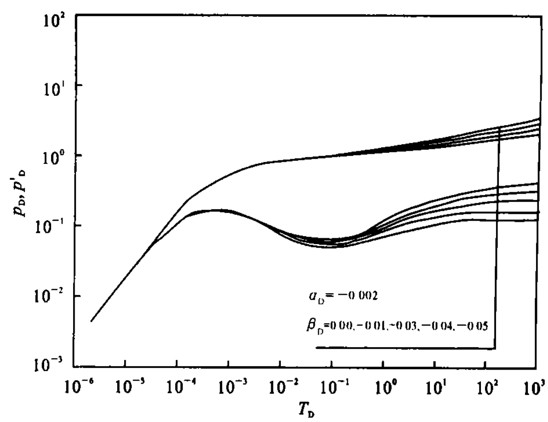

图 4　孔隙度、渗透率指数变化对理论曲线的影响

3　实际井例分析

为了说明模型的使用情况, 选择了我国某油田的一口地质情况比较清楚的测试井作为实例井进行分析. 已知油藏厚度为 5.32 m, 孔隙度为 0.23%, 地层体积系数为 1.08, 综合压缩系数为 0.001 45, 井的半径为 0.1 m, 流量为 20 m^3/d. 首先按常规油藏封闭边界模型解释, 然后按变形介质模型进行解释, 分析成果见表 1.

表 1　实际井例分析成果对照表

参数	常规介质模型	变形介质模型
渗透率 /$10^{-3}\mu m^2$	18.79	地层: 18.95 井底: 28.52
表皮系数	5.4	5.0
井筒存储系数 /($m^3 \cdot MPa^{-1}$)	0.053 2	0.047 3
边界/m	封闭边界 1: 132 封闭边界 2: 183 封闭边界 3: 224 封闭边界 4: 350	/

计算得到的表皮系数 $S \approx 5$, 说明井底存在污染. 从该井的地质资料看, 该井所在区块没有任何边界或断层, 但采用常规油藏模型分析时只能加边界使压力导数曲线上翘才能得到较好的拟合. 另外在短短的 24 h 之内, 对于渗透率为 $18.79 \times 10^{-3}\ \mu m^2$ 的地层, 压力波传播到 300 m 之外是不合理的, 虽然实测压力曲线与理论曲线拟合(图 5)的形态较好, 但结果是不可信的. 利用变形介质油藏模型分析可以得到压力导数曲线上翘的根本原因. 由于该井是一口注水井, 地层为胶结砂岩, 在注水过程中使近井地带的地层发生变形, 导致渗透率从 $18.95 \times 10^{-3}\mu m^2$ 增大到井底附近的 $28.52 \times 10^{-3}\mu m^2$. 实测

压力曲线与变形介质模型理论曲线拟合见图6.

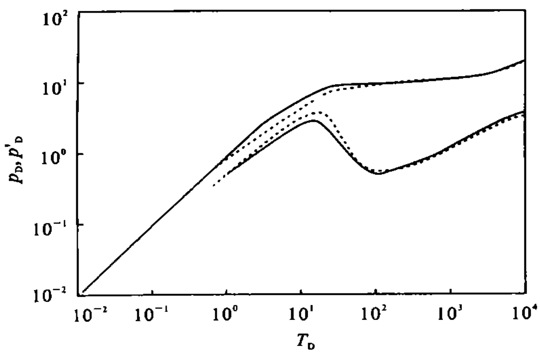

图5 常规均质模型拟合分析图

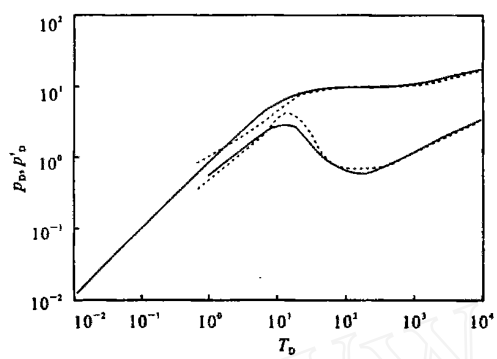

图6 变形介质模型拟合分析图

4 结论

(1)建立了变形介质无限大地层、圆形定压和圆形封闭外边界地层条件下,考虑井筒储存和表皮效应影响的不稳定渗流数学模型,用数值法求解,绘制出相应的压力及其导数典型曲线.

(2)变形介质的影响主要集中在井筒附近.离井筒越远,孔隙度和渗透率变化越小.

(3)通过对不稳定渗流压力动态理论曲线的分析表明,变形介质特性主要影响曲线的中、后期形态,而对曲线的早期形态影响不大.变形介质油藏压力导数曲线的早期纯井储段仍为斜率为1的直线,而其径向流段不再为0.5的水平线,而是导数曲线不断上翘,介质变形越严重,上翘也越高,并且最后趋于水平直线段.

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Shang-741 well-block are divided. The reservoir characteristics of the igneous rock in the area are analyzed. The formulas of calculating the occurrence and opening degree of fracture and the porosity, the permeability and saturation of igneous rock reservoir are also presented, and the evaluation of this kind of reservoir can be carried out according to the five parameters. Through the evaluation of the reservoir in this area, the effective fracture belt and the crude oil distribution in this area are determined. The study result in this paper can guide the design of development plan of this area.

Key words: Shang-741 wellblock; igneous rock; fracture system; reservoir evaluation

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Well test analysis under the variation of porosity and permeability caused by formation deformation

Abstract: The deformation of reservoir media can be divided into three types: elastic, plastic and elastic-plastic deformation. The porosity and the permeability of reservoir are changing as the reservoir media is deforming. The transient flow of the fluid in plastically deformed reservoir is studied in this paper. The well test model is established under the exponential change laws of the porosity and the permeability. Wellbore pressure-time curves are gained by finite element method and their characteristics are analyzed. The application of the well test model is demonstrated by a case, and the satisfied results are got.

Key words: deformed media; transient flow in porous media; well test analysis

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Geological risk analysis in multi-well drilling prospect plan of new exploration areas

Abstract: There are many uncertainties in oil and gas exploration, which result in risks. Especially, because of lack of data, there are higher risks in new area exploration. The risks come from geological complexities, technical factors, financial factors and political factors, and the risks from geological complexities is the primary. The authors put forward a method to analyze the success ratios of the different multi-well drilling prospect plans by using binomial distribution probability model. This method only needs a few data and therefore it is very suitable to the drilling prospect in new areas. The predicted success ratios can be used as the worst outcomes for supplying decision reference to investors.

Key words: new exploration area; multi-well drilling prospect; risk analysis; binomial distribution probability model

SHI Bao-hong, HAN Zong-wen, KANG Yong-shang (Research Institute of Petroleum and Natural Gas Geology, Xi'an Shiyou University, Xi'an 710065, Shaanxi, China) JXSYU 2004 V. 19 N. 2 p. 21-24

Prediction of development indexes of heavy oil reservoir steam-injecting production

Abstract: Logarithm normal distribution model, Compertz model and injection-production curve are selected as production prediction model, water-cut prediction model and oil/gas ratio model respectively. The development indexes can be predicted by simultaneously solving the three models. The result of a case shows that the development indexes and whole development process can be predicted by this method, and this can supply basis for development planning and reservoir engineering design of heavy oil reservoirs.

Key words: heavy oil reservoir; steam injection; development index; prediction model

MIN Ling-yuan, SUN Jian-fang, HAO Lin (Research Institute of Geosciences, Shengli Oilfield Co. Ltd., Dongying 257015, Shandong, China) JXSYU 2004 V. 19 N. 2 p. 25-26

Experimental study on increasing recovery factor of light oil reservoir by air injection

Abstract: Abroad, a lot of experimental study is carried out on increasing the recovery factor of light oil reservoir by air injection, and some field test results are also obtained. But at home, the study is only in beginning. The thin crude oil of Shanshan oilfield is taken as experimental sample, its oxidation rate and oxygen consumption at different temperatures, the temperature of taking place high-temperature oxidation, the lowest supply volume of air for maintaining high-temperature oxidation and the recovery factor of air injection displacement oil are studied in the paper.

Key words: light oil reservoir; air injection; low-temperature oxidation; high-temperature oxidation;