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考虑幂律性的稠油油藏调和递减方程

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摘要: 稠油的渗流过程具有明显的非牛顿幂律性,目前常用的 Aprs 递减模型未考虑稠油的幂律性对产量递减规律的影响。基于幂律性的稠油油藏产量方程和相渗曲线,重新推导了调和递减方程,利用新建的产量方程,可分析幂律性对稠油油藏产量的影响,预测其产量及递减规律。实例应用结果表明,稠油的幂律性对产量递减规律影响显著,幂律指数越小,油井产量越低,递减速度越快;幂律指数对递减率的影响主要表现在油田生产初期,而生产一段时间后,不同幂律指数下的递减率逐渐趋于一致;当幂律指数大于 0.8 时,幂律指数对产量和递减率的影响相对较小。

关键词: 稠油 幂律性 调和递减 产量方程 相渗曲线 递减规律
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稠油油藏开发是目前石油工业稳定发展的重要基础之一。稠油渗流具有较强的非牛顿流体渗流特征,即幂律性,前人关于稠油油藏的幂律性对产量的影响[1-2]进行了大量研究。对于预测注水油藏开发指标而言,经典的 Arps 递减模型[3-10]是目前应用最广泛的方法之一,由于该方法未考虑稠油油藏的流体特征,其产量递减规律能否沿用常规油藏的分析方法需要进一步验证。笔者在考虑幂律性稠油油藏产量方程和相渗曲线的基础上,从渗流理论出发,重新推导了 Aprs 递减模型中的调和递减方程,并进行了应用分析。

1 幂律性稠油油藏产量方程

考虑幂律性稠油油藏的产量方程[11-12]为

$$q_o=2\pi h\left(\frac{\Delta p}{\frac{1}{KK_{ro}}\times\frac{C\left(3+\frac{1}{n}\right)^n}{4\left(\sqrt{8KK_{ro}\phi}\right)^{n-1}}\times\frac{\left(r_e^{\,1-n}-r_w^{\,1-n}\right)}{1-n}}\right)^{\frac{1}{n}}\tag{1}$$

式中: q_o为油井的产量, m^3/s; h 为地层厚度, m; Δp 为生产压差, MPa; K 为绝对渗透率, μm^2; K_{ro}为油相相对渗透率; C 为稠度系数, $Pa\cdot s^n$; n 为幂律指数; ϕ 为孔隙度; r_e为油藏边界半径, m; r_w为井筒半径, m。

油田刚投入生产时,其油相相对渗透率为 1, 油井初始产量为

$$q_i=2\pi h\left(\frac{\Delta p}{\frac{1}{K}\times\frac{C\left(3+\frac{1}{n}\right)^n}{4\left(\sqrt{8K\phi}\right)^{n-1}}\times\frac{\left(r_e^{\,1-n}-r_w^{\,1-n}\right)}{1-n}}\right)^{\frac{1}{n}}\tag{2}$$

式中: q_i为油井初始产量, m^3/s。

由式(1)和式(2)可得

$$q_o=q_iK_{ro}^{\frac{n+1}{2n}}\tag{3}$$

从式(3)可以看出,随着生产的不断进行,油相相对渗透率逐渐下降,产量递减。

2 广义调和递减方程

在注采平衡的条件下,产量与地层含水饱和度之间的关系[13]为

$$\frac{dS_w}{dt}=\frac{q_oB_o}{V\phi}\tag{4}$$

式中: S_w为含水饱和度; t 为时间, s; B_o为原油体积系数; V 为油层体积, m^3。

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将式(3)代入式(4)可得

$$\frac{\mathrm{d}S_{\mathrm{w}}}{\mathrm{d}t}=\frac{q_{\mathrm{i}}K_{\mathrm{ro}}^{\frac{n+1}{2n}}B_{\mathrm{o}}}{V\phi} \tag{5}$$

油相相对渗透率与含水饱和度的关系[13]为

$$K_{\mathrm{ro}}(S_{\mathrm{w}})=a\mathrm{e}^{-bS_{\mathrm{w}}} \tag{6}$$

式中：a 与 b 均为常数。

将式(6)代入式(5)，并积分，可得

$$\int_{S_{\mathrm{wi}}}^{S_{\mathrm{w}}}\frac{\mathrm{d}S_{\mathrm{w}}}{\left(a\mathrm{e}^{-bS_{\mathrm{w}}}\right)^{\frac{n+1}{2n}}}=\int_{0}^{t}\frac{q_{\mathrm{i}}B_{\mathrm{o}}}{V\phi}\mathrm{d}t \tag{7}$$

式中：S_{wi} 为束缚水饱和度。

对式(7)积分可得

$$\mathrm{e}^{bS_{\mathrm{w}}}=a\left(\frac{q_{\mathrm{i}}B_{\mathrm{o}}}{V\phi}\times\frac{n+1}{2n}bt+1\right)^{\frac{2n}{n+1}} \tag{8}$$

由式(4)、式(6)和式(8)可得

$$q_{\mathrm{o}}=q_{\mathrm{i}}\left(\frac{q_{\mathrm{i}}B_{\mathrm{o}}}{V\phi}\times\frac{n+1}{2n}bt+1\right)^{-1} \tag{9}$$

令 $D_{\mathrm{i}}=\frac{q_{\mathrm{i}}B_{\mathrm{o}}}{V\phi}b$，$m=\frac{2n}{n+1}$，则式(9)可简化为

$$q_{\mathrm{o}}=q_{\mathrm{i}}\left(\frac{D_{\mathrm{i}}}{m}t+1\right)^{-1} \tag{10}$$

式(10)即为广义调和递减方程，该式与 Aprs 调和递减模型具有严格的一致性。在不考虑稠油的幂律性时，即 $n=1$ 时，式(10)可简化为

$$q_{\mathrm{o}}=q_{\mathrm{i}}\left(D_{\mathrm{i}}t+1\right)^{-1} \tag{11}$$

式(11)即为 Aprs 调和递减模型中的调和递减方程，该方程是广义调和递减方程的一个特例。

3　实例应用

渤海绥中油田 G 区是典型的重质稠油油藏，平均渗透率为 $1\ 320\times10^{-3}\ \mu\mathrm{m}^2$，孔隙度为 28%，地下原油粘度为 200～250 mPa·s，石油地质储量为 $2\ 900\times10^4\ \mathrm{m}^3$，原油幂律指数为 0.8，束缚水饱和度为 0.21。由研究区相渗曲线(图 1)可知，含水饱和度与油相相对渗透率之间存在明显的指数关系。根据式(10)可预测该油田的年产油量、累积产油量和年递减率(图 2)。

由图 2 可知，原油的幂律指数对油藏产量的影响十分显著，幂律指数越小，即非牛顿流体渗流特征越强，原油在流动过程中需要克服的阻力越大，递减速度越快，年产油量和累积产油量越低；幂律指数对递减率的影响主要表现在油田生产初期，而当油田生产一段时间之后，递减率逐渐趋于一致；无论是产量还是递减率，当幂律指数大于 0.8 时，幂律指数对二者的影响均相对较小。

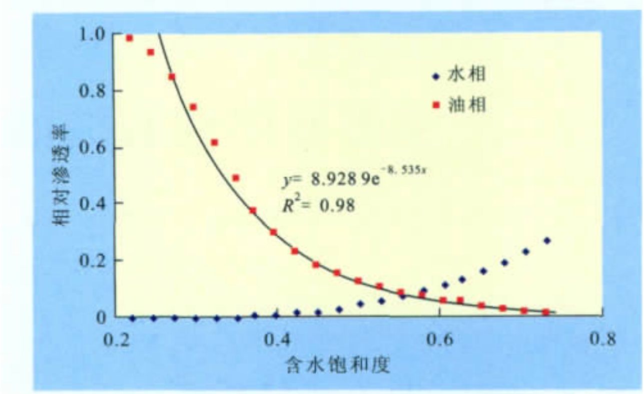

图 1　渤海绥中油田 G 区相渗曲线

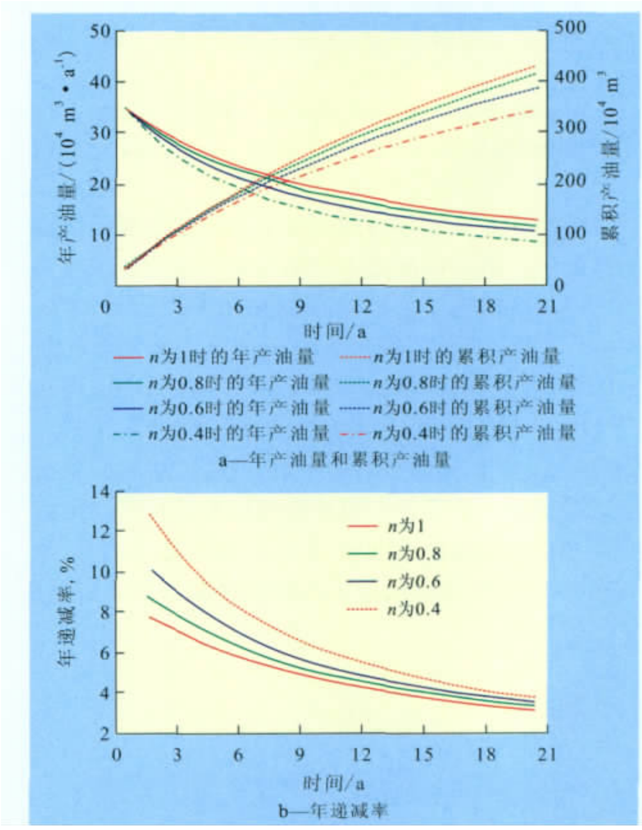

图 2　渤海绥中油田 G 区生产曲线

随着生产的不断进行，稠油油藏的产量呈现不同程度的递减，考虑幂律性的稠油油藏递减规律明显不同于牛顿流体的常规油藏(n 为 1)。

4　结论

在考虑稠油幂律性的基础上，结合油田相对渗透率曲线特征，推导了 Aprs 递减模型中的广义调和

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依据式(15)绘制实际值与计算值的 $f_w—R^*$ 的关系图(图 4)。从图 4 可见,式(1)和式(2)的计算值与实际值相差甚远,而式(15)的计算值与实际值拟合相对较好,可以用于预测含水率上升规律。

实例分析结果表明,新型水驱特征曲线在中低含水阶段适用性较好,但随着含水率的逐渐上升,在高含水、特高含水阶段其适应性有所降低,相对实际值而言,预测值会出现较大误差。在实际应用过程中,应结合实际生产动态资料,在合理开发阶段运用该水驱特征曲线进行动态分析及可采储量的预测。

6　结论

依据 2 个双对数广义水驱特征曲线方程推导了一种新型水驱特征曲线,由于 n 取值不同,该水驱特征曲线的 $f_w—R^*$ 关系图不是一条曲线而是一系列曲线的组合,适用范围相对较广。

通过分析 $f_w—R^*$ 关系图,选取不同的参数 c 和 n 值,能在图版上呈现出水驱特征曲线从凹型过渡到 S 型再到凸型的过程。由于 n 值的不同决定着曲线类型不同,对于 n 值的选取一般采用试凑法,主要是由于其选取的值一般较小,选取的范围不大,容易找到适合实际油藏的水驱特征曲线。

新型水驱特征曲线在中低含水阶段较为适用,但在高含水、特高含水阶段其适应性有所降低,误差会较大,应在合理的开发阶段使用新型水驱特征曲线。

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递减方程,并结合油田实际生产参数进行了分析。研究结果表明,幂律性对稠油油藏产量影响十分显著,幂律指数越小,即油田原油非牛顿流体渗流特征越强,年递减率越大,年产油量和累积产油量越小;当幂律指数大于 0.8 时,幂律指数对油田生产的影响相对较小。在实际生产中应该尽可能降低原油的非牛顿流体性能,以提高稠油油藏的采收率。

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Ma Kuiqian, Liu Yingxian, Zhang Jun et al. Study of harmonic decline equation considering power law fluid feature for heavy oil reservoir. *PGRE*, 2012,119(4):97–98.

Abstract: It is obvious that there is power law feature for heavy oil, but the normal Aprs decline equation can not describe the power law feature for heavy oil. Aiming at this phenomenon, we conducted the harmonic decline equation based on the production equation and relative permeability curve of heavy oil reservoir. By means of this new equation, we can analyze the production of heavy oil reservoir, and we also can forecast the production decline rule. The solution of the study shows that the power law feature of the heavy oil effects the production decline law obviously, the higher of the power low index, the lower of the production, so, the power law feature should be considered when we forecast the production of the heavy reservoir, so as to make sure that the result of the forecast is reasonable.

Key words: heavy oil; power law; harmonic decline; production equation; relative permeability curve; decline law

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Zhou Peng, Chen Xiaofan, Yue Ping et al. Establishment of a new type of water drive characteristic curve. *PGRE*, 2012, 19(4):99–102.

Abstract: In the analysis and prediction of water drive performance of reservoirs, water–drive characteristic curves used to predict recoverable reserves, recovery efficiency and evaluate reservoir performance in a water–drive oilfield, so, its characteristic curves are widely used in study and field application, but it can only correspond a single relationship between water cut and reserves recovery percent. In order to better reflect and describe the different types of the rising trend of water cut of water drive reservoir, a new type of water drive characteristic curves has been established based on the two existed double logarithmic water flooding characteristic curves. Accordingly, the water cut and degree of recovery can be obtained and then it is taken as a function of style to draw the convex function, S, concave curve type of diagram of this function. The new drive characteristic curves of water has been used in a real field case, by choosing different parameters to predict recoverable reserves in this block, comparing with the actual value and selecting the one with smaller error, we build the best expression of the water drive curve to predict the rising trend of water cut in this block. Through comparative analysis of two instances, the new water drive characteristic curve is more suitable in medium–high water stage, but low feasibility for high and higher water cut stage.

Key words: water drive characteristic curve; recoverable reserves; water cut; recovery percentage of reserves; water drive reservoir

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Lu Cong, Guo Jianchun, Wang Jian et al. Study and application of massive hydraulic fracturing technique in Y104–1C well conglomerate formation. *PGRE*, 2012,19(4):103–105.

Abstract: Aiming at the fact that the southern areas of Bohai conglomerate reservoir natural capacity is low, without obvious interlayer, filter lost badly, and conventional hydraulic fracturing is low in production stimulation, this paper conducted the research and application of technology on Y104–1C well. According to the reservoir geological characteristics and well conditions, the paper studied the fracturing scale, the perforating section, and the optimization of fracturing material selection, as well as field application. We completed the fluid injection into well up to 1000 m^3 with proppant of 120 m^3 at pump displacement rate of 7.2 m^3/min. After treatment, average fluid flowing production achieved 45.2 t/d, average daily oil production at 31.7 t, and the stimulation performance and the economic benefit are remarkable. This well fracturing technique, the successful application in the southern areas of Bohai conglomerate reservoir, is a significant breakthrough, and has provided valuable experience.

Key words: conglomerate; massive hydraulic fracture; perforation; proppant; Bonan area

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Qu Zhanqing, Zhao Yingjie, Wen Qingzhi et al. Fracture parameters optimization in integral fracturing of horizontal well. *PGRE*, 2012,19(4):106–110.

Abstract: Horizontal well fracturing technology has been widely used, and greatly improved low–permeability reservoir production and recovery, it has become a cutting–edge technology of developing low permeability reservoirs. However, the fracturing technology is now only based on the single well fracturing, without considering the impact of well network. This paper studied the entire target block to enhance the recovery of the reservoir, and proposed the basic idea for fracturing parameters optimization design of horizontal well fracturing. Based on the optimization of horizontal well fracturing well pattern, and considering the parameters of horizontal well fracturing, such as the number of fractures, length, spacing, distribution, and angle, we predict the production performance of fractured horizontal wells. By analyzing the impact of each parameter on the cumulative production of oil wells, we got the degree of influence of fracture parameters for the fracturing horizontal well capacity, and got the main factors and secondary factors. On this basis, we obtained the optimized combination of fracture parameters, and achieved a good solution to the problem of a horizon well overall fracturing parameter optimization.

Key words: horizontal wells; integral fracturing; numerical simulation; fracture parameters; optimization design

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