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基于层间均衡驱替的分层注水井层间合理配注方法

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摘要:在长期的水驱过程中,受层间储层物性差异的影响,多层合采油藏层间动用状况差异大,层间矛盾突出。分层注水技术是改善特高含水期层间矛盾的有效方法,其成功的关键是根据各小层的储层物性和动用状况确定各层的配水量。为此,以层间均衡动用为目标,综合考虑储层物性和动用状况,利用Buckley-Leverett非活塞式水驱油理论,建立了注水井分层配水量的计算方法,并编制了计算程序。分析结果表明:层间配水量的差异受油层厚度、剩余油饱和度和调控时间等因素的综合影响;所计算的配水量在给定的调控时间内使各小层达到均衡驱替状态,能够满足分层注水井层间配注的要求。

关键词:多层油藏 层间矛盾 分层注水 计算模型 均衡驱替
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层系细分重组是改善层间驱替不均衡,提高采收率的重要技术[1]。细分重组后的单元层间非均质性依然存在,有些层仍然得不到有效驱替。

对层系细分重组后的单元,采用分层注水技术可有效改善层间驱替不均衡的状况[2-7]。分层注水成功的关键是根据各小层的储层物性和动用状况来确定各层的配水量。目前,分层注水井各层配水量的计算方法主要是依据层间静态参数[5-7],或者以管理人员的生产经验为主。杜庆龙等综合考虑注水井各小层地层系数和其周围各油井方向的渗流阻力系数,建立了利用垂向劈分系数计算注水井分层配水量的方法[8];吴家文等提出了根据各层段剩余油饱和度确定配水量的方法[9];石晓渠等用劈分系数法代替传统的KH法或H法进行注水井层间合理配水量的计算[10],劈分系数包括小层渗透率、油层厚度、油水井连通系数、层间干扰系数、沉积微相影响系数、水井对应的油井数和注采井距等。这些层间配水量的分配方法有的考虑参数较多,且有的参数难以定量化计算,导致难以在矿场推广应用;而且未将层间动用状况与实现层间的均衡动用相结合,使得层间非均衡动用的状况难以大幅度改善。为此,笔者以实现层间均衡驱替为目标,研究了分层配水量的计算方法,以期为分层注水井的层间合理配注提供依据。

1 分层注水井分层配水量计算方法

1.1 计算思路

所谓层间均衡驱替,是指通过调配从分层注水井注到各小层的水量,使各层的采出程度或者剩余油饱和度(或者出口端含水饱和度)相同。

在给定某小层注水量的情况下,根据Buckley-Leverett非活塞式水驱油理论[11],可以计算得到给定时间内小层出口端的含水饱和度;反过来,给定某个出口端的含水饱和度,可以计算得到在给定时间内小层所需的累积注水量,在恒速注水的情况下,可得到小层的平均配水量;因此在总注水量一定的情况下,通过确定给定时间内各层达到均衡驱替时出口端的含水饱和度,使计算得到的各小层的配水量之和与总注水量相等,此时各层的配水量就是各小层在给定时间内实现均衡驱替的配水量。

1.2 给定出口端含水饱和度的分层配水量计算方法

对于多层合采油藏,受层间干扰的影响,即使进入特高含水期后,有的小层含水率很高,但有的小层却很低,甚至未见水。为此,分2种情况建立了给定出口端含水饱和度的分层配水量计算方法。

1.2.1 未见水小层

对于未见水小层,在生产一段时间后,注采井

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间可分为油水两相区和纯油区2部分，此时其中某小层的平均含水饱和度可表示为

$$\overline{S_{wi}} = \frac{\overline{S_w}\phi_i A_i x_{fi} + S_{wc}\phi_i A_i (L - x_{fi})}{\phi_i A_i L}$$

$$i = 1, 2, \cdots, n \tag{1}$$

式中：$\overline{S_{wi}}$ 为第 i 小层的平均含水饱和度；i 为小层序号；$\overline{S_w}$ 为见水前油水两相区的平均含水饱和度；ϕ_i 为第 i 小层的孔隙度；A_i 为第 i 小层的横截面积，m^2；x_{fi} 为第 i 小层油水前缘位置，m；S_{wc} 为束缚水饱和度；L 为注采井距，m。

根据小层的注采数据和储层参数，可得到目前小层的平均含水饱和度，根据式(1)可求得第 i 小层油水前缘位置为

$$x_{fi} = \frac{(\overline{S_{wi}} - S_{wc})L}{\overline{S_w} - S_{wc}} \tag{2}$$

根据Buckley-Leverett非活塞式水驱油理论[11]，T_1 时刻第 i 小层的累积配水量为

$$\int_0^{T_1} Q_i \mathrm{d}t = \frac{x_{fi}\phi_i A_i}{f'_w(S_{wf})} \tag{3}$$

式中：T_1 为注水时间，d；Q_i 为第 i 小层配水量，m^3/d；t 为时间，d；$f_w(S_{wf})$ 为油水前缘含水饱和度对应的含水率；S_{wf} 为油水前缘含水饱和度。

分层注水一段时间后，第 i 小层出口端含水饱和度为 S_{w2i} 时所需要的累积配水量为

$$\int_{T_1}^{T_1+\Delta t} Q_i \mathrm{d}t = \frac{L\phi_i A_i}{f'_w(S_{w2i})} - \frac{x_{fi}\phi_i A_i}{f'_w(S_{wf})} \tag{4}$$

式中：Δt 为分层注水时间，d；$f_w(S_{w2i})$ 为第 i 小层出口端含水饱和度对应的含水率。

假设在 Δt 内，小层的配水量保持恒定，根据式(3)和式(4)，可求得第 i 小层的平均配水量为

$$\overline{Q_i} = \frac{\phi_i A_i}{\Delta t} \times \left[\frac{L}{f'_w(S_{w2i})} - \frac{x_{fi}}{f'_w(S_{wf})}\right] \tag{5}$$

式中：$\overline{Q_i}$ 为第 i 小层的平均配水量，m^3/d。

1.2.2　已见水小层

对于已见水小层，同样可根据小层的注采数据和储层参数，得到各小层目前的平均含水饱和度，第 i 小层 T_1 时刻出口端的含水饱和度表达式为

$$S_{wi} = \overline{S_{wi}} - \frac{1 - f_w(S_{wi})}{f'_w(S_{wi})} \tag{6}$$

式中：S_{wi} 为第 i 小层 T_1 时刻出口端的含水饱和度；$f_w(S_{wi})$ 为第 i 小层 T_1 时刻出口端含水饱和度对应的含水率。

式(6)为含有出口端含水饱和度的隐函数，可采用迭代法求解得到出口端的含水饱和度。

根据Buckley-Leverett非活塞式水驱油理论[11]，在 Δt 内第 i 小层出口端含水饱和度从 S_{wi} 增至 S_{w2i} 所需要的累积配水量表达式为

$$\int_{T_1}^{T_1+\Delta t} Q_i \mathrm{d}t = \frac{L\phi_i A_i}{f'_w(S_{w2i})} - \frac{L\phi_i A_i}{f'_w(S_{wi})} \tag{7}$$

假设在 Δt 内，小层的配水量保持恒定，根据式(7)可求得第 i 小层的平均配水量为

$$\overline{Q_i} = \frac{L\phi_i A_i}{\Delta t}\left[\frac{1}{f'_w(S_{w2i})} - \frac{1}{f'_w(S_{wi})}\right] \tag{8}$$

1.3　均衡驱替时出口端含水饱和度确定方法

在分层注水井注水量保持恒定的情况下，采用迭代法求得各层达到均衡驱替时出口端的含水饱和度。

在调控时间和目前各层的平均含水饱和度已知的情况下，首先假定各层达到均衡驱替时出口端的含水饱和度为 S_{w2i}，根据式(5)和式(8)可得到各层所需的配水量。判断各层的配水量之和与分层注水井的总注水量是否相等或者满足精度要求，如果不满足，改变 S_{w2i} 值，重新计算各层的配水量，并进行判断，直到满足精度要求，此时各层配水量即为在给定时间内各层达到均衡驱替所需的配水量。

2　方法验证及分析

根据上述方法编制了计算程序，并以东辛油田营8断块油藏某井组为例，分析了油层厚度、剩余油饱和度和调控时间等对层间配水量的影响。该井组的地层原油粘度为10 mPa·s，注采井距为300 m，其相对渗透率曲线如图1所示。

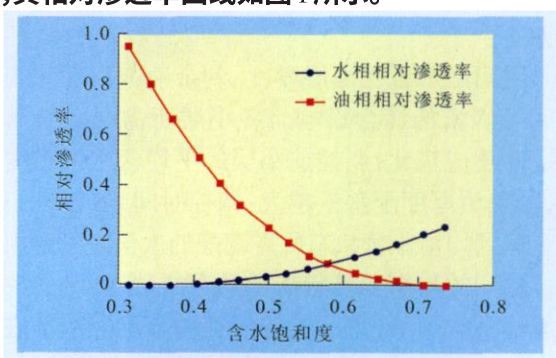

图1　营8断块油藏相对渗透率曲线

2.1　层间油层厚度对层间配水量的影响

假定某井组中有3个小层，油层厚度分别为2，4和6 m，初始含水饱和度及其他储层参数相同，分层注水井总注水量为100 m^3/d，采用所建方法计算得

到3个小层均衡驱替所需的配水量分别为16.67,33.33和50 m^3/d,这表明各小层所需的配水量与其油层厚度成正比。因此,在小层的采出程度或剩余油饱和度相同的情况下,按照油层厚度进行层间配水能够达到层间均衡驱替的状况。

2.2 层间剩余油饱和度差异对层间配水量的影响

假定3个小层的厚度均为4 m,调控前其平均剩余油饱和度分别为0.45,0.5和0.55,调控时间为1 a,分层注水井总注水量为100 m^3/d,采用所建方法计算得到3个小层均衡驱替所需的配水量分别为29.2,34.8和36.0 m^3/d。这表明,在油层厚度相同的条件下,各小层所需的配水量与其剩余油饱和度成正比,剩余油饱和度越高,达到层间均衡驱替所需的层间配水量也越多。

2.3 综合影响

由表1可见营8断块油藏某井组分层注水前的开发状况。通过分层注水调控,分层注水井的总注水量为50 m^3/d,假设达到层间均衡驱替时的时间分别为1和5 a,分层配水量计算结果(表1)表明:单位厚度配水量受调控前小层含水饱和度的影响较大,调控前小层的平均含水饱和度越小,其单位厚度配水量越大;当调控时间分别为1和5 a时,层间单位厚度配水量分别相差6.96和1.45 $m^3/(d\cdot m)$,这说明调控时间越短,各小层为了达到均衡驱替状态所需调配的水量差别越大。

根据营8断块油藏某井组的小层数据和物性参数建立了油藏数值模拟模型,对表1中分层配水量的计算结果进行验证。平面网格数目为75×50,网格步长为4 m×4 m,纵向上为3层,对应井组的3个小层。根据表1中调控时间为5 a的分层配水量进行模拟,5 a后3个小层最终剩余油饱和度非常接近,其出口端含水饱和度分别为64.21%,64.04%和64.25%,可近似看作已达到均衡驱替状态,从而佐证了所建方法的准确性。

表1 营8断块油藏某井组沙二段各小层开发状况及不同调控时间下的配水量

小层	分层注水前开发状况				调控时间为1 a		调控时间为5 a	
	油层厚度/m	注采井距/m	采出程度,%	平均含水饱和度,%	配水量/($m^3\cdot d^{-1}$)	单位厚度配水量/($m^3\cdot d^{-1}\cdot m^{-1}$)	配水量/($m^3\cdot d^{-1}$)	单位厚度配水量/($m^3\cdot d^{-1}\cdot m^{-1}$)
8^2	6.2	300	29.2	61.5	8.4	1.35	21.8	3.52
8^4	3.2	300	20.3	57.3	17.5	5.47	13.8	4.31
8^5	2.9	300	13.9	48.7	24.1	8.31	14.4	4.97

3 结论

以层间均衡驱替为目标,利用Buckley-Leverett非活塞式水驱油理论,综合考虑各小层储层物性和目前动用状况,建立了分层注水井层间配水量的计算方法。

层间配水量受油层厚度、剩余油饱和度和调控时间等因素的综合影响。各小层所需配水量与其油层厚度成正比;调控前小层的平均含水饱和度越小,其单位厚度配水量越大;调控时间越短,各小层为了达到均衡驱替状态所需调配的水量差别越大。

层间的均衡驱替状态是动态的,在给定的调控时间达到均衡后,继续按照计算的分层配水量进行注水开发一段时间后会出现新的不均衡状态,此时应根据层间驱替状况重新进行层间配水量的计算。

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cance to further improve the water flooding recovery factor of the fault block oil reservoir in high water cut stage.
Key words: fault block reservoir; layer block; static geological feature; dynamic performance; recovery factor
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Liu Chao, Ma Kuiqian, Chen Jian et al. Research on quantitative characterization of reservoir heterogeneity and adjustments suggestion in LD oilfield. *PGRE*, 2012, 19(5): 88-90.

Abstract: There are some defects in the existing evaluation systems of reservoir heterogeneity such as its unbounded parameters, high subjectivity classification and low degree of quantification. Based on Lorenz curve method, with the new transform process of data, a new parameter named as comprehensive coefficient of heterogeneity is used in reservoir heterogeneity research. This operation is very simple and the parameter has the virtues of strong comparison, quantitative characterization of heterogeneity degree and is applicable for any type of reservoirs. In the comprehensive research of reservoir heterogeneity in LD oilfield, the application result indicates that the level of LD oilfield reservoir heterogeneity is moderate, but the interlayer and horizontal heterogeneity is strong. For the heterogeneity characteristics of LD oilfield, the appropriate development adjustments are carried out: the main development method is directional wells with few horizontal wells or multi-lateral wells supplemented in E_3d^{2U} reservoir. At the same time, the separate stratum development and separated layer and injection process are used in E_3d^{2L} reservoir. It has significant practical guidance in oilfield adjustment and enhanced oil recovery. It is remarkable that the reduction in water cut is 9%, while the daily oil production increased by about 1 000 m^3/d.
Key words: reservoir heterogeneity; Lorentz curve; formation interference; separate stratum development; development adjustments
Liu Chao, Tianjin Branch of CNOOC Ltd., Tianjin City, 300452, China

Du Dianfa, Wang Yujing, Hou Jiagen et al. Study on water flooding pattern of thin-layered reservoirs with edge and bottom water-case of $K_1h_2^{\ 3}$ reservoir of Lu9 wellblock in Luliang oilfield. *PGRE*, 2012, 19(5): 91-93.

Abstract: Thin-layered reservoirs with edge and bottom water are rare home and abroad. The water intrusion to oil well in this kind reservoir is very complex. The water cut of the oil well increases fast after the well is put into production, and the recovery factor is low. The production rate declines rapidly, and the ultimate recovery ratio is also very low. Taking $K_1h_2^{\ 3}$ reservoir of Lu9 wellblock in Luliang oil field as an example, a concept model is built on the base of the whole region history matching. An orthogonal test is introduced to study the sensitive parameters and the water/oil distribution feature of water flooding pattern of the thin-layered reservoir with edge and bottom water. According to the numerical modeling result and dynamic documents of the whole region, five kinds of water flooding patterns are classified, which are injecting water enhanced bottom, injecting water cross-flow, bottom water coning, edge water intruding and compounding. And, the target boundary is given to the patterns. It is presented by the field application that the target boundary is reliable and it can be supplied as the theoretic foundation for the water/oil control measures for this kind of reservoir in the middle and later stage.
Key words: thin-layered; edge and bottom water; numerical simulation; orthogonal test; water flooding pattern
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Cui Chuanzhi, Jiang Hua, Duan Jiehong et al. Reasonable injection rate allocation method of separate-layer water injection wells based on interlayer equilibrium displacement. *PGRE*, 2012, 19(5): 94-96.

Abstract: Affected by the differences of reservoir properties between layers, the interlayer producing situation and interlayer inconsistency of commingled reservoirs have large differences in the long-term process of water flooding. Separate-layer water injection technology is an effective method to ameliorate the contradictions among the high water cut stage layers. The key to the success of separate-layer water injection is to determine the distributional water injection rate according to the reservoir properties and development situations of each layer. This paper presents a method to calculate distributional water injection rate of each layer by use of the Buckley-Leverett displacement theory. This method takes into account of the reservoir physical properties and development situations. The aim of this method is to realize the interlayer equilibrium displacement. The results show that the differences of distributional water injection rate among layers is comprehensively affected by layer thickness, development status and regulatory time etc. And, the calculated distributional water injection rate in the regulatory time can make each layer achieve a balanced flooding state, and can meet the requirements of injection rate allocation of separate-layer water injection wells.
Key words: multilayer reservoir; interlayer contradiction; separate-layer water injection; computation model; equilibrium displacement
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Xiao Yang, Jiang Tongwen, Feng Jilei et al. Study of dynamic analytic method on fractured-vuggy carbonate reservoir. *PGRE*, 2012, 19(5): 97-99.

Abstract: Fractured-vuggy carbonate reservoir has very strong heterogeneous, anisotropic and multi-scale feature. The applicability of traditional development dynamic analytic method of sandstone reservoirs and fractured carbonate reservoir is limited. In order to solve the problems appeared in the process of production dynamic analysis in Tarim oilfield, this paper is based on the applicability of traditional dynamic analytic method, and considering the features of fractured-vuggy carbonate reservoir, as well as the research result in recent years and the author's research experience to analyzes the practical conditions equivalent for various production dy-