薄层边底水油藏水淹模式
——以陆梁油田陆9井区呼二三油藏为例

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摘要:薄层边底水油藏生产井来水关系复杂,投产后含水率迅速上升,无水采收率低,产量递减快,最终采收率低。以陆梁油田陆9井区呼二三油藏为例,在对全区历史拟合的基础上,建立了概念模型,采用正交试验方法研究了薄层边底水油藏水淹模式的参数敏感性及油水分布特征,结合全区数值模拟结果及动态资料,将该类油藏水淹模式分为注入水加强底水水淹型、注入水窜进水淹型、底水锥进水淹型、边水侵入水淹型和复合水淹型5类,并分析了各种水淹模式的指标界限。应用水淹模式指标界限对研究区50口生产井进行水淹分析,经现场分析及数值模拟验证,准确率达84.8%。

关键词:薄层 边底水油藏 数值模拟 正交试验 水淹模式

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在开发过程中,薄层边底水油藏油水分布模式与普通砂岩油藏差别很大。随着油藏注水开发的深入,开发矛盾主要体现在2个方面:①中高含水期生产井来水关系复杂,包括边底水入侵、注入水水窜[1],剩余油分布规律认识不够清楚;②平面与垂向压力匹配不均衡,含水率上升速度加快,产量递减幅度大。目前,边底水油藏的开采仍以油藏精细描述为基础,立足水驱开发,配以适当的技术措施,深入研究水驱规律及可采剩余油分布,制定合理的开发技术政策界限和开发技术,以达到控水稳油、改善开发效果的目的[2]。为此,笔者以陆梁油田陆9井区呼二三($K_1h_2^3$)油藏为例,利用数值模拟技术,对该油藏的来水方向、油水分布模式进行了研究,以期为改善此类油藏的开发效果提供理论依据。

1 区域地质概况

陆梁油田位于准噶尔盆地陆梁隆起西部的三个泉凸起,其中陆9井区$K_1h_2^3$油藏探明含油面积为6.7 km^2,石油地质储量为544×10^4 t。与块状底水油藏相比,该油藏构造幅度低,高孔高渗透,边水活跃,底水分布范围较大,底水层段厚度在构造含油范围内差异大,油层薄,油层段可动水饱和度较高,油、水层段物性好,连通性好。

2 概念模型的建立

在陆9井区$K_1h_2^3$油藏全区历史拟合的基础上,选取其中相邻的1口生产井和1口注水井,建立概念模型。在平面上采取均匀网格,步长为20 m×10 m,垂向上划分为10层,上面9层为油层,底部1层为水层,网格总数为40×40×10,共16 000个。在模型的边部及底部设置了Cater-Tracy水体用以模拟边底水[3],2井距离为300 m。油层有效厚度约为3.6 m,孔隙度为33%,水平渗透率为1 800×10^{-3} μm^2,垂向渗透率为水平渗透率的1/10;脱气原油密度为0.883 g/cm^3,地层原油粘度为18 mPa·s,体积系数为1.066 m^3/m^3,压缩系数为1.702 7×10^{-4} MPa^{-1}。地层水密度为1 g/cm^3,地层水粘度为0.9 mPa·s,体积系数为1.0 m^3/m^3,压缩系数为0.435×10^{-4} MPa^{-1}。原始地层压力为10.2 MPa,饱和压力为9 MPa。

3 油藏水淹模式

3.1 油藏敏感参数分析

由于陆9井区$K_1h_2^3$油藏为薄层边底水油藏,在

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构造含油范围内不同部位的储层物性、隔夹层分布及底水层厚度差异大，生产井避射高度、生产参数及注水井注水强度也不同，这些因素导致了不同部位生产井的来水方向、水淹速度不同[4]，因此，其水淹模式不尽相同。

由于采油速度、注水强度、底水层厚度、边水体积、水平渗透率和垂向渗透率等是影响水淹模式敏感性的主要参数[5]，故采用正交试验方法，对各敏感参数进行分析，各参数水平如表1所示。对不同参数的25组试验[6]进行数值模拟计算，当采出程度为10%时停止，并以含水率计算得分。结果（表2）表明，对油藏含水率上升的影响程度由强到弱依次为水平渗透率（E）、垂向渗透率（F）、采油速度（A）、边水体积（D）、底水层厚度（C）和注水强度（B），其中边水体积在计算时用边水区与油区半径之比表示。

表1 水淹模式敏感参数水平

水平序号	采油速度，%	注水强度/($m^3 \cdot d^{-1}$)	底水层厚度/m	边水区与油区半径之比	渗透率/$10^{-3}\mu m^2$ 水平	渗透率/$10^{-3}\mu m^2$ 垂向
1	0.25	12	0.5	1.5	450	9
2	0.5	18	1	2	900	18
3	1	24	2	4	1 800	90
4	2	36	4	8	7 200	180
5	4	48	8	∞	14 400	900

表2 水淹模式敏感参数正交试验结果

参数	采油速度，%	注水强度/($m^3 \cdot d^{-1}$)	底水层厚度/m	边水区与油区半径之比	渗透率/$10^{-3}\mu m^2$ 水平	渗透率/$10^{-3}\mu m^2$ 垂向
k_1	0.745	0.517	0.544	0.514	0.610	0.518
k_2	0.537	0.511	0.493	0.582	0.555	0.650
k_3	0.457	0.490	0.516	0.566	0.666	0.511
k_4	0.469	0.598	0.508	0.583	0.501	0.636
k_5	0.455	0.547	0.603	0.417	0.332	0.348
R	0.290	0.108	0.110	0.166	0.334	0.302
较优水平	A_5	B_3	C_2	D_5	E_5	F_5
因子主次	3	6	5	4	1	2

注：k_1，k_2，k_3，k_4和k_5为敏感参数各水平得分的算术平均值；R为因子极差；A—F各参数的下标为其水平序号。

各敏感参数与含水率上升的关系分别为：①油藏水平渗透率越低，含水率上升越快。这是因为油藏水平渗透率越低，相同采出程度的油藏边水水侵量越大，水油比越高。反之，生产井含水率上升越慢[7]。②垂向渗透率越大，生产井含水率上升越快。这是因为，垂向渗透率越大，在较小的生产压差下，底水向上锥进越快，生产井含水率上升越快。③采油速度越高，含水率上升越快。这是因为采油速度越高，生产压差越大，底水锥进越快，水锥越高越陡。④边水体积越大，边水越活跃，相同压降下水侵量越大，生产井含水率上升越快。⑤底水层厚度越大，底水越活跃，生产井含水率上升速度越快。⑥注水强度越大，注入水突进到生产井速度越快，生产井含水率上升越快[8]。

3.2 水淹模式指标界限确定

导致生产井水淹的来水方向既有可能是单一方向的来水，也可能是多方向来水共同作用的结果。因此，储层特征及开采工艺等不同时，生产井水淹模式也不同[9]。根据全区含水饱和度在平面和纵向上的分布及生产井含水率的变化规律，将薄层边底水油藏生产井水淹模式分为5种：注入水加强底水水淹型、注入水窜进水淹型、底水锥进水淹型、边水侵入水淹型和复合水淹型。

不同水淹模式的形成条件和储层特点分别为：①注入水加强底水水淹型。注入水下行，使底水能量增强，造成底水锥进。其储层特点为底水水层厚度较大，底水较活跃，储层物性好，无有效隔夹层，边水不活跃。此模式多出现在油藏内部底水区。②注入水窜进水淹型。注入水直接侵入生产井井底，造成生产井水淹。其储层特点为油、水层之间存在有效隔夹层或垂向渗透率较小或底水不活跃，水平渗透率较高，边水体积较小。此模式多出现在油藏内部边底水影响较弱、注水强度较高的井组。③底水锥进水淹型。底水上升导致生产井水淹。其储层特点为油、水层之间无隔夹层，储层物性较好，底水活跃，边水不活跃。这类水淹模式多出现在油藏内部，底水活跃而边水不活跃且注水强度较小的井组[10]。④边水侵入水淹型。边水侵入到生产井井底，导致生产井水淹。其储层特点为底水不活跃，或垂向渗透率较低，或油、水层之间存在有效隔夹层，水平渗透率较低，边水较活跃。⑤复合水淹型。其生产井的水淹模式包括上述2种或多种水淹模式。由于油藏地质状况复杂，导致生产井水淹的因素不止一个，许多生产井可能同时受到边水、底水及注入水的影响，因此，复合水淹型在全区均有分布[11]。

根据5种水淹模式特点，结合正交试验结果分析，得到不同水淹模式的指标界限（表3），其中复合水淹型为多种模式组合，无明确指标界限。因此，要判断1口生产井的水淹模式，只要知道该井的各敏感参数的大小，结合表3即可判断。

表3　水淹模式指标界限

水淹模式	采油速度,%	注水强度/($m^3·d^{-1}$)	底水层厚度/m	边水区与油区半径之比	渗透率/10^{-3} μm² 水平	渗透率/10^{-3} μm² 垂向
注入水加强底水水淹型	≥0.25	≥24	≥1	≤4	≥900	≥90
注入水窜进水淹型	≤1	≥36	≤1	≤4	≥1 800	≤18
底水锥进水淹型	≥1	≤36	≥1	≤8	≥450	≥90
边水侵入水淹型	≤1	≤18	≤1	≥8	<900	≤18

4　实例验证

应用水淹模式指标界限对陆9井区$K_1h_2^3$油藏50口生产井进行了水淹分析,其中注入水加强底水水淹型、注入水窜进水淹型、底水锥进水淹型、边水侵入水淹型和复合水淹型对应的井数分别为16,5,17,2和10口,经现场分析及数值模拟验证准确率达到84.8%。如陆3054井所在位置储层特征和开采工艺参数为:水平渗透率为2 800×10^{-3} μm²,垂向渗透率为220×10^{-3} μm²,无隔夹层;陆3054井位于底水区内部,远离边水,受边水影响较小,而底水层厚度较大,为3.5 m;采油速度约为2.5%;相邻注水井陆3064井注水速度平均为38 m³/d。根据指标界限确定陆3054井水淹模式为注入水加强底水水淹型。

由陆9井区$K_1h_2^3$油藏陆3054井不同时间的水淹剖面(图1)可以看出,陆3064井注入水由油层底

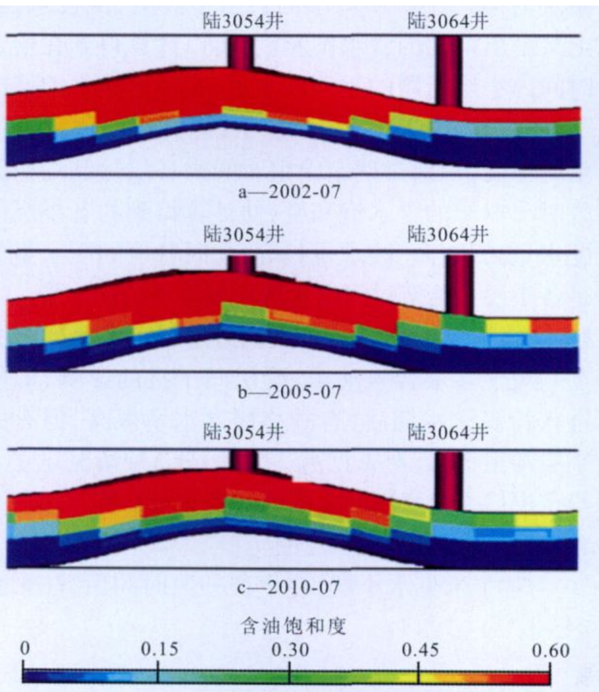

图1　陆3054井不同时间的水淹剖面

部到达生产井陆3054井井底,注入水促使底水上升,导致陆3054井水淹。结果表明,按上述指标界限确定的水淹类型是可靠的,同时水淹模式的确定也为该井后期综合治理提供了理论依据。

5　结论

由正交试验得到影响薄层边底水油藏含水率上升的因素由强到弱为:水平渗透率、垂向渗透率、采油速度、边水体积、底水层厚度和注水强度。

导致生产井水淹的来水包括边水、底水和注入水,油藏不同部位生产井受来水的影响程度不同。薄层底水油藏的水淹模式可分为5种类型:注入水加强底水水淹型、注入水窜进水淹型、底水锥进水淹型、边水侵入水淹型和复合水淹型。储层特征参数及开采工艺参数不同,生产井水淹模式也不相同。

薄层边底水油藏含水率上升快,水淹模式复杂,应针对油藏不同部位、不同水淹模式的生产井采取相应的控水稳油措施,以改善油藏的开发效果。

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编辑　常迎梅

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
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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-