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孤岛油田层系井网互换油井致效机制及见效模式

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摘要:孤岛油田西区北Ng3-4开展层系井网互换先导试验,通过层系井网互换,改变液流方向,提高波及体积,互换后该区块取得了较好的开发调整效果,但单井实施效果差异较大。采用Tanimoto系数法求解驱替压力梯度和水油渗流速度比2个判别参数场间的向量相似度,引入耗水控制指数评价参数评价变流线致效机制。结合油井见效规律,将油井见效特征归纳为4种模式:即时见效型、滞后见效性、反复见效型和无效型。致效机制研究结果表明,油井互换后所处流线部位及井区油水分布,直接影响互换后油井对现层系的剩余油动用状况及高耗水层带的控制程度,进而影响互换后油井的生产效果。

关键词:层系井网互换;致效机制;见效模式;特高含水期;孤岛油田

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Study on response mechanism and mode of oil well after layer and well pattern interchange in Gudao Oilfield

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Abstract: A pilot test of the layer and well pattern interchange was carried out in Ng3-4 strata in the north of the west area of Gudao Oilfield. The layer and well pattern interchange altered the fluid flow direction and increased the swept volume. After the layer and well pattern interchange, the marked results of development and adjustment were achieved in the block, but the results varied greatly between individual wells. The Tanimoto coefficient was used to calculate the vector similarity between the fields of two discriminant parameters, i.e. the displacement pressure gradient and the water-oil seepage velocity ratio, and the water consumption control index was introduced to evaluate the response mechanism of the variable streamline. According to the response characteristics of oil wells, the responses were summarized into immediate response, delayed response, repeated response and no response. The research results of the response mechanism demonstrate that the streamline position of the existing strata where oil wells are located in and the differential distribution of oil and water in the well area directly affect the production status of remaining oil and the control degree of the high water consumption zones through the oil wells after the layer and well pattern interchange. As a result, the production of the oil wells is influenced after the layer and well pattern interchange.

Key words: layer and well pattern interchange; response mechanism; response mode; ultra-high water cut stage; Gudao Oilfield

进入特高含水期油藏的剩余油分布更加复杂、剩余油富集区减小,在特高含水和低油价双重压力下,仍以投资新井来实现变流线调整的方式难以持

续,依靠常规的调整挖潜措施改善开发效果的难度加大。为进一步提高特高含水期油藏水驱采收率,改善平面、纵向动用差异,学者们在矢量开发调整、

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变流线调整、细分层系、层系重组等方面开展了大量研究^[1-4]。在特高含水期,利用多层系油藏现有井网进行变流线调整,实现低油价下老油田效益开发,是特高含水期油藏延长经济寿命期的关键^[5]。胜利油区孤岛油田西区北Ng3-4区块1976年开始实施反九点井网两层系合采,1990年后整体加密为正对行列井网,经过40多年的开发,目前已进入特高含水后期开发阶段^[6]。为此,该区块开展层系井网互换试验,通过转变层系的井网,改变液流方向,扩大波及体积,互换后取得一定的开发效果,但单井效果差异较大^[7-8]。大庆油区从井网开发现状、存在问题及油层动用状况等方面,开展了杏四一六北区块一次加密井网2套层系(萨尔图、葡14及以下油层)互换可行性研究^[9],但未开展层系互换后油井见效差异的研究。为此,笔者从注采系统控制油藏耗水率的角度,开展变流线致效机制研究,分析油井不同见效特征的原因,结合井网与剩余油的配置关系,总结提炼出4种见效模式,为同类油藏变流线调整提供指导。

1 地质概况及开发现状

胜利油区孤岛油田西区北是以新近系馆陶组疏松砂岩为储层的大型披覆背斜构造整装普通稠油油藏,其主要地质特征包括:①储层物性较好,属于高孔高渗透油藏,但非均质性较强。②纵向上含油小层多,井段长,主力层砂体厚度大,延伸距离远,非主力层砂体发育零散(图1)。③上层系Ng3、

下层系Ng4均发育一套厚油层,Ng3⁵和Ng4⁴砂体厚度平均为10~12 m,平均有效厚度为9 m。④层系间隔层发育稳定,平均厚度为3.4 m,上、下层系仅在试验区东部存在连通区,占全区面积的7%。

主要开发现状为:①上、下层系井网长期未调整,注采流线固定。研究区1990年细分为Ng3和Ng4共2套开发层系。②上、下层系井网注采流线差异较大、角度较大。上层系采用北偏西30°行列井网,下层系采用北偏东10°行列井网,2套层系井网夹角为40°(图2)。③上、下层系动用状况及剩余油分布存在较大差异。受储层物性及非均质性的影响,油藏层系间注采状况以及主力层与非主力层的采出状况均差异较大^[10-13]。

研究区剩余油总体呈普遍分布、局部富集^[14]的特点。受沉积相和注采流线等因素影响,由2012年以来剩余油新井饱和度统计得知,平面上剩余油饱和度差异大,水井排及主流线剩余油饱和度相对较低(30%~40%),油井排及断层边部剩余油饱和度高(40%~50%);不同层系同一井点处于不同流线部位,剩余油饱和度差异也较大。以孤岛西5-斜检131取心井为例,该井位于上层系非主流线位置的剩余油饱和度为41%,位于下层系主流线上的剩余油饱和度仅为25.2%。低剩余油饱和度主流线区域表现为明显的高耗水特征,注水利用率低。

2 层系井网互换变流线调整技术

层系井网互换变流线调整技术是针对纵向多



图1 孤岛油田西区北Ng3-4油藏剖面(EW向)

Fig.1 Profile of Ng3-4 reservoir in north of west area of Gudao Oilfield(east-west direction)

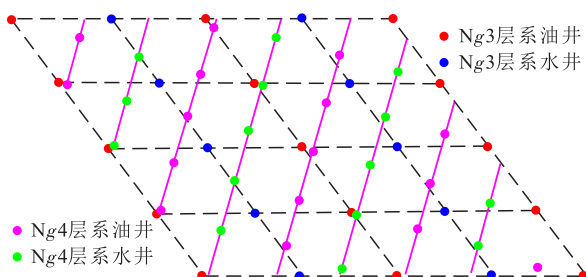


图2 孤岛油田西区北Ng3-4层系叠合井网

Fig.2 Superimposed well pattern of Ng3-4 strata in north of west area of Gudao Oilfield

层系油藏流线固定、不同层系间井网形式交错及动用状况差异大的问题,考虑充分利用老井,以提高油藏采收率和延长油藏经济寿命期为目标,通过层系井网互换变流线、侧钻避高耗水层带、注采结构调整,改变液流方向,抑制高耗水层带,实现多层系油藏井网综合利用变流线而采用的调整技术。

层系井网互换方式、流线转变角度、油井相对位移等因素影响着变流线调整的效果,通过建立孤岛油田西区北典型正对行列式井网,研究层系井网互换方式(图3)、流线转变角度及油井相对位移对变流线调整效果的影响,建立变流线技术政策界限图版(图4)。研究结果表明:在层系井网互换调整过程中,油水井同时实施及先水井后油井效果均较好,且层系井网互换后流线转变角度约为50°、油井

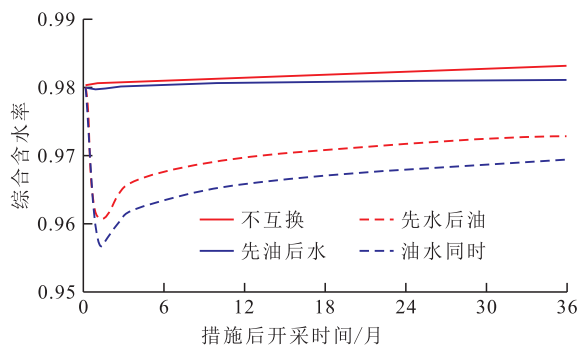


图3 不同层系井网互换方式的含水率变化

Fig.3 Water cut variation curves of different layer and well pattern interchange modes in different strata

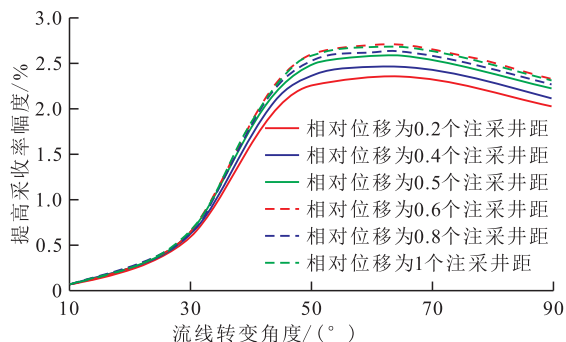


图4 变流线技术政策界限图版

Fig.4 Boundary chart of technology policy on variable streamlines

相对位移大于半个注采井距能获得较好的变流线调整效果。

3 油井致效机制

冯其红等基于流线模型引入瞬时流场潜力系数评价流场调整效果^[14],但未能反映出转流线对抑制油藏耗水率的影响。而特高含水后期油藏高饱和度剩余油富集区域规模越来越小,油藏发育明显的高耗水层带,影响转流线后的油井效果的主要致效原因是注采系统对高耗水区域的控制程度。分别选取驱替压力梯度和水油渗流速度比作为特高含水期油藏转流线调整开发效果评价的判识参数。采用Tanimoto系数法求解2个判识参数场间的向量相似度,来衡量驱替压力梯度参数场和水油渗流速度比参数场间的匹配性关系,通过匹配性评价参数可判断转流线效果。其中,驱替压力梯度参数场,由达西公式推导可得*i*方向的驱替压力梯度表达式为:

$$\nabla p_i = \frac{Q_i}{TRAN_i} \times \frac{1}{M} \quad (1)$$

同理,得到*j*和*k*方向的驱替压力梯度表达式为:

$$\nabla p_j = \frac{Q_j}{TRAN_j} \times \frac{1}{M} \quad (2)$$

$$\nabla p_k = \frac{Q_k}{TRAN_k} \times \frac{1}{M} \quad (3)$$

则任意网格驱替压力梯度表达式为:

$$\nabla p = \sqrt{(\nabla p_i)^2 + (\nabla p_j)^2 + (\nabla p_k)^2} \quad (4)$$

其中:

$$M = \frac{K_{ro}}{\mu_o B_o} \quad (5)$$

水油渗流速度比参数场的计算式为:

$$R = \frac{v_w}{v_o} = \frac{AK_w \nabla p}{AK_o \nabla p} = \frac{\mu_w L}{\mu_o L} \quad (6)$$

将驱替压力梯度参数场及水油渗流速度比参数场处理成向量,采用Tanimoto系数法计算其相似度,其表达式为:

$$T(\nabla p, R) = \frac{\nabla p R}{\|\nabla p\|^2 + \|R\|^2 - \nabla p R} = \frac{\sum \nabla p_i R_i}{\sqrt{\sum \nabla p_i^2} + \sqrt{\sum R_i^2} - \sum \nabla p_i R_i} \quad (7)$$

引入耗水控制指数表征注采系统抑制高耗水层带的程度,其表达式为:

$$K = 1 - T(\nabla p, R) \quad (8)$$

该方法计算的耗水控制指数范围为[0, 1],耗水控制指数越趋向于1,表明当前注采政策越合理,油藏耗水率越低。

4 油井见效模式

孤岛油田西区北Ng3-4实施层系井网互换调整后,日增油量为39.8 t/d,含水率下降2.4%,运行成本降低183元/t,整体调整效果显著,但单井效果相差较大。井网互换后油井耗水控制指数统计结果(图5)表明,互换后油井所在注采单元耗水控制指数差异较大,反映变流线调整后井网对高耗水层带的控制程度差异大,导致变流线调整后油井的见效特征不同。

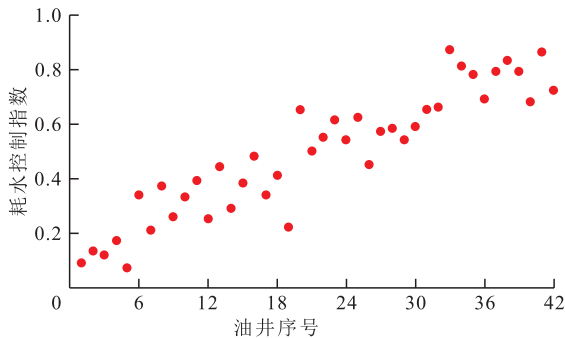


图5 井网互换后油井耗水控制指数统计

Fig.5 Statistics of water consumption control indexes in oil wells after layer and well pattern interchange

孤岛油田层系井网互换方案制定和实施的根本目的是通过层系井网互换调整油井附近流场,从而改善油井的生产效果,并能达到快速见效^[15-19]。但通过油井开发动态分析可知,层系井网互换后的见效状况并不一致,耗水控制指数高的井区井网对剩余油控制程度高,高耗水层带不发育或得到有效抑制,转流线见效快。研究将层系井网互换后油井见效模式归纳为即时见效型、滞后见效型、反复见效型和无效型共4种类型。

即时见效型 即时见效模式的油井一般位于该层系原注采分流线附近,其周围有大量剩余油,进而使得互换后该井的耗水率降低,开发效果得到有效改善。井网互换前,油井西6-121位于下层系井网中,水井西5-142和西5-12驱替原油分别流向油井西6-12和西6-11,该注采方向高耗水层带不发育,计算耗水控制指数,选取注采井连线及油井排间半个注采井距控制的长方形区域,该注采单元

耗水控制指数为0.87,油井西6-121位于油水井排注采分流线上,使得该处大量剩余油未得到有效驱替;当下层系井网换到上层系后,参照油井西6-12,油井西6-121相对位移为半个注采井距,流线转变角度为42°,且该井位于剩余油富集区域,水井西6-132和西5-122与油井西6-121存在直接的注采对应关系,油井西6-121处于注采主流线上,可使油井西6-121附近大量剩余油被水井西6-132和西5-12驱替,剩余油得到有效的动用,油井西6-121立即出现增油降水现象(图6)。

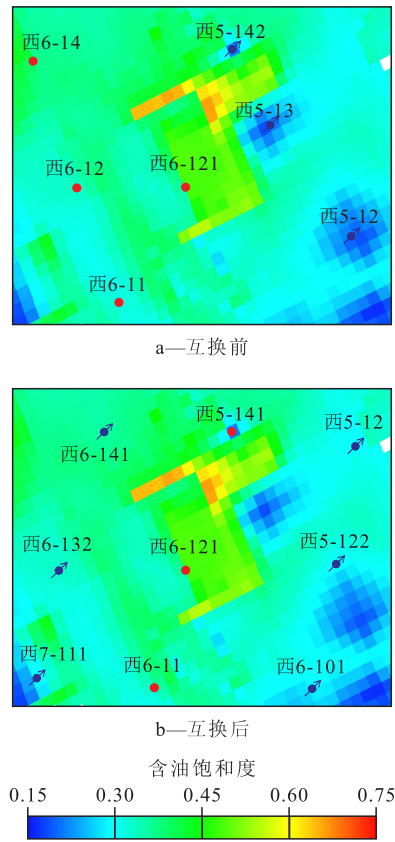


图6 井网互换前后油井西6-121井位

Fig.6 Location map of Well X6-121 before and after layer and well pattern interchange

滞后见效型 滞后见效型为层系井网互换后油井产量未立即上升,而是过一段时间后出现明显的增油降水状况,存在效果改善滞后现象。该现象的油井一般是互换后油井井点附近强水淹、剩余油赋存量较少,而新建立的注采关系井间存在剩余油富集区。通过注水井一段时间的驱替,剩余油到达油井井底开始见效,因此存在一定程度的滞后。井网互换前油井西8-101处于下层系,油井西8-101附近存在明显的未得到有效动用的剩余油,当下层系井网互换到上层系后,油井西8-101附近的注采对应关系较少,只有水井西8-132和西7-122,新注采井网条件下注采单元耗水控制指数为0.76,油井

附近的原油未得到及时的驱替,存在滞后现象(图7)。

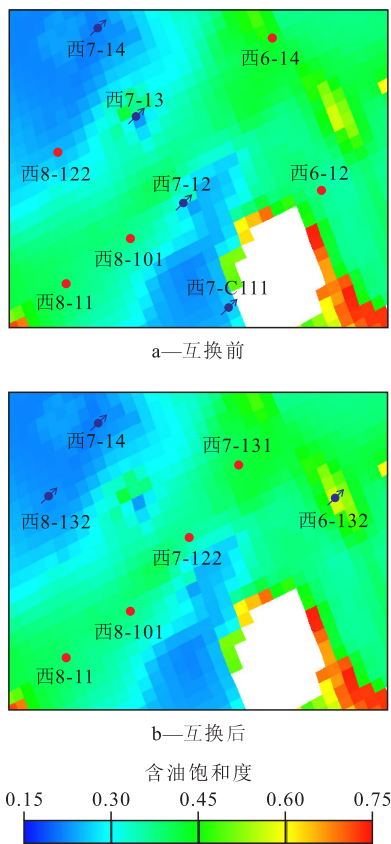


图7 井网互换前后油井西8-101井位
Fig.7 Location map of Well X8-101 before and after layer and well pattern interchange

反复见效型 反复见效型为进行层系井网互换后油井产量出现反复波动的现象且多向注采对应。各注采连线上剩余油驱替至油井井底的时间不同,导致油井产油量和含水率出现反复波动。

层系井网互换前油井西5-141处于下层系,且处于水井排水井之间,水井西5-142和西5-13驱替原油至油井西6-12,使油井西5-141处于注采分流线上,且处于水井排一侧,所以该油井处存在高饱和度剩余油区域,但剩余油富集较少,当下层系井网互换至上层系后,注采单元耗水控制指数为0.69,由于油井西5-141处存在剩余油,因此水井西6-141和西6-132注水可使部分剩余油采出,但由于剩余油较少,所以产量下降迅速。相比滞后见效型,反复见效型见效期存在明显的分段特征(图8)。

无效型 无效型为井网互换后油井的产油含水效果没有改善。出现无效型模式的油井往往是由于油井互换后所在层位剩余油较少,水淹严重,或互换后受储层非均质性、油水井工作制度等的影响未建立起有效的注采驱替关系。

井网互换前油井西4-141处于下层系,水井西

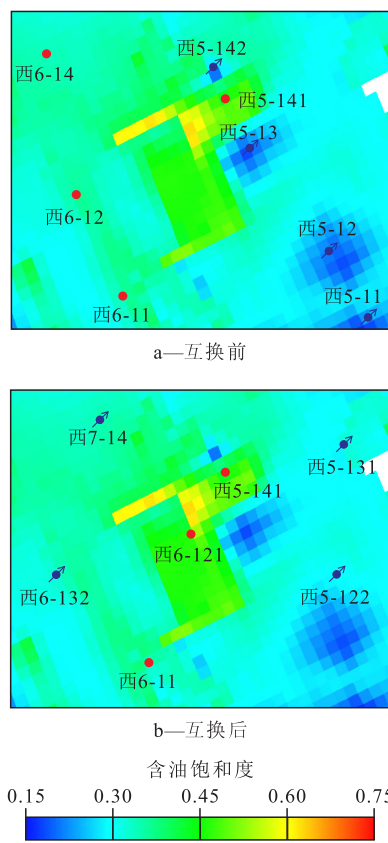


图8 井网互换前后油井西5-141井位
Fig.8 Location map of Well X5-141 before and after layer and well pattern interchange

3-151和西3-142驱替原油至油井西4-15,而油井西4-141正处于水井西3-142与油井西4-15注采主流线上,使油井西4-141附近原油驱替充分,井区高耗水层带发育,互换层系后,注采单元耗水控制指数仅为0.29,井区注入水低效循环,调整效果差。该类油井可通过老井侧钻等方式避开高耗水区域改善开发效果(图9)。

总体来看,原注采井对各注采单元的动用情况直接影响该油井附近的剩余油分布,进而影响互换井初期的生产情况。若层系井网互换后油井位于原注采分流线上,则该油井附近剩余油较富集,动用状况较好,该油井为即时见效型或滞后见效型;若互换后的油井位于原注采主流线上,则该油井附近剩余油较少,驱替状况较差,该油井为无效型。

5 结论

对孤岛油田西区北层系井网互换调整后的油井开发特征进行了研究和分类,基于油井见效程度将油井见效分为即时见效型、滞后见效型、反复见效型和无效型共4种类型,进而对油井出现不同见效模式的致效机制进行了研究。通过选取驱替压

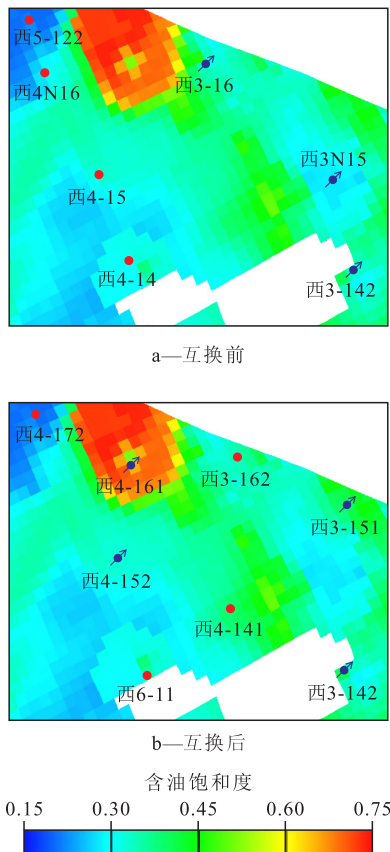


图9 井网互换前后油井西4-141井位

Fig.9 Location map of Well X4-141 before and after layer and well pattern interchange

力梯度和水油渗流速度比2个判识参数场,利用Tanimoto系数法求解2个参数场间的向量相似度,引入耗水控制指数评价层系井网互换后注采井网对高耗水层带的控制作用。揭示了层系井网互换后油井致效的根本原因。

综合油井见效模式及致效机制,对油田进行层系井网调整的建议有:①进行井网调整时,油井调整至注采分流线,以提高注采井网对剩余油的控制程度。②油井调整到注采主流线等高耗水区域附近,应通过老井侧钻、堵水调剖等方式改善转流线效果。

符号解释

- A——网格体截面积, m^2 ;
- B_o ——原油体积系数, 无因次;
- i ——三维坐标 x 方向;
- j ——三维坐标 y 方向;
- k ——三维坐标 z 方向;
- K ——渗透率, mD ;
- K_o ——油相有效渗透率, mD ;
- K_{ro} ——油相相对渗透率, 无因次;
- K_w ——水相有效渗透率, mD ;

- L ——网格体长度, m ;
- M ——流度系数, $m/(mPa \cdot s)$;
- ∇p ——任意网格 i, j, k 方向叠加后的驱替压力梯度, 10^{-1} MPa/m ;
- p_i ——网格 i 方向压力, 10^{-1} MPa ;
- $\nabla p_i, \nabla p_j, \nabla p_k$ —— i, j, k 方向的驱替压力梯度, 10^{-1} MPa/m ;
- Q_i, Q_j, Q_k —— i, j, k 方向的油相渗流速度, m^3/d ;
- R ——水油渗流速度比, 无因次;
- R_i ——网格 i 方向水油渗流速度比, 无因次;
- T ——Tanimoto 系数, 无因次;
- $TRAN_i, TRAN_j, TRAN_k$ —— i, j, k 方向传导率, 10 $mPa \cdot s \cdot m^3/(MPa \cdot d^{-1})$;
- v_w ——水相渗流速度, m^3/d ;
- v_o ——油相渗流速度, m^3/d ;
- μ_o ——油相黏度, $mPa \cdot s$;
- μ_w ——水相黏度, $mPa \cdot s$ 。

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