特高含水后期层系井网及注采优化方法与应用
——以 S 油田 T 块为例

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摘　要：针对 S 油田 T 块特高含水后期纵向干扰严重、平面井网不完善及驱替不均衡等问题，根据油藏工程理论和数理优化方法，纵向上建立了以拟渗流阻力级差为主要指标的近阻组合优化方法，平面上建立了以平均含水饱和度方差最小化为目标函数的差异调控矢量井网和矢量注采优化方法。基于该优化方法，在矿场试验中提出了纵向近阻组合优化、平面矢量井网及矢量注采优化的调整思路与对策。调整后，T 块油藏采收率提高了 3.2 个百分点，现场应用效果显著，研究成果对特高含水后期油田的开发调整对策具有针对性较强的指导作用和借鉴意义。

关键词：层系井网优化；注采调整；均衡驱替；特高含水后期
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Optimization method and application of well pattern and injection production system in ultra-high water cut stage: A case study on block T of S oilfield

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Abstract: Aiming at the problems of serious vertical interference, imperfect well pattern and unbalanced displacement in the ultra-high water cut stage in block T of S oilfield, a near resistance combination optimization method with pseudo seepage resistance parameter as the main index is established longitudinally according to reservoir engineering theory and mathematical optimization method. The vector well pattern of differential control and injection production optimization method with minimizing the variance of average water saturation as the objective function are established on the plane. Based on this optimization method, the adjustment ideas and countermeasures of vertical near resistance combination optimization, plane vector well pattern and vector injection production optimization are put forward in field test. After adjustment, the recovery rate of T block reservoir has been increased by more than 3.2%, and the field application effect is remarkable. The research results provide guidance and reference for the development

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and adjustment countermeasures of oil fields in ultra-high water cut stage.

Keywords: Optimization of well patterns; Injection production system adjustment; Equilibrium displacement; Ultra-high water cut stage

0　前言

S 油田 T 块是一个北高南低的穹隆背斜构造油藏，含油面积 19.1 km^2，石油地质储量 3 740×10^4 t，平均有效厚度 10.9 m，平均孔隙度 30%，渗透率范围 100～2 800 mD。油藏发育 3 个砂层组，17 个含油小层，其中 1 砂层组砂体大面积分布，2、3 砂层组条带状分布。1964 年投入开发，先后经历了天然能量开发阶段、注水开发阶段、边部加密完善阶段、加密井网综合治理阶段、注聚开发阶段、后续水驱开发阶段，目前进入特高含水开发后期。主要开发矛盾有如下三个。

1）纵向小层多，层间干扰严重。调整前采用一套层系开发，从单采井情况看，1 砂层组单井液量是 2、3 砂层组的 2 倍左右，含水 97.2%，采出程度 35%，2、3 砂层组主力层含水平均 93.5%，采出程度为 29%，非主力层采出程度仅为 22%。

2）平面井网完善性差。注聚开发阶段未对层系井网实施调整，由于套损、套坏、改层等原因，后续水驱开发阶段井网适应性逐渐变差。

3）注采不平衡矛盾突出。单井最大日产液量与最小日产液量相差 8 倍左右。

1　优化方法研究

1.1　纵向近阻组合优化方法

传统层系细分重组以静态指标为主，不能反映特高含水后期层间剩余油差异分布特征，重组过程中难以综合考虑多种指标[1-5]。进入特高含水后期，综合考虑渗透率、原油黏度、油层厚度等静态因素以及剩余油饱和度、压力系数等动态因素对层间干扰的影响[6-10]，提出以拟渗流阻力级差为主要指标，建立了特高含水后期纵向近阻组合优化方法。

两相渗流时，由达西定律得到产液量公式为：

$$Q_t = \left(\frac{k_o}{\mu_o} + \frac{k_w}{\mu_w}\right) \cdot A \cdot \frac{\Delta p}{L} = \frac{\Delta p}{\dfrac{\mu_o \mu_w}{k_o \mu_w + k_w \mu_o} \dfrac{L}{A}} = \frac{\Delta p}{R} \tag{1}$$

式中：Q_t 为产液量，m^3；k_o 为油相有效渗透率，mD；k_w 为水相有效渗透率，mD；μ_o 为地层原油黏度，mPa·s；μ_w 为地层水黏度，mPa·s；A 为渗流截面积，m^2；L 为渗流截面间的距离，m；Δp 为渗流截面间的压力差，MPa；R 为渗流阻力，mPa·s/(μm^2·m)。

其中拟渗流阻力参数的计算公式为：

$$R' = \frac{\mu_o \mu_w}{k_o \mu_w + k_w \mu_o} \tag{2}$$

式中：R' 为拟渗流阻力，mPa·s/μm^2。它表示的物理意义是随饱和度变化的油水两相渗流能力。

根据 S 油田 T 块油藏的小层个数、有效厚度、渗透率、原油黏度等基本物性参数分布情况，建立了 100～1 000 mD、100～1 500 mD、100～2 000 mD、100～3 000 mD 四个不同渗透率分布范围的多层相似概念模型，数值模拟计算得到不同渗透率分布范围对应的拟渗流阻力级差与采出程度的关系曲线，见图 1。结果表明，随着拟渗流阻力级差的增大，开发效果变差，拟渗流阻力级差在 4～5 内时关系曲线出现突变点，因此在特高含水后期层系重组时拟渗流阻力级差应控制在 4～5 以内。

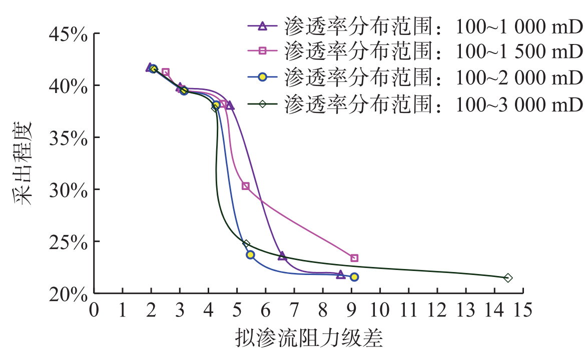


图 1　不同渗透率分布范围拟渗流阻力级差与采出程度关系曲线图

Fig. 1　Relationship curve between pseudo seepage resistance parameter level difference and recovery degree in different permeability ranges

同时对于纵向上受储层韵律性及隔夹层控制、顶部剩余油富集的厚层单元，层内通过堵剂对高渗透层段进行封堵[11-15]，实现深部液流转向，可以进一步提高纵向上均衡驱替程度[16-17]。

1.2　平面矢量井网及矢量注采优化方法

特高含水期以前主要考虑不同方向渗透率、油层厚度等因素影响，其均衡驱替标准是注入水到达周围每口生产井时间相同[18-21]。特高含水后期主要考虑储层动态非均质性影响，此阶段均衡驱替标准可表述为各注采控制面积内平均含水饱和度方差最小[22-24]。因此，平面矢量井网优化和矢量注采优化目标函数取各注采控制面积内平均含水饱和度方差最小化。

$$\min \frac{1}{n}\sum\left[\overline{S_w}-E(\overline{S_w})\right]^2 \tag{3}$$

式中：$\overline{S_w}$ 为平均含水饱和度；$E(\overline{S_w})$ 为平均含水饱和度方差。

矢量井网优化过程中需要对井位进行必要的约束以保证井位不会越过边界[6]。因此，加上边界约束：

$$(X+\Delta X, Y+\Delta Y) \in \Omega \tag{4}$$

式中：Ω 为油藏含油面积，m^2。

矢量注采优化是在矢量井网优化基础上，进一步改善油藏驱替的均衡程度，优化过程中需要对压力、总配注量、总配产量进行必要的约束，其中压力约束是保证井底压力在合理范围内，不会出现压力过低或者压力过高压裂地层[6]。

$$p_{min} < p_i < p_{max} \tag{5}$$

式中：p_i 为井底压力，MPa；p_{min} 为最小井底压力，MPa；p_{max} 为最大井底压力，MPa。

2 应用实例

2.1 纵向近阻组合优化

针对 S 油田 T 块油藏层间干扰严重的问题，根据纵向近阻组合优化方法，由调整前的一套层系细分为 1 和 2～3 两套层系，其中 1 砂层组为一套层系，2～3 砂层组为一套层系。调整后，拟渗流阻力级差由一套层系的 5.96 下降为 1 层系的 3.2 和 2～3 层系的 3.8，见表 1。油藏数值模拟预测结果表明，综合含水达到 98% 时，细分调整方案比细分前方案提高采出程度 2.7%，明显地改善了油藏开发效果。

表 1　S 油田 T 块特高含水后期层系重组方案表

Tab. 1　Layer series reorganization scheme in the ultra-high water cut stage in block T of S oilfield

砂层组	小层号	有效厚度 /m	渗透率 /mD	采出程度	剩余油饱和度	拟渗流阻力/($mPa\cdot s\cdot \mu m^{-2}$)	拟渗流阻力级差
1	1	8.0	2 810	35.8%	0.47	2.80	3.2
	2	2.1	1 454	31.2%	0.45	4.65	
	3	1.6	734	25.6%	0.51	8.96	
	4	1.2	647	22.5%	0.55	8.55	
2	1	1.0	112	19.9%	0.62	14.12	3.8
	2	2.3	1 517	30.8%	0.49	6.00	
	3	2.3	1 383	28.5%	0.45	4.89	
	4	2.9	1 365	28.7%	0.48	6.29	
	5	2.2	613	22.4%	0.44	10.31	
	6	2.3	598	21.3%	0.47	13.18	
3	1	1.9	585	20.2%	0.46	12.45	
	2	1.9	513	21.9%	0.48	14.17	
	3	3.2	1 158	30.5%	0.47	6.81	
	4	3.0	1 326	28.5%	0.40	3.73	
	5	2.8	1 311	27.8%	0.41	3.99	
	6	1.8	592	20.6%	0.58	11.30	
	7	2.0	538	21.4%	0.56	12.09	

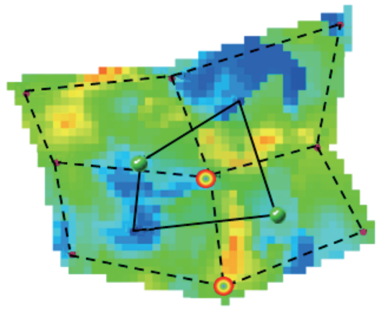
2.2 平面矢量井网及矢量注采优化

2.2.1 平面矢量井网优化

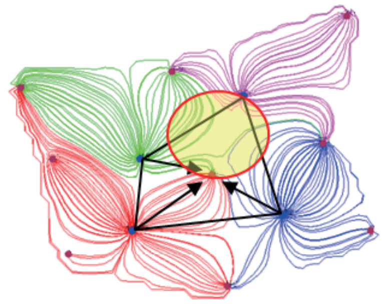
通过平面矢量井网优化方法部署 1 层系和 2～3 层系新井井位，优化后，1 层系平均井距 300 m，2～3 层系平均井距 280 m。选取中部典型井组进行深入分析，优化结果表明，油井井位向剩余油高饱和度区域偏移 75 m，非主流线区域流线增多，油井受效方向增加，井组区域剩余油饱和度方差下降 7%，驱替更加均衡，见图 2。

2.2.2 矢量注采优化

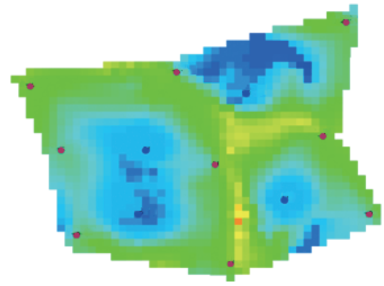
通过矢量注采优化方法优化注采结构，优化后，1 层系液量变化超过 30% 的井共 17 口，占总井数的 10%，2～3 层系液量变化超过 30% 的井共 14 口，占总井数的 9%。同样选取中部典型井组进行深入分析，优化结果表明，对液量重新进行调配，调整幅度大的井占到 38%，剩余油富集区流线增多，高度水淹区流线减少，井组区域剩余油饱和度方差下降 5%，驱替更加均衡，见图 3。



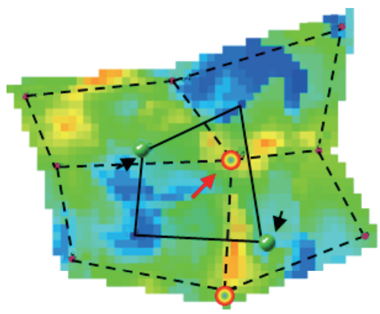
a) 优化前井网
a) Well pattern before optimization



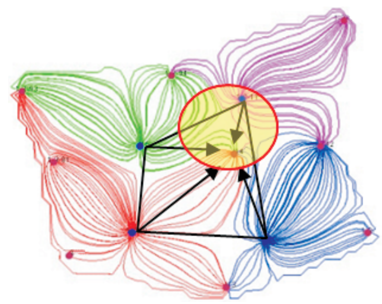
b) 优化前流线分布
b) Streamline distribution before optimization



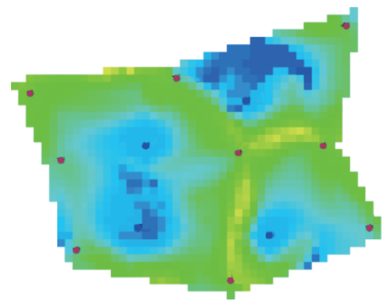
c) 优化前饱和度分布
c) Saturation distribution before optimization



d) 优化后井网
d) Optimized well pattern



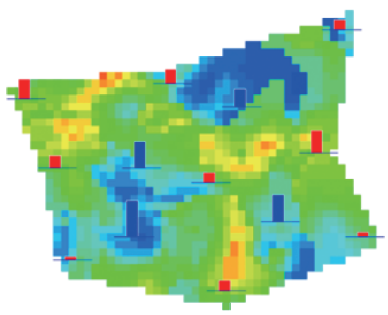
e) 优化后流线分布
e) Streamline distribution after optimization



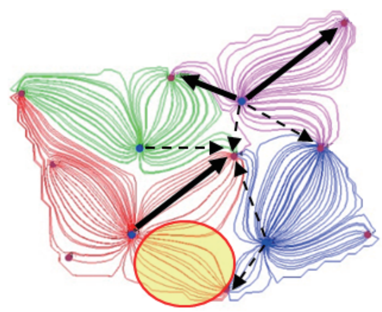
f) 优化后饱和度分布
f) Saturation distribution after optimization

图 2　典型井组平面矢量井网优化前后结果对比图

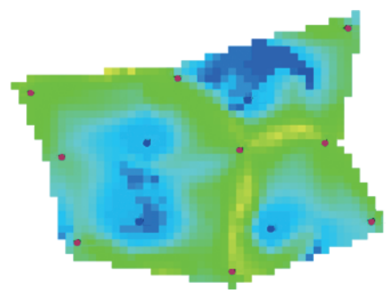
Fig. 2　Comparison of results before and after vector well pattern optimization of typical well group



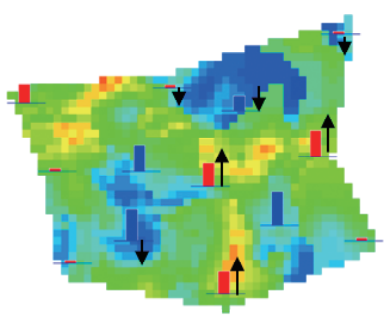
a) 优化前液量
a) Liquid rate before optimization



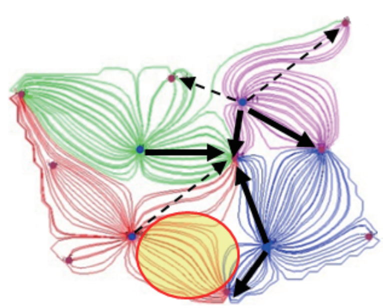
b) 优化前流线分布
b) Streamline distribution before optimization



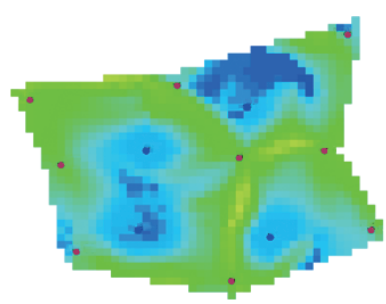
c) 优化前饱和度分布
c) Saturation distribution before optimization



d) 优化后液量
d) Liquid rate after optimization



e) 优化后流线分布
e) Streamline distribution after optimization



f) 优化后饱和度分布
f) Saturation distribution after optimization

图 3　典型井组矢量注采优化前后结果对比图

Fig. 3　Comparison of results before and after vector injection production optimization of typical well group

2.3 实施效果

调整后,S 油田 T 块油藏注采对应率由调整前的 83.8% 上升至 89%,水驱储量控制程度由 87% 上升到 92.5%,单元日产液能力由 6 309 t 上升到 7 006 t,日产油能力由 265.4 t 上升至 324.4 t,含水由 95.8% 下降到 95.34%,自然递减由 11.5% 下降为 5.3%,提高采收率 3.2 个百分点。

3 结论

1)针对特高含水后期层间矛盾,创建了纵向近阻组合优化方法,提出的拟渗流阻力参数是表征随饱和度变化的油水两相渗流能力,能够有效反映油藏层间矛盾,通过数值模拟计算进一步确定特高含水后期层系重组拟渗流阻力级差应控制在 4 ~5 以内。

2)针对特高含水后期平面矛盾,以平均含水饱和度方差最小化为目标函数有效表征了特高含水后期油藏均衡驱替程度,形成了实现油藏均衡高效驱替的平面矢量井网及矢量注采优化方法。

3)根据 S 油田 T 块油藏的主要开发矛盾及剩余油分布情况,采用纵向近阻组合优化、平面矢量井网及矢量注采优化调整技术思路与对策,油藏开发指标得到明显改善,提高采收率 3.2 个百分点,在特高含水后期油田开发中具有广阔的推广应用前景。

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