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# 不同类型油藏非均相驱均衡驱替方式及效果评价

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**摘　要**　非均相驱协同矿场调整措施在孤岛油田中一区 Ng3 单元取得了良好的降水增油效果. 然而，由于实际地层非均质性复杂、层间井网部署的差异及不同层位化学剂注入量不同，非均相驱在动用平面和纵向分布剩余油的过程中会相互影响，很难明确不同方式均衡驱替贡献力度，难以阐明不同类型剩余油的动用机制. 为此，本文采用数值模拟方法，基于目标区块实际地层参数，建立了五种不同类型剩余油油藏机理模型，通过受效剩余油分布、洗油效率、波及系数、平面含水饱和度变异系数及纵向吸水不均衡系数等指标，评价了非均相驱平面及纵向均衡驱替效果，阐明了剩余油动用机制. 数值模拟研究表明，非均相驱协同井网调整或分层配注等矿场调整措施，能最大程度扩大波及、提升均衡驱替效果. 针对不同类型剩余油油藏，明确了均衡驱替方式贡献力度及实施优先级，实际应用时应根据油藏类型和矿场实施条件，选取适宜的均衡驱替方式. 本研究为矿场非均相驱动用不同类型剩余油提供了合理的解释，对非均相驱在矿场不同类型油藏的进一步推广应用提供参考.

**关键词**　非均相驱；均衡驱替；剩余油动用；数值模拟；井网调整；分层配注

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# Balanced displacement methods and effect evaluation of heterogeneous combination flooding in different reservoirs

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**ABSTRACT**　The synergistic oil production using heterogeneous combination flooding and field adjustment measures achieved good results in increasing oil production and decreasing water cut in the Ng3 block of the Gudao Oilfield. However, because of the complex heterogeneity of the actual formation, differences in the deployment of interlayer well networks, and different injection volumes of chemical agents in different layers, the extraction of planar and vertical remaining oil by heterogeneous combination flooding is affected. Clarifying the contributions of different balanced displacement methods and elucidating the mechanism of extracting the different types of remaining oil are difficult. Therefore, this study establishes five different types of models for remaining oil reservoirs based on the actual formation parameters of target blocks using reservoir numerical simulations. The remaining oil, extracted remaining oil, oil displacement efficiency, sweep coefficient, planar water saturation variation coefficient, and vertical water absorption imbalanced coefficient are used to evaluate the balanced displacement effects of heterogeneous combination flooding. On this basis, the mechanism of the remaining oil extraction was elucidated. The numerical simulation results show that field adjustment measures such as well

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network adjustment and layered injection allocation for heterogeneous combination flooding can maximize the balanced displacement effect. For different types of remaining oil reservoirs, the priority of implementing balanced displacement methods was clarified. In practical applications, suitable balanced displacement methods should be selected based on the type of reservoir and conditions of the field implementation. In reservoirs with developed high-permeability zones, heterogeneous combination flooding effectively creates advantageous channels for water flow. Meanwhile, well network infilling can increase the swept volume of heterogeneous combination flooding in low-permeability areas and enhance the displacement efficiency of the enriched remaining oil. The balanced displacement effect of heterogeneous combination flooding was better than that of the well network adjustment. In reservoirs with imperfect injection production well networks, improving the well network can increase the sweep range of streamlines, and synergistic heterogeneous combination flooding can dynamically regulate and strengthen the extraction of remaining oil. The balanced displacement effect of well network adjustment is better than that of the heterogeneous combination flooding. In unconnected reservoirs, the enriched remaining oil blocked by faults is difficult to connect with production wells. Thus, well network adjustment can effectively overcome the blocking effect of faults and extract unconnected remaining oil. The balanced displacement effect of well network adjustment is better than that of the heterogeneous combination flooding. In rhythmic reservoirs, injected fluids flow along high-permeability water-flooded intervals. Heterogeneous combination flooding can effectively plug them, thereby increasing the water absorption of weak, low-permeability water-flooded intervals and extracting the high-saturation remaining oil. In interbed reservoirs, layered water injection can significantly improve the degree of vertical water absorption imbalance. Heterogeneous combination flooding further played a role in conformance control and oil displacement at different layers, enhancing the sweep effect and improving oil displacement efficiency, effectively extracting the remaining oil controlled by the interbeds. The effect of heterogeneous combination flooding on improving balanced displacement is better than that of layered water injection, and the layered allocation of heterogeneous combination flooding can achieve vertical balanced displacement to the maximum extent. This study provides a reasonable explanation for extracting different types of remaining oil and achieving balanced displacement for heterogeneous combination flooding and affords reference significance for future promotion and field applications in different reservoirs.

**KEY WORDS**　heterogeneous combination flooding; balanced displacement; remaining oil extraction; reservoir numerical simulation; well network adjustment; layered injection allocation

我国大庆、胜利等主力油田均已进入高/特高含水开发阶段[1]，化学驱是高含水油藏大幅度提高采收率的重要手段[2−5]. 实施聚合物驱仅能采出原油原始地质储量的 40%～50%[6−7]，且聚合物驱后储层非均质性更强，高耗水层带发育，剩余油分散更零散[8−9]，需要应用调驱力度更强的驱油体系以满足油田进一步提高采收率和实现均衡驱替的要求[10]. 在传统的由聚合物和表面活性剂配制而成的均相驱油体系中，引入黏弹性颗粒复配形成非均相复合驱油体系，作为聚合物驱后油田的接替驱油体系[11−13]. 目前，众多研究人员从实验和数值模拟两个方面对非均相体系中黏弹性颗粒的封堵、运移、调剖和驱油能力进行了大量研究[14−19]，证明了应用非均相体系是高含水油藏提高采收率行之有效的手段[20−21]，丰富和发展了油气渗流理论[22]. 矿场实践也表明，采用黏弹性颗粒的非均相驱能取得良好的降水增油效果[23−24]. 结合平面及纵向矿场调整措施，非均相驱在胜利油田先导试验区成功应用[25]. 由于储层条件、注采井网布置和驱油体系等因素影响，驱替往往是不均衡的，油田开发实践表明，均衡驱替程度与开发效果息息相关[26]. 因此，结合强化的化学驱体系和油藏工程方法可以更大程度实现均衡驱替. 然而，对非均相驱与矿场调整措施的协同均衡驱替机理认识不清，严重制约矿场推广应用. 基于实际地质模型数值模拟研究发现，非均相驱有效动用了聚驱后不同类型剩余油[27]. 然而，由于实际地层平面和纵向非均质性复杂、层间井网部署的异步性及分层注剂的差异性，非均相驱协同矿场调整措施动用平面和纵向剩余油，实现均衡驱替的过程中会相互影响，很难明确不同方式均衡驱替贡献力度，难以阐明不同类型剩余油的动用机制. 为此，本文针对不同类型油藏剩余油，结合目标区块实际地层参数，建立对应的油藏数值模拟机理模型，评价平面及纵向非均相驱均衡驱替效果，明确均衡驱替方式贡献力度及实施优先级，揭示平面和纵向上不同类型剩余油的动用机制.

## 1　不同类型油藏机理模型建立

对于聚合物驱后不同类型剩余油油藏，非均

相驱的均衡驱替方式和效果不同, 作用机理尚不明确. 通过数值模拟方法, 基于矿场先导试验区数值模拟模型主要物性参数, 建立不同类型油藏数值模拟机理模型, 主要包括高渗带发育型、注采不完善型、不连通型、韵律型和隔夹层型(图 1, $K$ 为渗透率, 文中所有场图中红色圆点代表生产井, 蓝色圆点代表注入井). 前四种模型的网格大小为 50×50×10, 共 25000 个模拟网格. $I$ 和 $J$ 方向的网格步长分别为 10 m 和 10 m, 纵向上划分 10 层网格, 步长为 5 m; 隔夹层型模型网格大小为 50×50×30, 共 75000 个模拟网格, 其他基础参数保持一致. 模型基本参数见表 1, 相对渗透率曲线见图 2, $K_{rw}$ 为水相相对渗透率, $K_{ro}$ 为油相相对渗透率. 模拟的具体方案为: 水驱至含水率 98%—聚合物驱 0.3 倍孔隙体积(PV)—后续水驱至含水率(体积分数, 全文同)98%—前置段塞 0.1PV(1625 mg·L$^{-1}$ 聚合物+1625 mg·L$^{-1}$ 预交联凝胶颗粒(PPG))—非均相主段塞 0.3PV(1200 mg·L$^{-1}$ 聚合物+1200 mg·L$^{-1}$PPG+4000 mg·L$^{-1}$ 表面活性剂). 非均相驱是一个复杂的化学驱油过程, 为研究方便并恰当地结合数值模拟, 利用数值模拟商业软件 CMG, 采用残余阻力系数、不可及孔隙体积、吸附浓度等参数近似表征非均相中 PPG 的方式实现非均相驱替数值模拟.

## 2 均衡驱替评价方法

### 2.1 受效剩余油饱和度

为直观地描述剩余油动用区域和动用程度, 采用侯健等[28–30]提出的“受效剩余油饱和度”概念. 受效剩余油饱和度是指在地层条件保持不变情况下实施某种开发方式前后剩余油饱和度差值.

$$S_{oe} = S_{ob} - S_{oa} \tag{1}$$

式中, $S_{oe}$ 为受效剩余油饱和度; $S_{ob}$ 和 $S_{oa}$ 分别为某种开发方式前后含油饱和度.

### 2.2 波及系数和洗油效率

波及系数与洗油效率可定量表征油藏整体开发效果, 波及系数为驱替液所波及的孔隙体积与总孔隙体积之比, 洗油效率为波及范围内的原油产出体积与波及范围内原油总体积之比. 波及系

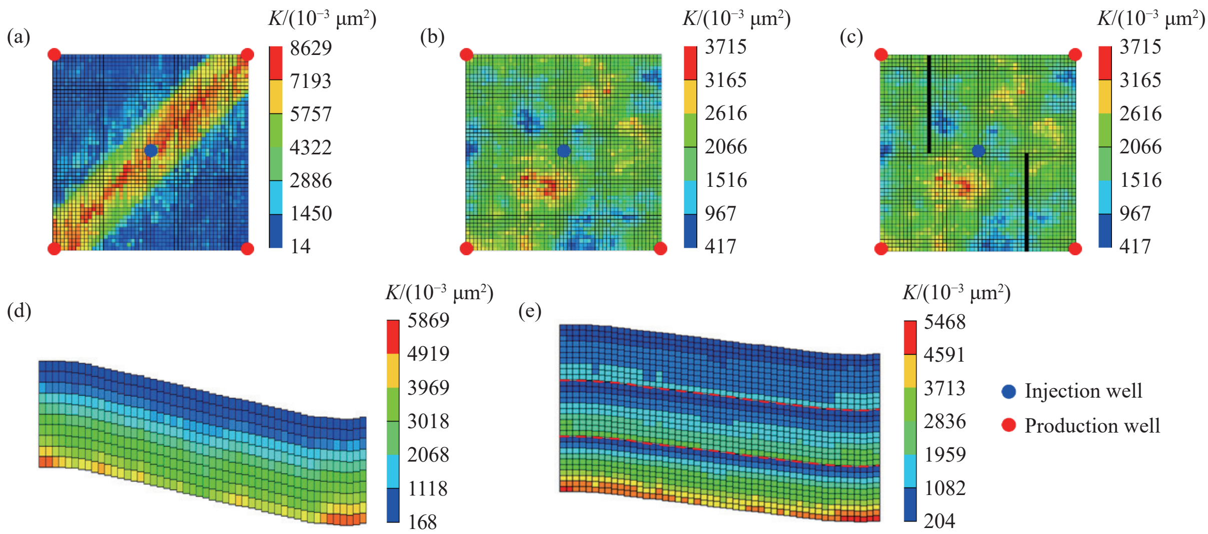


**图 1** 不同类型油藏机理模型. (a) 高渗带发育型; (b) 注采不完善型; (c) 不连通型; (d) 韵律型; (e) 隔夹层型

**Fig.1** Numerical simulation models: (a) reservoirs with developed high permeability zones; (b) reservoirs with imperfect well networks; (c) reservoirs with unconnected zones; (d) reservoirs with rhythm; (e) reservoirs with interlayers

**表 1** 油藏物性参数

**Table 1** Reservoir physical parameters

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| Depth/m | 1173–1230 | Oil covering area/km$^2$ | 0.275 |
| Geological reserves/(10$^4$ t) | 123 | Formation pressure/MPa | 12 |
| Crude oil viscosity/(mPa·s) | 46.3 | Temperature/℃ | 69.5 |
| Average porosity/% | 33 | Permeability/(10$^{-3}$ μm$^2$) | 1500–2500 |
| Formation water salinity/(mg·L$^{-1}$) | 5923 | Crude oil volume factor | 1.105 |

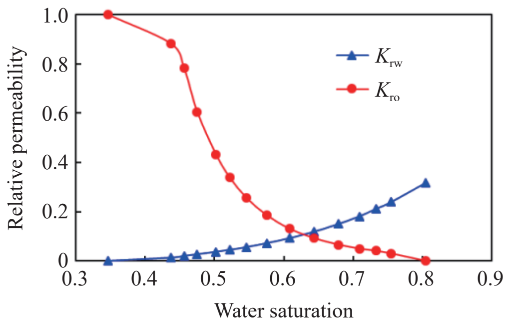


图 2　相渗曲线

Fig.2　Relative permeability curves

数可通过剩余油饱和度和压力数据，再根据油藏工程原理计算得到. 由于其中包括了地层弹性能量产生的部分，在计算时需加以剔除.

原始地层压力为 $P_i$，开发过程中当压力下降至 $P$ 时，单位岩石孔隙体积释放的弹性能量 ($\Delta V$) 为：

$$\Delta V=(C_f+C_oS_{oi}+C_wS_{wc})(P_i-P) \tag{2}$$

岩石流体总压缩系数 $C_t=C_f+\phi(S_{oi}C_o+S_{wc}C_w)$，去除岩石孔隙弹性能量后的含油饱和度降低值 ($\Delta S_o$) 为：

$$\Delta S_o=S_{oi}-S_{oIJ}-C_tS_{oi}(P_i-P_{IJ})>0 \tag{3}$$

式中，$C_f$、$C_o$、$C_w$ 分别为储层岩石、油相、水相的压缩系数，$MPa^{-1}$；$S_{oi}$ 为原始含油饱和度，$S_{wc}$ 为地层束缚水饱和度；$\phi$ 为孔隙度；$S_{oIJ}$ 和 $P_{IJ}$ 分别为网格 $(I, J)$ 目前时刻的含油饱和度和压力.

计算某一时间节点网格含油饱和度的变化值，统计满足条件的网格数，得到所波及的孔隙体积，其与总孔隙体积之比即为波及系数. 通过波及区域的含油饱和度变化可得到洗油效率 ($E_d$)：

$$E_d=\frac{\Delta S_o}{S_{oi}} \tag{4}$$

考虑到数值模拟网格大小，以网格洗油效率大于 0.3 为有效波及基准，计算得到波及系数：

$$W_{sweep}=\frac{\sum M_{mesh}(E_d>0.3)}{\sum M_{mesh}} \tag{5}$$

式中，$M_{mesh}$ 为网格孔隙体积.

### 2.3　平面含水饱和度变异系数

平面含水饱和度的差异是驱替不均衡的结果，结合数学统计方法，引入含水饱和度变异系数评价油藏平面驱替均衡程度. 含水饱和度变异系数为含水饱和度标准差与平均值之比，相比于方差和标准差，可消除量纲和平均值的影响.

$$H_{sw}=\frac{D_{sw}}{\overline{S}_w}=\frac{1}{\overline{S}_w}\sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(S_{wi}-\overline{S}_w\right)^2} \tag{6}$$

式中，$H_{sw}$ 为含水饱和度变异系数；$D_{sw}$ 为含水饱和度标准差；$\overline{S}_w$ 为平均含水饱和度；$S_{wi}$ 为第 $i$ 个网格的含水饱和度；$n$ 为统计网格个数.

### 2.4　纵向吸水剖面不均衡程度

引用洛伦兹曲线[31]定量表征油藏纵向吸水剖面不均衡程度. 将各层吸水量和射开有效厚度降序排列，以累计厚度百分比为横坐标、累计吸水量百分比为纵坐标，绘制洛伦兹曲线，如图 3 所示. 斜率 45°的直线 $OB$ 为绝对均衡线，折线 $OAB$ 为绝对不均衡线，$OB$ 与 $OAB$ 所围区域的面积为 $N_{\Delta OAB}$，$OCB$ 与 $OB$ 所围区域的面积为 $N_{OCB}$，定义 $N_{OCB}$ 与 $N_{\Delta OAB}$ 之比为吸水不均衡系数. 洛伦兹曲线弧度越小，面积 $N_{OCB}$ 越小，吸水不均衡系数越小，表明各层吸水量差别越小，纵向吸水剖面越均衡.

$$G=\frac{\int_0^1[J(h)-h]\mathrm{d}h}{\int_0^1 h\mathrm{d}h}=2\int_0^1 J(h)\mathrm{d}h-1 \tag{7}$$

式中，$G$ 为吸水不均衡系数；$J(h)$ 为总吸水量比例，%；$h$ 为累计射开砂岩厚度比例，%.

## 3　均衡驱替效果评价及剩余油动用机制

### 3.1　平面均衡驱替方式及效果评价

针对聚驱后平面不同类型油藏剩余油，对比聚驱含水 98%、聚驱后非均相驱含水 98%、聚驱后井网调整含水 98% 和聚驱后井网调整非均相驱含水 98% 时刻均衡驱替效果，通过受效剩余油、洗油效率、波及系数和平面含水饱和度变异系数等指标进行评价，其中，波及系数和平面含水饱和度变异系数统计分别见表 2 和表 3(表中 HCF 表示非均相复合驱；WNA 表示井网调整；WNI 表示井网完善；PF 表示聚合物驱).

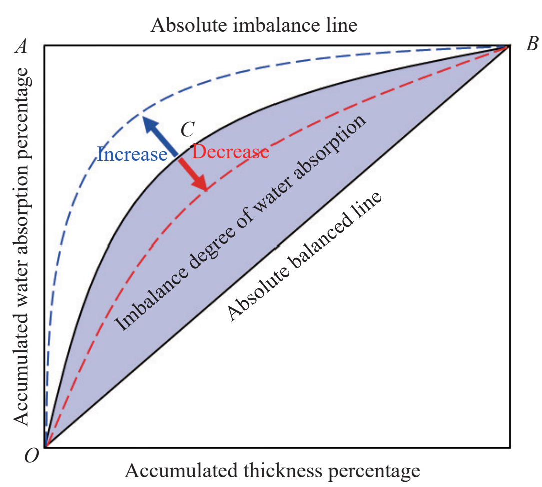


图 3　吸水洛伦兹曲线

Fig.3　Lorenz curve of water absorption

表 2 波及系数计算结果

Table 2 Sweep efficiency in each development method

| Reservoir type | Development method | Sweep efficiency/% | Increased value/% |
|---|---|---|---|
| Reservoirs with developed high permeability zones | HCF | 96.052 | 7.860 |
| | WNA | 94.676 | 6.484 |
| | HCF after WNA | 98.484 | 10.292 |
| Reservoirs with imperfect injection production well networks | HCF | 93.704 | 5.440 |
| | WNI | 93.932 | 5.668 |
| | HCF after WNI | 97.248 | 8.984 |
| Reservoirs with unconnected zones | HCF | 91.696 | 6.960 |
| | WNA | 92.888 | 8.152 |
| | HCF after WNA | 96.124 | 11.388 |

表 3 含水饱和度计算结果

Table 3 Water saturation statistics of each development method

| Reservoir type | Development method | Mean | Standard deviation | Coefficient of variation |
|---|---|---|---|---|
| Reservoirs with developed high permeability zones | PF | 0.717 | 0.092 | 0.128 |
| | WNA | 0.740 | 0.082 | 0.111 |
| | HCF | 0.775 | 0.076 | 0.098 |
| | HCF after WNA | 0.782 | 0.072 | 0.092 |
| Reservoirs with imperfect injection production well networks | PF | 0.727 | 0.080 | 0.110 |
| | HCF | 0.764 | 0.072 | 0.094 |
| | WNI | 0.775 | 0.071 | 0.092 |
| | HCF after WNI | 0.782 | 0.070 | 0.090 |
| Reservoirs with unconnected zones | PF | 0.685 | 0.142 | 0.207 |
| | HCF | 0.709 | 0.140 | 0.198 |
| | WNA | 0.734 | 0.126 | 0.172 |
| | HCF after WNA | 0.765 | 0.120 | 0.157 |

#### 3.1.1 高渗带发育型油藏

高渗带发育型油藏在开采过程中含水上升很快, 高含水期稳产难度大, 注入流体主要沿着高渗带窜流, 低渗区域波及效果差导致剩余油大量富集. 由剩余油分布(图 4)与受效剩余油分布(图 5)可知, 聚驱后高渗带内流线分布密集, 驱替效率高, 剩余油很少, 大部分富集剩余油分布在两侧的低渗区流线很难波及. 非均相驱后, 驱替液沿原始流线扩大波及, 低渗区剩余油有明显受效, 剩余油分布更加均衡. 井网调整水驱后, 流线被加密井引至低渗区, 受效剩余油分布在新加密井附近; 由于水驱洗油效率低, 剩余油受效程度低且驱替并不均衡. 井网调整非均相驱后, 井网的引效作用扩大了非均相驱在低渗区的波及范围和高洗油效率, 驱替更加均衡.

由提高洗油效率分布(图 6)和波及系数(表 2)可知, 非均相驱提高洗油效率区间为 [0.7, 1.0), 占比 24.8%; 井网调整提高洗油效率区间为 [0.5, 0.8), 占比 10.1%; 井网调整非均相驱提高洗油效率区间为 [0.7, 1.0), 占比最高, 为 29.5%, 洗油效率区间从低洗油效率转为高洗油效率. 井网调整非均相驱的波及系数大于单一开发方式; 此外, 非均相驱提高波及优于井网调整. 由含水饱和度变异系数结果(表 3)可知, 井网调整非均相驱后含水饱和度变异系数最小, 说明注入流体分布最均匀, 平面均衡驱替效果最佳.

#### 3.1.2 注采不完善型油藏

对于注采不完善型油藏, 由于原始注采井网不完善, 缺少生产井的区域井网未能有效控制, 富集了大量剩余油. 从受效剩余油分布(图 7)可知,

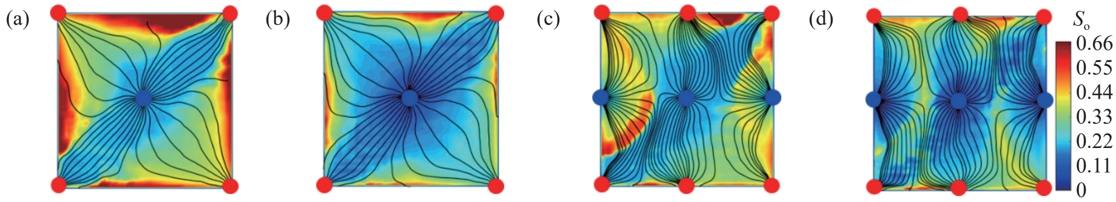


图 4　剩余油分布. (a) 聚合物驱; (b) 非均相驱; (c) 井网调整; (d) 井网调整非均相驱

**Fig.4**　Remaining oil distribution: (a) PF; (b) HCF; (c) WNA; (d) HCF after WNA

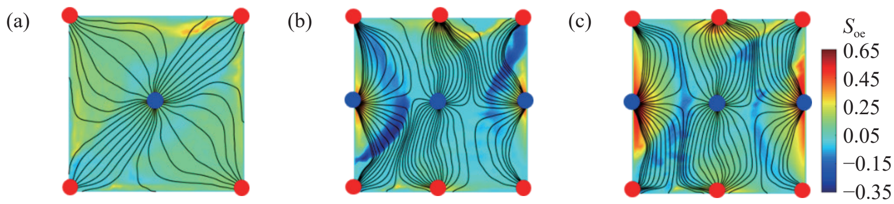


图 5　受效剩余油分布. (a) 非均相驱; (b) 井网调整; (c) 井网调整非均相驱

**Fig.5**　Response remaining oil distribution: (a) HCF; (b) WNA; (c) HCF after WNA

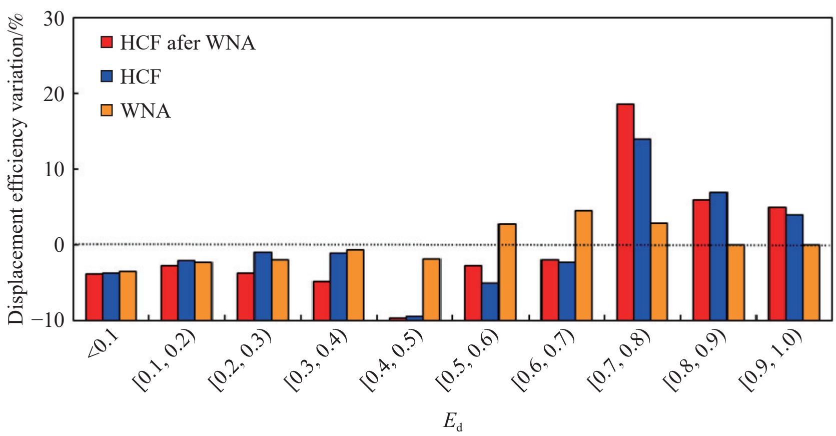


图 6　提高洗油效率区间分布

**Fig.6**　Distribution of enhanced displacement efficiency

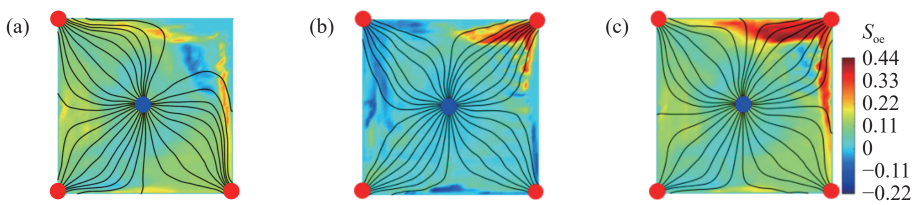


图 7　受效剩余油分布. (a) 非均相驱; (b) 井网完善; (c) 井网完善非均相驱

**Fig.7**　Response remaining oil distribution: (a) HCF; (b) WNI; (c) HCF after WNI

非均相驱通过扩大流线在井网未控制区域的波及范围动用剩余油；但由于井网不完善，右上部角隅处剩余油无明显受效. 井网完善后水驱，新流线能波及到角隅处，也是受效剩余油的主要分布区域；井网完善非均相驱流线波及范围进一步扩大且分布均匀，原始井网未控制区富集剩余油受效程度大幅提升.

由提高洗油效率分布（图 8）和波及系数（表 2）可知，井网完善提高洗油效率区间为 [0.6, 0.8)，占比 18.1%；非均相驱和井网完善非均相驱提高洗油效率区间为 [0.7, 1)，占比分别为 32.7% 和 39.0%. 井网完善非均相驱波及系数大于单一开发方式；此外，井网完善提高波及优于非均相驱. 由含水饱和度变异系数结果（表 3）可知，井网完善非均相驱含水饱和度变异系数最小，说明注入流体平面均衡驱替效果最佳.

### 3.1.3　不连通型油藏

断层的存在会影响注采井之间的连通性，使

注采井间流线分布产生显著变化, 断层附近存在大量高饱和度剩余油被遮挡, 流线无法波及. 由受效剩余油分布(图 9)可知, 非均相驱沿着初始主流线扩大波及范围并动用剩余油; 注采流线平行于断层延伸方向的井网调整方式, 能显著改善了断层对剩余油的遮挡作用, 流线能有效波及和动用被遮挡的剩余油; 井网调整非均相驱在改善剩余油不连通的同时, 能使非均相驱在更大的范围内充分发挥扩大波及和强化洗油作用, 流线的波及范围更广, 断层附近不连通的剩余油受效显著.

由提高洗油效率分布(图 10)和波及系数(表 2)可知, 井网调整提高洗油效率区间为 [0.6, 0.8), 占比 18.6%; 非均相驱显著提高洗油效率区间为 [0.7, 1.0), 占比 33.0%; 井网调整非均相驱著提高洗油效率区间为 [0.6, 1.0), 占比 40.3%. 井网调整非均相驱波及系数大于单一开发方式; 此外, 井网调整提高波及优于非均相驱. 由含水饱和度变异系数结果(表 3)可知, 井网调整非均相驱含水饱和度变异系数最小, 说明注入流体平面均衡驱替效果最佳.

### 3.2 纵向均衡驱替方式及效果评价

#### 3.2.1 韵律型油藏

正韵律型油藏在开采过程中由于储层韵律性

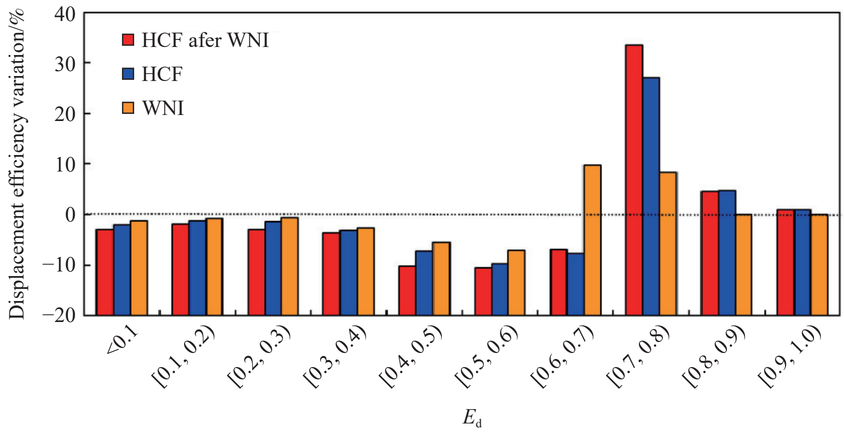


**图 8** 提高洗油效率区间分布

**Fig.8** Distribution of enhanced displacement efficiency

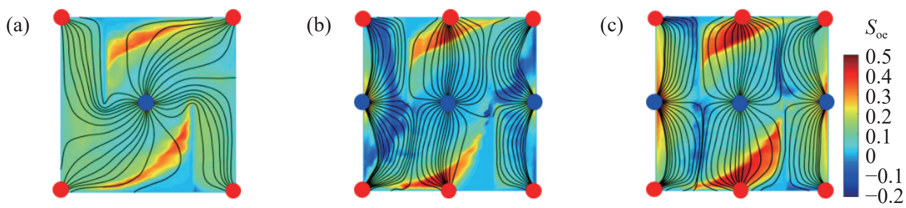


**图 9** 受效剩余油分布. (a) 非均相驱; (b) 井网调整; (c) 井网调整非均相驱

**Fig.9** Response remaining oil distribution: (a) HCF; (b) WNA; (c) HCF after WNA

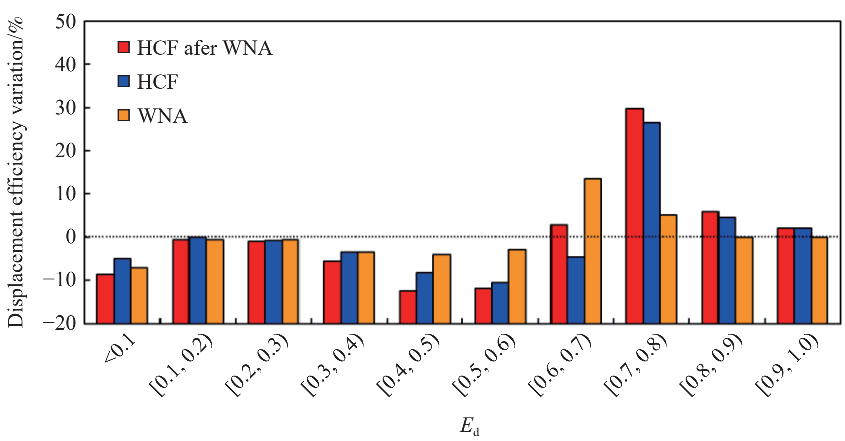


**图 10** 提高洗油效率区间分布

**Fig.10** Distribution of enhanced displacement efficiency

和重力的影响，油藏下部水淹严重，剩余油较少，而中上部水淹弱，存在大量的剩余油难以开采出来．井网调整措施无法克服储层韵律和重力作用，难以取得较好的开发效果．聚驱后非均相驱纵向注采剖面受效剩余油分布见图 11．非均相驱后，受效剩余油主要分布在两个区域，一是在注入井井筒附近形成一个“锥形”受效区，这是由于非均相驱在井筒周围的强化洗油作用；二是注采井中间部位形成一个类似“三角形”受效区，这是由于非均相驱对下部层位的封堵导致剩余油的受效区域向中上部层位扩展．非均相驱能有效储层韵律性和重力的影响从而动用剩余油，使纵向驱替更均衡．

由洗油效率频率分布(图 12)和各层提高波及系数(图 13)可知，非均相驱显著提高了油藏中上部层位的波及和洗油效率．由纵向吸水洛伦兹曲线(图 14，WF 表示水驱)可知，非均相驱后洛伦兹曲线的弧度明显减小，这是由于非均相驱后中上层的吸水量增加，吸水不均衡系数由聚驱后的 0.436 下降至 0.335，纵向吸水不均衡程度降低，有利于实现纵向均衡驱替．

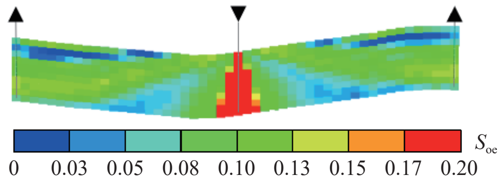


**图 11**　受效剩余油分布

**Fig.11**　Response remaining oil distribution

3.2.2　隔夹层型油藏

由于受重力作用及隔夹层对流体在层间交互流动的隔挡作用影响，油藏开采过程下层水淹严重，剩余油较少，而中上层水淹弱，存在大量的剩余油，且由于不渗透隔夹层的纵向隔挡作用，附近会残留大量剩余油．各开发方式受效剩余油纵向分布见图 15．非均相驱笼统注入的方式，各层受效剩余油分布与韵律型油藏模拟结果类似；按剩余油饱和度进行分层注水后，上、中、下三层配注量依次降低，受效剩余油分布范围从下到上不断扩大，上层受效程度最高；分层配注非均相驱后中上层剩余油得到进一步的强化受效，受隔夹层遮挡

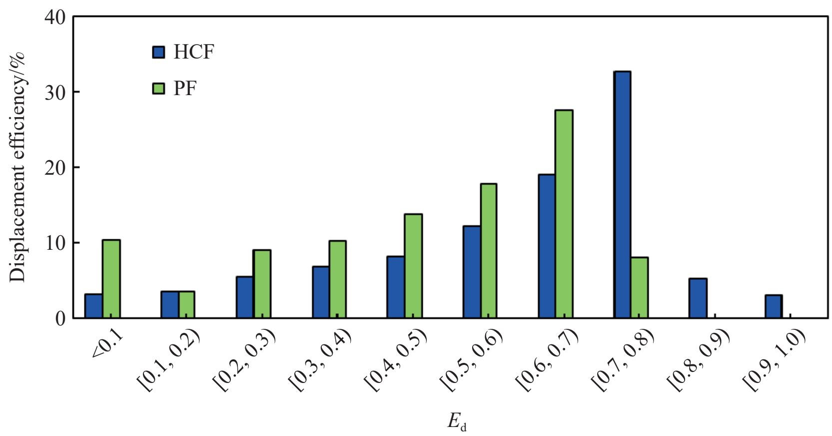


**图 12**　洗油效率区间分布

**Fig.12**　Displacement efficiency frequency

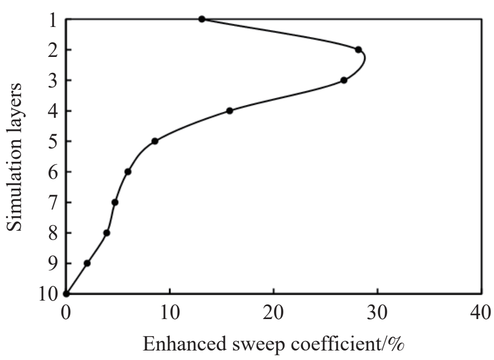


**图 13**　提高波及系数

**Fig.13**　Enhanced sweep efficiency

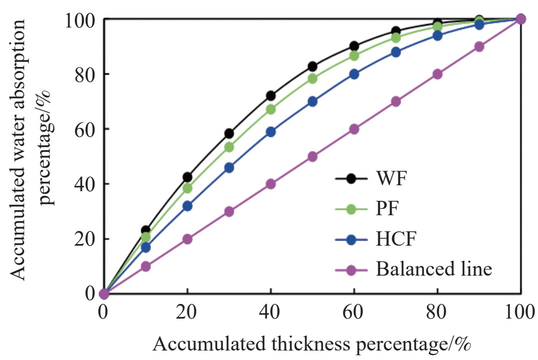


**图 14**　吸水洛伦兹曲线

**Fig.14**　Lorenz curve of water absorption

控制的富集剩余油受效明显, 层间剩余油饱和度差距显著缩小, 纵向驱替更加均衡.

由各层提高波及系数和提高洗油效率(图 16, LWI 表示分层注水; LAHCF 表示分层配注非均相驱)可知, 非均相驱在中上层的提高波及系数和洗油效率高于下层; 分层注水大幅提高了中上层的波及系数, 洗油效率提高幅度较低; 分层配注非均相驱大幅提高了中上层位的波及系数和洗油效率, 明显优于单一开发方式.

由纵向吸水洛伦兹曲线(图 17)可知, 非均相驱后洛伦兹曲线的弧度有一定程度减小, 吸水不均衡系数由聚驱后的 0.442 下降至 0.401; 分层配注非均相驱后洛伦兹曲线的弧度大幅度减小, 吸水不均衡系数下降至 0.303, 说明吸水不均衡程度大幅度降低, 纵向驱替更加均衡.

### 3.3 不同油藏均衡驱替方式优先级

根据平面和纵向不同类型剩余油油藏不同开发方式均衡驱替效果评价, 明确了不同油藏均衡驱替方式优先级. 高渗带发育型油藏, 均衡驱替方式优先级为井网调整非均相驱>非均相驱>井网调整; 注采不完善型油藏, 均衡驱替方式优先级为井网完善非均相驱>井网完善>非均相驱; 不连通型油藏, 均衡驱替方式优先级为井网调整非均相驱>井网调整>非均相驱; 韵律型油藏, 非均相驱能有效提升纵向均衡驱替效果; 隔夹层型油藏, 均衡驱替方式优先级为分层配注非均相驱>非均相驱>分层注水.

## 4 结论

(1) 非均相驱协同井网调整及分层配注等矿场调整措施, 能最大程度扩大波及、提升均衡驱替效果. 针对不同类型剩余油油藏, 明确了不同方式均衡驱替贡献力度和实施优先级, 实际应用时应根据油藏类型和矿场实施条件, 选取适宜的均衡驱替方式.

(2) 高渗带发育型油藏, 非均相驱均衡驱替效果优于井网调整; 不连通型和注采不完善型油藏, 井网调整均衡驱替效果优于非均相驱; 韵律型油藏, 非均相驱能有效提升纵向均衡驱替程度; 隔夹层型油藏, 非均相驱提升均衡驱替效果优于分层注水, 分层配注非均相驱能最大程度实现纵向均衡驱替.

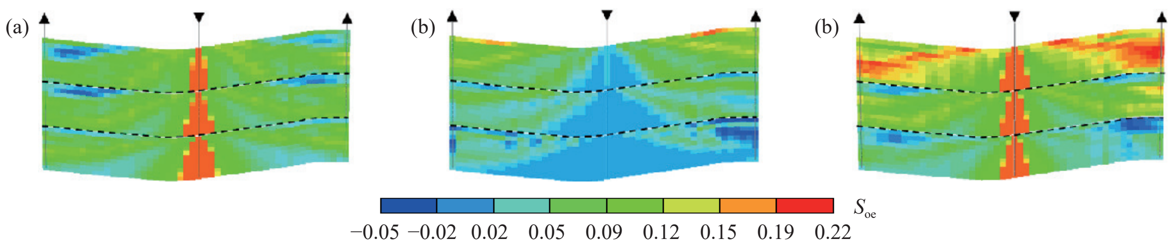


图 15 受效剩余油分布. (a) 非均相驱; (b) 分层注水; (c) 分层配注非均相驱

**Fig.15** Response remaining oil distribution: (a) HCF; (b) layered water injection; (c) layered allocation of HCF

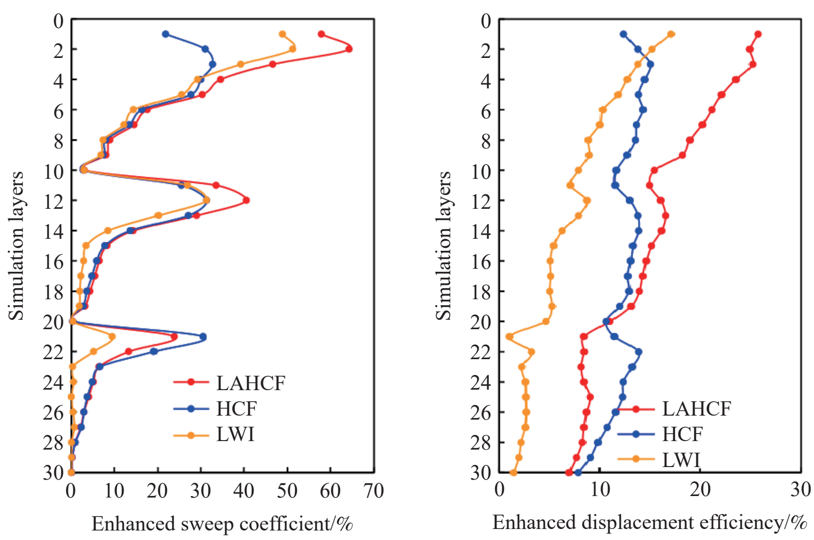


图 16 各层提高波及系数 (a) 和洗油效率 (b)

**Fig.16** Enhanced sweep efficiency (a) and displacement efficiency (b) of each layer

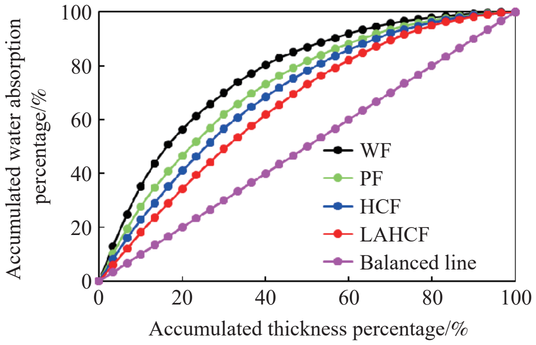


**图 17**　吸水洛伦兹曲线

**Fig.17**　Lorenz curve of water absorption

(3) 对于高渗带发育型油藏，非均相驱能有效封堵高渗层，通过加密注入井和生产井可扩大非均相驱在低渗区的波及并强化驱替出富集剩余油；注采不完善型油藏的剩余油主要集中于井网未控制区域，完善井网可增加驱替液流线波及范围，协同非均相驱可动态调控和强化动用剩余油；对于不连通型油藏，断层附近遮挡的富集剩余油难以与生产井有效连通，井网调整可有效克服断层对剩余油的遮挡作用，动用不连通剩余油；韵律型油藏中，注入流体易沿着高渗水淹层窜流，非均相驱能有效封堵高渗层，从而增加低渗层吸水量，动用高饱和度剩余油；对于隔夹层型油藏，分层注水能显著改善纵向吸水不均衡程度，非均相驱进一步在不同层位发挥调驱作用，强化扩大波及和提高洗油效率，有效动用受隔夹层控制的剩余油.

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