

引用格式: 罗宪波. 海上砂砾岩油藏层间与层内干扰实验研究[J]. 油气藏评价与开发, 2024, 14(1): 117-123.

LUO Xianbo. Laboratory experiment on interlayer and intralayer interference in offshore sandy conglomerate reservoir[J]. Petroleum Reservoir Evaluation and Development, 2024, 14(1): 117-123.

DOI: 10.13809/j.cnki.cn32-1825/te.2024.01.016

# 海上砂砾岩油藏层间与层内干扰实验研究

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**摘要:** 油田开发过程中普遍存在着层间与层内干扰, 对于纵向上没完全隔开的海上强非均质性巨厚砂砾岩油藏而言尤为如此, 是油藏细分层系的基础和内因。矿场上, 干扰数据主要由生产测井得到, 开发经验表明干扰系数随开发阶段、时间变化而变化, 生产测井普遍为单点测试, 无法得到全周期干扰系数。因此, 有必要对层间与层内干扰进行室内实验研究。干扰系数理论研究涉及参数众多且随时间变化, 可以解释多层合采油井整体产油能力低于分层开采累加量现象, 未能解决其形成的理论根源, 所以采用了一维岩心驱替实验装置进行了层间和层内干扰的研究, 实验表明: 巨厚砂砾岩油藏层间干扰随着时间推移, 含水上升, 干扰系数逐渐增大, 但在高含水期有所下降, 导致层间干扰的原因是单驱与合驱时各岩心驱替压力梯度不同; 巨厚砂砾岩油藏层内干扰在早期采油指数干扰系数较大, 随着含水增加, 采油指数干扰系数逐渐变小, 层内干扰产生的实质是不同储层渗流阻力变化随着时间的变化, 导致储层流量分配的改变。

**关键词:** 砂砾岩油藏; 层间干扰; 层内干扰; 干扰系数; 岩心驱替实验

中图分类号: TE357

文献标识码: A

## Laboratory experiment on interlayer and intralayer interference in offshore sandy conglomerate reservoir

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**Abstract:** The interlayer and intralayer interference, which is commonly existing in the process of oilfield development, especially for the offshore strongly heterogeneous huge thick sandstone and conglomerate reservoirs that are not completely separated vertically, is the basis and internal cause of reservoir subdivision. In practice, interference data are primarily obtained from production logging, which shows that the interference coefficient changes with the development stage and over time. Since production logging is typically a point test, it does not capture the full cycle interference coefficient, highlighting the need for laboratory studies on interlayer and intralayer interference. The theoretical study of interference coefficient involves numerous parameters and the interference coefficient changes with time. This theory can explain the phenomenon that the overall oil production capacity of multi-layer combined production wells is lower than the cumulative amount of multi-layer production, but it fails to solve the theoretical root cause of its formation. So a one-dimensional core displacement experimental device was used for the study of the interlayer and intralayer interference. The experiment shows that for the interlayer interference, the interference coefficient gradually increases with time as water cut rises, but decreases in high water cut period. This is due to the difference in the displacement pressure gradient of each core during single flooding and combined flooding. While for the intralayer interference, the interference coefficient of oil production index is large in the early stage, and gradually decreases with the increase of water cut. The essence of the interference is that the change of seepage resistance of different reservoirs with time results in the change of reservoir flow distribution.

**Keywords:** glutenite reservoir; interlayer interference; intralayer interference; interference coefficient; core displacement experiment

收稿日期: 2023-02-22。

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基金项目: 国家科技重大专项“渤海油田加密调整及提高采收率油藏工程技术示范”(2016ZX05058-001)。

受各层段储层岩性、物性以及开采过程中各层段地层压力与流体物性差异等的影响<sup>[1-3]</sup>,对于纵向上没完全隔开的海上强非均质性厚油藏而言,在采用大井距和多层合注合采注水开发方式时,始终会存在层与层之间相互制约和干扰的问题,不恰当的开发模式会导致各层吸水能力、产出状况以及水淹程度差异加剧,生产动态上反映出较大的层间矛盾,从而影响各层段和油藏整体的均衡动用和油藏最终采收率<sup>[4-7]</sup>。为了提高各层储量均衡动用程度和油藏整体最终采收率,需要从降低油藏注水开发层间矛盾角度出发,把握层间干扰影响主要因素,通过多层合采层间干扰程度表征和评价研究,找出影响层间干扰程度主控因素,为强非均质厚油藏开发技术策略和措施制定提供依据。

## 1 地质油藏概况

C油田位于渤海中西部海域,区域上为依附于石南一号边界断层发育的复杂断块构造,平面划分6个含油井区,含油层系包括新近系明化镇组、馆陶组、古近系东营组。储层物性上明化镇组、馆陶组为高孔高渗,东二段为中孔中渗,东三段为中低孔中低渗。流体性质上明下段为重质油,馆陶组为中一重质油,东二段、东三段为轻质油。油藏类型上发育构造油藏、岩性-构造油藏、岩性油藏,以构造油藏为主。该油田于2014年10月发现,主力单元东三段为砂砾岩储层,经油层段测试,产能高,为构造、岩性-构造油藏,原油黏度介于0.64~1.95 mPa·s,为轻质油,原油性质好。

C油田东三段为陡坡带扇三角洲沉积体,发育巨厚砂砾岩储层,非均质性强,岩性复杂,岩性以巨厚砂砾岩、含砾砂岩、细砂岩等沉积为主,整体储层及岩性组合横向变化快,平面、纵向上非均质性强,物性差异明显,具有“厚、杂、强、大”4项特征。“厚”是指东三段发育巨厚层砂砾岩沉积,单个油层厚度超140 m;“杂”是指具有十分复杂的岩性,井上钻遇多种类型岩性;“强”是指储层非均质性强,横向、纵向储层物性差异程度较高;“大”是指储量规模大。纵向上,含砾使得地层岩性复杂,非均质性强,岩性识别及参数评价存在不确定性;平面上,两期扇体叠置导致地震响应变化大,储层横向预测存在困难,岩性及物性差异大,储层横纵向非均质性强,东三段油藏

为渤海首例巨厚砂砾岩油藏注水开发项目,储层精细研究及开发方式在渤海油田无类似研究经验可借鉴,缺少开发经验。

东三段在采用大井距和多层合注合采注水开发方式时,由于纵向上夹层没完全隔开,始终存在层间以及厚油层内的干扰问题,不恰当的开发模式会导致层间、层内不同部位吸水能力、出油状况以及水淹程度不同,生产动态上反映出较大的层间矛盾,从而影响各层段以及层内油藏整体的均衡动用和油藏最终采收率。为了提高各层及层内储量均衡动用程度和油藏最终采收率,结合国内外类似油藏成功开发经验,需要通过建立层间干扰表征模型,明确层间和层内干扰的实质,形成多层合采产能预测方法,分析多层合采产能主控因素,为优化论证油藏开发层系、层内分段注采模式和合理井网井距,提升C油田东三段强非均质巨厚油藏注水开发效果,为东三段巨厚油藏制定合理的开发策略奠定实验基础。

## 2 干扰系数

目前,定量表征层间干扰程度的方法是通过定义层间干扰系数来表征多层合采开发导致油井的产液能力、产油能力和采出程度相较于单注单采时的降低程度<sup>[8-10]</sup>,如式(1)一式(3),包括采液指数干扰系数式(1)、采油指数干扰系数式(2)和采出程度干扰系数式(3)。其中,采液指数可替换为日产液量,定义为日产液量干扰系数;采油指数可替换为日产油量,定义为日产油量干扰系数;采出程度可替换为累产油量或累产液量,定义为累产油量或累产液量干扰系数。

$$\alpha(t) = \left[ \sum_{i=1}^n J_{\text{dli}}(t) - \sum_{i=1}^n J_{\text{hli}}(t) \right] / \sum_{i=1}^n J_{\text{dli}}(t) \quad (1)$$

$$\beta(t) = \left[ \sum_{i=1}^n J_{\text{doi}}(t) - \sum_{i=1}^n J_{\text{hoi}}(t) \right] / \sum_{i=1}^n J_{\text{doi}}(t) \quad (2)$$

$$\gamma(t) = \left[ \sum_{i=1}^n E_{\text{rdi}}(t) - \sum_{i=1}^n E_{\text{rhi}}(t) \right] / \sum_{i=1}^n E_{\text{rdi}}(t) \quad (3)$$

式中: $\alpha(t)$ 为采液指数干扰系数; $\beta(t)$ 为采油指数干扰系数; $\gamma(t)$ 为采出程度干扰系数; $J_{\text{dli}}(t)$ 为第*i*层单采时的采液指数,单位 $\text{m}^3/(\text{d}\cdot\text{MPa})$ ; $J_{\text{doi}}(t)$ 为第*i*层单采时的采油指数,单位 $\text{m}^3/(\text{d}\cdot\text{MPa})$ ; $E_{\text{rdi}}(t)$ 为第*i*层单采时的采出程度; $J_{\text{hli}}(t)$ 为多层合采时第*i*层的采液指数,单位 $\text{m}^3/(\text{d}\cdot\text{MPa})$ ; $J_{\text{hoi}}(t)$ 为多层合采时第*i*层的采油指数,单位 $\text{m}^3/(\text{d}\cdot\text{MPa})$ ; $E_{\text{rhi}}(t)$ 为多层合采时第*i*层的采出程度。

### 3 室内实验研究

层间非均质实验大致可以分为2大类<sup>[11-12]</sup>:一类是利用“一维岩心驱替实验”研究层间非均质干扰;另一类是利用“三维大模型驱替”实验研究层间非均质干扰。基于当前几种典型的干扰系数定量表征模型,最终确定建立以“单采、合采的采油指数”作为衡量指标和以“单采、合采的采出程度”作为衡量指标的2种层间干扰系数求取方法,计算公式如式(2)和式(3)所示。

实验研究考虑到实验压力以及渗透率条件能够比较准确模拟,因此,采用了一维岩心驱替实验装置进行研究,在现有层间非均质实验模拟基础上,还设计了层内干扰的实验。

实验提取C油田东三段储层主体特点,按照相似原理设计出多层合采层间与层内干扰研究物理模型,并开展多层合采层间干扰实验研究,以期探索层间干扰的实质,为建立多层合采层间干扰模型,为开展层间与层内干扰程度定量表征理论研究提供依据。

#### 3.1 层间干扰实验

##### 3.1.1 实验流程

①岩心气测孔隙度及渗透率测试,岩心抽真空饱和模拟地层水;②装入驱替装置,逐个测试单相水液测渗透率;③逐个岩心油驱水,建立束缚水饱和度,采用定流量的驱替方式,逐个岩心水驱油,求取残余油饱和度;④再次逐个岩心油驱水,建立束缚水饱和度,并与初期束缚水饱和度对比,直至束缚水饱和度与初次测定束缚水饱和度基本接近进行下步实验;⑤按照储层基本情况选择岩心组合,采用定流量的驱替方式,进行并联驱替,驱替至组合岩心含水至98%,计算总体驱油效率和每个岩心的驱油效率,与③中每个岩心驱油效率比较,得到干扰系数;⑥若上

述第5步结束时,产水基本来自最高贡献岩心,关闭此岩心,继续进行驱替,至组合岩心含水至98%,若此时产水基本来自最高贡献岩心,关闭此岩心,继续驱替,直至最后一个岩心。

##### 3.1.2 层间干扰实验方案

采用定流量对比单采和合采驱替产出情况,确定干扰系数<sup>[13-16]</sup>。实验单个岩心驱替流量为2 mL/min,4块岩心并联驱替流量采用8 mL/min,实验采用的4块岩心的基本参数如表1所示。

#### 3.2 层内干扰实验

模拟油藏存在层内非均质情况的生产动态,以及对应情况下的层内干扰情况,以期探索层内干扰的实质,以及检验采用干扰系数表征干扰效果。

##### 3.2.1 实验流程

①岩心气测孔隙度及渗透率测试,岩心抽真空饱和模拟地层水;②装入驱替装置,逐个测试单相水液测渗透率;③逐个岩心油驱水,建立束缚水饱和度,再以定流量的驱替方式,逐个组合岩心水驱油,求取组合岩心残余油饱和度;④再次逐个岩心油驱水,建立束缚水饱和度,并与初期束缚水饱和度对比,直至束缚水饱和度与初次测定束缚水饱和度基本接近进行下步实验;⑤装入实验装置,驱替至组合岩心含水至98%,计算总体驱油效率与③中每个岩心驱油效率比较,确定干扰效果影响程度。

##### 3.2.2 层内干扰实验方案

该实验是为了模拟油藏存在层内非均质情况的生产动态,以及对应情况下的干扰情况。实验采用的6块岩心,两两组合的模式进行实验,岩心基本情况数据如表2所示。3组串联组合(X1和4-3、X3和Z3、3-3和Z6)的渗透率分别是(55.69、59.26、58.13)×10<sup>-3</sup> μm<sup>2</sup>。

表1 层间干扰实验岩心基本参数

Table 1 Basic parameters of cores in interlayer interference experiment

岩心编号	长度/m	直径/m	干重/g	孔隙度/%	气测渗透率/10 <sup>-3</sup> μm <sup>2</sup>	液测渗透率/10 <sup>-3</sup> μm <sup>2</sup>
X4	0.058 2	0.025 4	53.60	26.42	66.89	69.66
Z6	0.052 5	0.024 4	50.84	30.70	99.34	53.49
X1	0.058 2	0.025 4	53.80	21.08	45.04	47.99
X3	0.058 3	0.025 4	55.63	21.08	12.11	21.27

表2 层内与层间非均质组合干扰实验岩心基本参数

Table 2 Basic parameters of core in the heterogeneous combination interference experiment within and between layers

岩心编号	长度/m	直径/m	干重/g	孔隙度/%	气测渗透率/ $10^{-3} \mu\text{m}^2$	液测渗透率/ $10^{-3} \mu\text{m}^2$
X1	0.058 2	0.025 4	53.80	21.08	45.04	47.99
Z6	0.052 5	0.024 4	50.84	30.70	99.34	53.49
X3	0.058 3	0.025 4	55.63	21.08	12.11	21.27
Z3	0.052 4	0.024 2	52.09	26.76	40.59	37.99
3-3	0.060 5	0.025 3	67.53	20.80	9.92	4.46
4-3	0.061 3	0.025 5	64.42	25.83	15.19	8.01

## 4 实验测试结果分析

### 4.1 层间干扰实验结果分析

模拟单个岩心单独驱替(单采)流量 2 mL/min, 并联驱替(合采)在 8 mL/min 情况下进行单个岩心驱替和并联驱替。为了与之前的文献实验结果相对比<sup>[17-26]</sup>, 采用相同含水率对应情况下的干扰系数进行了处理。当高渗岩心含水率达到 98% 时, 将其关闭。此时并联组合岩心含水率为 85%, 以此为含水率上限, 将合采采油指数与单采采油指数累加相比, 进行干扰系数分析。图 1 为定流量驱替条件下的单采与

合采的实验结果的对比, 由实验结果分析可知:

1) 合采时主要采油能力主要来自高渗层, 合采时的高渗层的驱替动力高于单采时的驱替动力(驱替压力梯度), 高渗岩心产油能力得到大幅度的提升。

2) 定流量驱替单采和合采时按照定义式计算有了干扰系数, 分析其原因是单驱与合驱时各岩心驱替动力(压力)完全不一样, 此时各岩心间并没有流体的交换。

3) 对比单采和合采采收率(关闭高渗层后继续驱替)可知: 高驱替压差(流量), 对低渗岩心可带来正面影响, 对高渗岩心却可能带来负面影响, 加速了优势渗流通道形成。

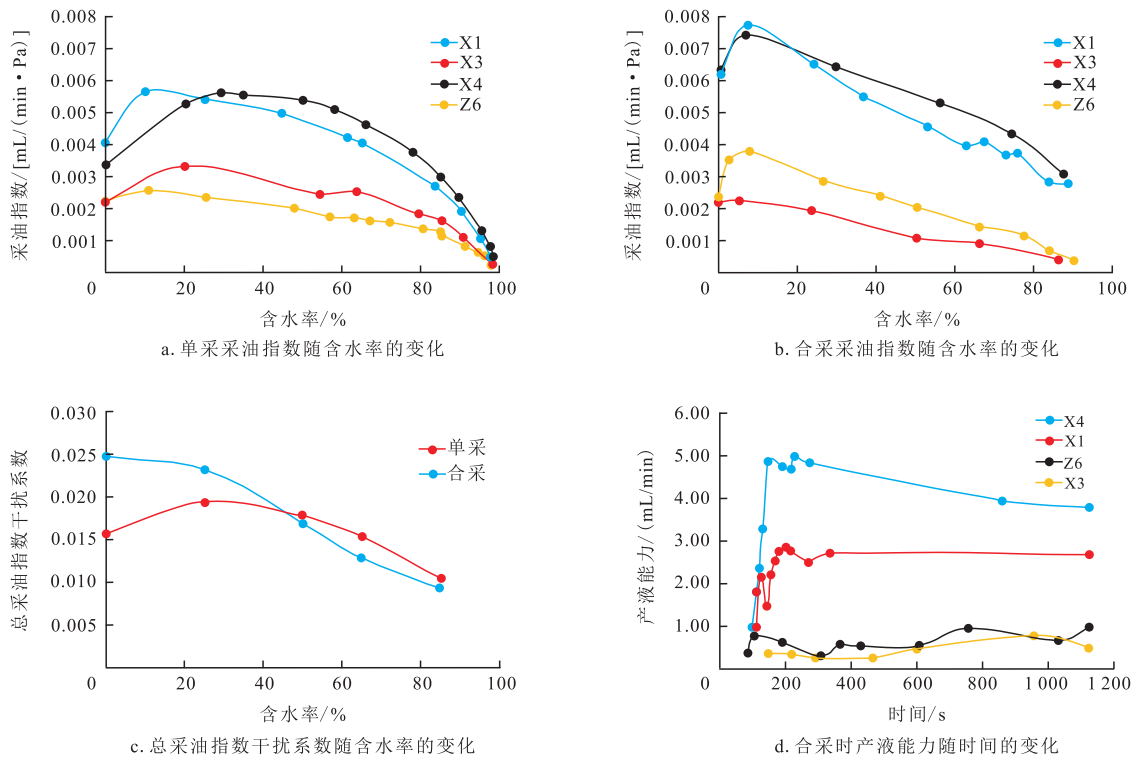


图1 定流量驱替条件下单采与合采的实验结果对比

Fig. 1 Comparison between experimental results of single production and combined production under constant flow displacement conditions

4) 巨厚砂砾岩油藏层间干扰随着时间推移,含水上升,干扰系数逐渐增大,但在高含水期有所下降(图2)。

#### 4.2 层内干扰实验结果分析

同时存在压力干扰与流体交换的干扰模拟实验,两岩心串联单独驱替(单采),合采时通过六通阀将串联岩心中部连通,驱替模式采用定流量模式。分析实验结果可知:

1) 对于串并结合驱替的模式,采油指数干扰系数在驱替的前半部分出现,在早期采油指数干扰系数较大,随着含水率增加采油指数逐渐变小(图3—图6),同时采油指数干扰系数也相应的变小(图7)。

2) 串并结合的模式在合采时必然同时存在层内的压力干扰与流体窜流,其单采和合采的流动路径、流动阻力发生变化,与前期的理论研究建立的模

型渗流过程完全不一致。虽然由定义计算依然出现了干扰系数,但可以看出:干扰系数只能表征不同驱替状态(流动的改变)带来的产量变化的影响,不能从本质上去描述层内干扰与窜流的问题。层内干扰的实质应该是不同储层渗流阻力变化随着时间的变化,导致储层流量分配的改变,其核心因素还是储层自身的非均质性带来的影响,而且是动态变化的;层内水窜必然沿着最小渗流阻力的流线发生,低渗(高渗流阻力)区域可能完全不能参与流动,造成大量剩余油产生,通过流动通道的调整,才能实现低渗区域的有效动用,如图8—图11所示。

### 5 结论与认识

1) 多层合采层间干扰实验研究表明,合采时主要采油能力来自于高渗层,高渗层的驱替压力梯度

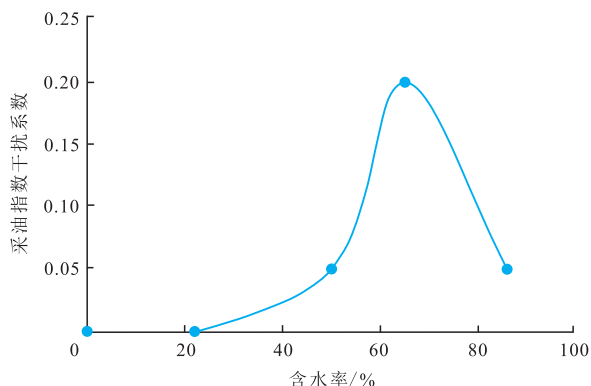


图2 采油指数干扰系数随含水率的变化

Fig. 2 Variation of production index interference coefficient with water cut

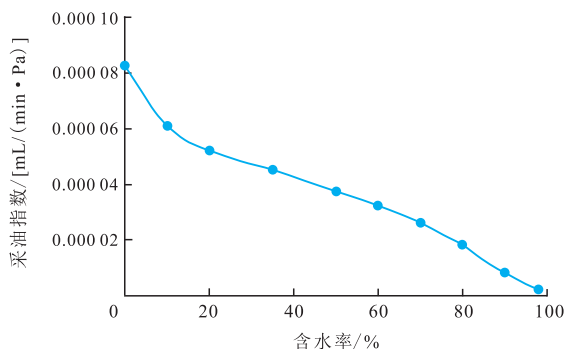


图3 岩心 X1 和岩心 4-3 串联单采采油指数随含水率的变化

Fig. 3 Variation of oil production index with water cut of core X1 and core 4-3 in series single recovery

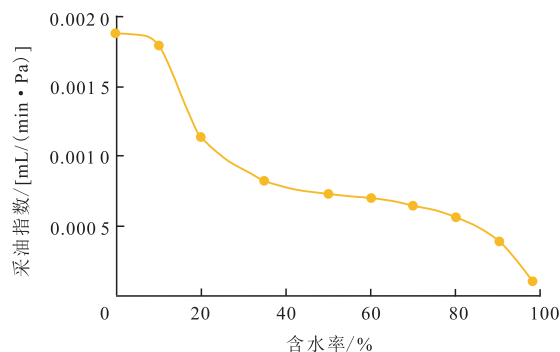


图4 岩心 X3 和岩心 Z3 串联单采采油指数随含水率的变化

Fig. 4 Variation of oil production index with water cut of core X3 and core Z3 in series single recovery

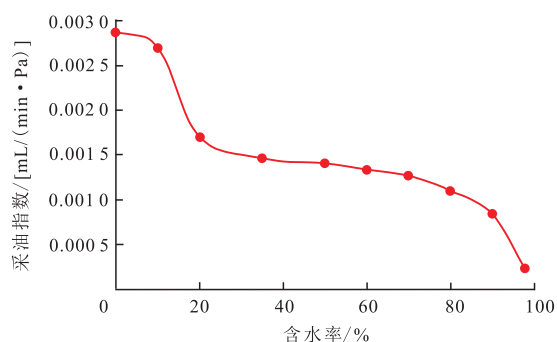


图5 岩心 3-3 和岩心 Z6 串联单采采油指数随含水率的变化

Fig. 5 Variation of oil production index with water cut of core 3-3 and core Z6 by series single recovery

高于单采时,高渗岩心产油能力得到大幅度的提升,导致层间干扰的原因是单驱与合驱时各岩心驱替压力梯度不同,建议以此作为依据,开展井网重组与调

整,提高油田采收率。

2) 层内干扰的实质是不同储层渗流阻力变化随着时间的变化,导致储层流量分配的改变,其核心

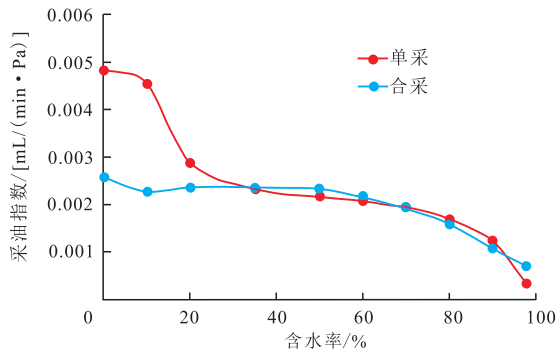


图6 采油指数随含水率的变化

Fig. 6 Variation of oil production index with water cut

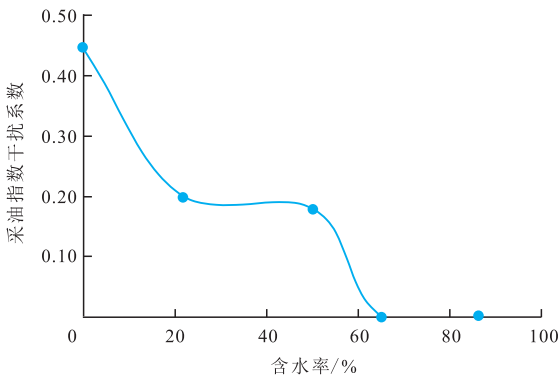


图7 采油指数干扰系数随含水率的变化

Fig. 7 Variation of production index interference coefficient with water cut

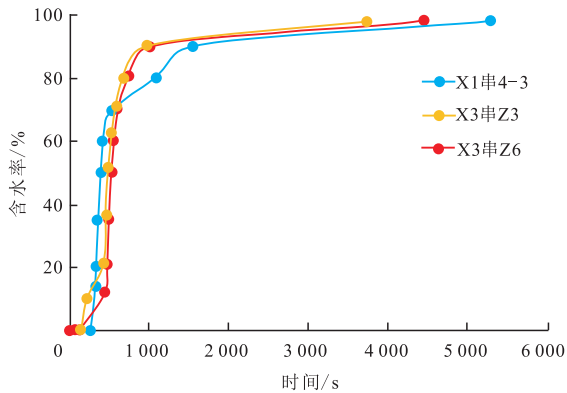


图8 单采时各岩心组合出口端的含水率随时间的变化

Fig. 8 Variation of water cut of each core combination with time during single production

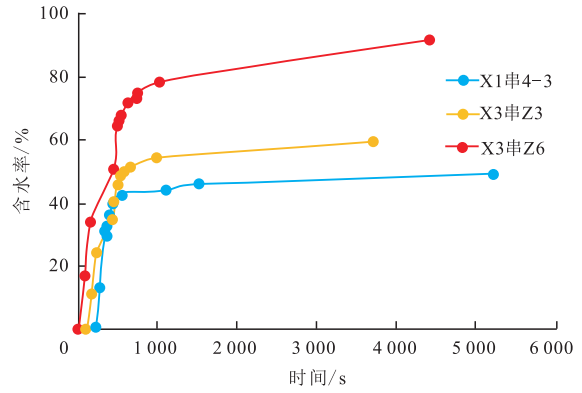


图9 单采时各岩心组合的含水率随时间的变化

Fig. 9 Variation of water cut of each core combination with time during single production

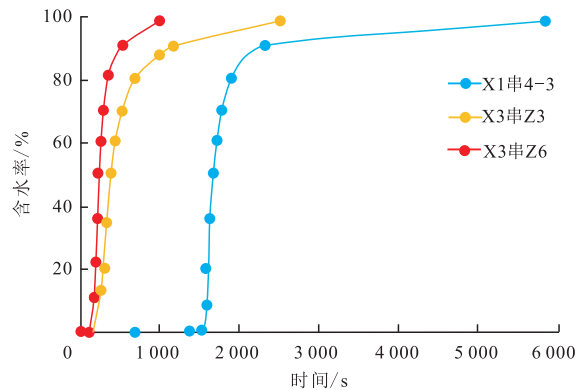


图10 合采时各岩心组合出口端的含水率随时间的变化

Fig. 10 Variation of water cut at the outlet of each core combination during combined production

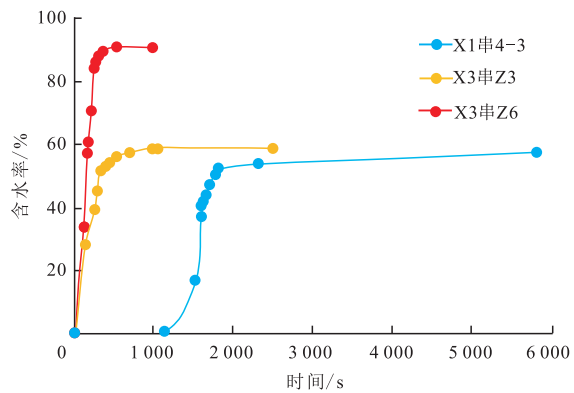


图11 合采时各岩心组合出口端的含水率随时间的变化

Fig. 11 Variation of water cut over time at the outlet of each core combination during combined production

因素是储层自身的非均质性带来的影响。

3) 巨厚层砂砾岩油藏,水窜必然沿着最小渗流阻力的流线发生,低渗(高渗流阻力)区域可能完全不能参与流动,造成大量剩余油产生,通过流动通道的调整,才能实现低渗区域的有效动用。

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