引用格式：张敏，金忠康，冯绪波．高含水油藏流动非均质性的表征及应用[J]. 油气藏评价与开发，2025，15(2)：274-283.
ZHANG Min, JIN Zhongkang, FENG Xubo. Characterization and application of flow heterogeneity in high water cut reservoirs[J]. Petroleum Reservoir Evaluation and Development, 2025, 15(2): 274-283.
DOI: 10.13809/j.cnki.cn32-1825/te.2025.02.012

高含水油藏流动非均质性的表征及应用

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摘要：注水开发油藏随着开发的深入，水驱矛盾愈加突出，地下渗流场、压力场和剩余油饱和度场差异较大，开展定量化流场差异性评价研究，可以有效地指导地下流场优化调控，动用挖掘不同类型剩余油，提高油藏水驱采收率。该研究对流动非均质性的动静态影响因素进行了分析，指出了考虑各种因素作用下评价流动非均质性的复杂性，以及开展量化评价研究的重要性。对比了多种不同的非均质性表征方式，最终优选洛伦兹系数进行评价。该系数适用于非正态分布对象，且分布介于0～1，可以进行流动差异性的定量表征。另外，选取流场最直观的表现流速作为计算指标来建立流动非均质性评价方法。为使计算更加快捷、方便、直观，建立平板模型解决裂缝内流动表征的问题，减少数值模拟中压裂缝的模拟工作，结合数值模拟与MATLAB编程技术，将模拟得到的压力数据转化为流速，计算得到以流速为评价对象的洛伦兹系数，实现了参数计算程序化问题，从而建立渗流差异表征方法。考虑有无高渗条带、有无裂缝、裂缝角度、高渗条带渗透率等因素，利用该方法对三角形井网、半反七点井网设计方案，研究洛伦兹系数与采收率的关系。分析发现对于三角形井网，洛伦兹系数小于0.94时，二者呈线性关系；而当洛伦兹系数大于0.94时，随着洛伦兹系数增大采收率呈指数下降，半反七点井网则在洛伦兹系数为0.96时发生这一变化。因而得到三角形井网和半反七点井网下流场差异性强弱界限值，分别为0.94和0.96。进而对G7断块开展现场应用，评价得到该区块有2个渗流差异较强的砂体，并对评价后渗流差异性强砂体制定调整对策，分别是井网优化+细分注水改善平面及纵向渗流差异，流场调整均衡平面渗流差异，开展周期注水降低流动非均质性。进而开展数值模拟对调整前后相应指标进行了对比，洛伦兹系数降至临界值以下，10 a采收率提高1个百分点，起到了控水稳油的效果。该研究切实可靠，可以指导油藏流场描述、剩余油挖潜，对油藏提高采收率具有重要意义。同时，主要研究对象为苏北断块油藏常见井网，在实际推广应用中应针对具体井网形式重新评价确定界限值。

关键词：高含水油藏；流动非均质性评价；裂缝内流动表征；降低渗流差异调整对策；剩余油挖潜
中图分类号：TE357 **文献标识码**：A

Characterization and application of flow heterogeneity in high water cut reservoirs

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Abstract: As waterflooding reservoirs continue to be developed, the conflicts in water flooding become more pronounced, with significant differences in the underground flow field, pressure field, and remaining oil saturation field. Conducting quantitative evaluation of flow field differences can effectively guide the optimization and control of underground flow fields, mobilize and exploit various types of remaining oil, and enhance the waterflooding recovery efficiency of the reservoir. The study analyzed the factors influencing flow heterogeneity, including static reservoir heterogeneity and dynamic factors such as fluid viscosity, well pattern, and artificial fractures. It highlighted the complexity of flow heterogeneity evaluation and emphasized the necessity of quantitative evaluation. Next, various methods for characterizing heterogeneity were compared, and the Lorenz coefficient was selected as a key parameter for characterizing flow heterogeneity. This coefficient is applicable to non-normally distributed data, ranging from 0 to 1, and can quantitatively characterize flow variability. Additionally, flow velocity, as the most intuitive representation of the flow field, was chosen as the computational indicator to develop a method for evaluating heterogeneity. From the parameter calculation results graph, the diagonal line with a slope of 1, where the Lorenz coefficient was 0, was referred to as the "completely homogeneous line," indicating the absence of heterogeneity in the evaluated object. Conversely, the largest triangle formed by this diagonal line and the x or y axis, where the Lorenz coefficient was 1, was termed the "completely heterogeneous line." To make computation faster, simpler, and more intuitive, a plate model was developed to characterize the flow in the fracture and reduce the

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基金项目：中国石化科技攻关项目"江苏油田百万吨稳产开发关键技术研究"（P22025）。

simulation workload of hydraulic fractures in numerical simulations. By integrating the pressure distribution data from numerical simulation with MATLAB programming, the pressure was converted into flow velocity, enabling the calculation of the Lorenz coefficient using flow velocity as the evaluation criterion. Consequently, a method for characterizing flow heterogeneity was established. Furthermore, the paper designed experimental plans for triangular well patterns and semi-inverse seven-spot well patterns considering factors such as the presence or absence of high-permeability zones and fractures, fracture angles, and permeability of high-permeability zones to investigate the relationship between the Lorenz coefficient and recovery coefficient. Among them, 17 schemes were designed for the triangular well pattern, while 21 schemes were developed for the inverted seven-spot well pattern. The analysis revealed that for triangular well patterns, a linear relationship was observed when the Lorenz coefficient was below 0.94. However, once the Lorenz coefficient exceeded 0.94, the recovery factor decreased exponentially with the increasing Lorenz coefficient. For inverted seven-spot well patterns, this transition occurred when the Lorenz coefficient reached 0.96. The thresholds distinguishing strong and weak seepage field differences were determined to be 0.94 for the triangular well pattern and 0.96 for the semi-inverse seven-spot well pattern. Specifically, for triangular well patterns, when the Lorenz coefficient exceeded 0.94, the recovery factor dropped sharply, indicating excessive flow heterogeneity. In such cases, flow field adjustments were necessary to improve development performance. Similarly, for inverted seven-spot well patterns, optimization and adjustment of the flow field were required when the Lorenz coefficient reached 0.96. Finally, the G7 reservoir was evaluated using the above method and adjustments were implemented to reduce seepage diversity. The evaluation yielded Lorenz coefficients of 0.949 6 for and 0.954 0 for two sand bodies, identifying these two sand bodies as areas with significant seepage disparities within the block. Further analysis revealed the reasons for the strong seepage disparities for the two sand bodies. In the eastern well area of the first sand body, a localized high-permeability zone was present, whereas the central and western regions exhibited weaker seepage. The causes were attributed to both static and dynamic factors: statically, the reservoir heterogeneity resulted in better physical properties and stronger seepage in the central and eastern parts, while the western part had poorer physical properties and weaker seepage; dynamically, the central region suffered from an incomplete well pattern, whereas the eastern region had a more well-developed well pattern. Although the western region had poorer physical properties, the G7-11 well, after the fracturing stimulation and with a relatively complete well pattern, exhibited locally strong seepage. In the second sand body, the central and eastern regions showed significant seepage disparities. The analysis attributed this to the strong reservoir heterogeneity causing substantial seepage differences statically, while dynamically, the overly dense well pattern and injection-production regime in the central and eastern regions exacerbated seepage disparities. Consequently, flow field adjustments were necessary. Strategies were formulated to address the pronounced seepage heterogeneity in these sand bodies post-evaluation. These strategies include optimizing the well pattern combined with segmented water injection to ameliorate both areal and vertical seepage disparities, adjusting the flow field to balance areal seepage differences, and implementing cyclic water injection to reduce flow heterogeneity. Numerical simulation was conducted to forecast the development trends, and a comparison of relevant indicators before and after the adjustments was carried out. The results showed that the Lorenz coefficient was reduced below the critical threshold, and the oil recovery efficiency increased by 1 percentage point over 10 years, effectively achieving water control and oil stabilization. The findings demonstrate that the proposed method can accurately evaluate seepage heterogeneity and help explore the residual oil, offering significant guidance for improving oil recovery efficiency. Meanwhile, this study determines the critical thresholds for strong and weak fluid flow heterogeneity in triangular and semi-inverse seven-spot well patterns, which are commonly found in Subei fault-block reservoirs. In practical applications, these threshold criteria should be re-evaluated based on specific well pattern configurations.

Keywords: high water cut reservoirs; flow heterogeneity evaluation; flow characterization in fracture; adjustment strategies to reduce seepage difference; residual oil exploration

目前，苏北主力油田均已进入高含水、特高含水阶段，采出程度高、整体水淹严重，剩余油高度分散，无效水循环严重，常规调整手段效果差、空间小[1-2]。要进一步提高采收率，需要开展流场精细描述，精准定位高渗通道，精准指导流场调整。

当前中国从事油藏流场表征的学者较多，主要借助油藏数值模拟与模糊数学的方法，选取表征参数加以一定的评价方法开展定量表征研究。陈民锋等[3]利用流动能力指数、日产液量和日注入量等参数，从动静态方面对剩余油进行定量表征；彭仕宓等[4]利用岩心分析资料得到各参数权重，并运用模糊综合评判法，对大孔道、窜流通道进行了定量表征；邹桂丽等[5]基于数值模拟得到各层优势流场分布，并针对性地开展了分区注采耦合与注采调控等调整措施；赵传峰等[6]考虑影响强流场分布的动静态因素，提出分级模糊评判方法，对高含水期油藏开展窜流通道的模糊评判；姜瑞忠等[7]则基于流场分布主要影响因素，利用BP神经网络聚类法，进行了优势流场与弱势流场的划分。目前，流场定量评价方法较为丰富，但大多采用多参数加以数学方法评判，现场应用较为复杂；另外，基于油藏数值模拟评价大部分为定性评价，不利于精准指导现场调整，且以上方法都没有进行定量评价，而直观、准确、实用的流场定量评价方法对指导现场

开发调整具有重要意义。

研究区域为苏北低渗断块油藏，大多采用压裂开发，在流场差异性定量评价中，需要综合考虑储层、人工裂缝、流体性质及井网等影响因素。利用已有方法需要考虑的参数较多，权重赋值主观因素较大，导致评价结果的不够客观准确。针对以上问题，选取了直观反映流场分布的流速这一参数，引入洛伦兹系数这一评价方法，开展了流动非均质性表征、评价研究。随后，基于流动非均质性评价方法，开展了G7断块渗流差异性的研究，并制定降低流动非均质性的调整对策，从而形成适应于苏北油田的流场评价、调整技术，为该类油藏提高采收率提供借鉴。

1 流动非均质性定量描述的意义

1.1 流动非均质性的影响因素

1.1.1 静态因素

储层非均质性普遍存在，对渗流非均质性起着基础性作用[8-10]。以含高渗条带储层模型为例，垂直高渗条带布油水井驱油面积远高于沿高渗条带布井，沿高渗条带布井极易产生窜流通道，因而二者在日产液量、含水率及累计产油量的变化上也有明显不同。

1.1.2 动态因素

1）流体黏度影响

被驱替流体与驱替流体流度差别引起指进现象，随着原油黏度的增大，流度比增加，指进现象加剧，流动非均质性随之增加[11-12]。

2）井网影响

井网形式不同时，产生流动非均质性的不同，水驱方向、扫油面积都不同，因而剩余油分布各有差异，最终采收率也不相同。

3）人工裂缝影响

人工裂缝的存在对流动非均质性具有双重影响[13-17]，如果裂缝沿高渗带会加剧非均质性，而如果裂缝垂直高渗带则会提高低渗区渗流能力，起到平衡流场的作用。

1.2 流动非均质性定量描述的意义

通过以上分析可知，储层非均质性的描述和评价能一定程度上反映渗流差异性，但无法明确反映裂缝的双重影响、流体性质及井网对渗流差异的影响，因此选取一个可以综合反映动静态及流体性质对渗流差异影响的参数，进而建立参数评价方法来定量表征油藏流动速度非均质程度，对于高含水期油藏流场评价及调整具有重要实用价值。

2 流动非均质性的表征及标准图版的建立

针对缺少渗流差异定量表征方法，难以量化描述流动非均质性的问题。引入洛伦兹系数表征流动非均质性，解决了裂缝等效渗流、数据提取和编程计算等技术问题，形成了实际油藏流动非均质性计算方法，并开展了开发指标与表征参数研究，形成了渗流差异表征实用技术。

2.1 表征参数的选取

储层非均质性常用评价方法有极差、突进系数、变异系数等[18-19]，蒋明煊[20]对渗透率非均质性评价实例对比表明，以上方法存在一定局限性，评价结果介于(0,∞)，不能确定平面整体非均质程度的大小，因而引入了洛伦兹系数[21]，其计算结果介于0～1，适用于参数的随机分布，可以比较合理地评价储层平面非均质程度。表1为不同非均质性表征方法计算结果及实用性对比。

表1 不同非均质性计算方法对比

Table 1 Comparison of different methods for calculating heterogeneity

表征方法	计算方法	示例结果	局限
极差	$T(k)=\max(k)-\min(k)$	2 543	难以建立起油藏非均质程度概念(0～∞)
突进系数	$J(k)=\max(k)/\bar{k}$	424.5	难以建立起油藏非均质程度概念(0～∞)
变异系数	$V(k)=\sqrt{E(k^2)-E^2(k)}/E(k)$	1.315	难以建立起油藏非均质程度概念(0～∞)
洛伦兹系数	$L(k)=2\int_0^1 \frac{\sum_{i=1}^{m}k_i n_i}{\sum_{i=1}^{n}k_i n_i}\mathrm{d}\left(\frac{\sum_{i=1}^{m}n_i}{\sum_{i=1}^{n}n_i}\right)-1$	0.656 8	可以确定非均质程度(0～1)

注：$T(k)$为极差；$J(k)$为突进系数；$V(k)$为变异系数；$L(k)$为洛仑兹系数；k为渗透率，单位10^{-3} μm²；$\bar{k}$为渗透率平均值，单位10^{-3} μm²；$\sqrt{E(k^2)-E^2(k)}$为样本数据的标准差；$E(k)$为样本数据的平均值；k_i为第i个样本的渗透率，单位10^{-3} μm²；n_i为第i个样本的编号；m为总的渗透率划分范围个数；n为总的岩样个数。

2.2　流动非均质性的计算

2.2.1　参数的选取与提取

用于计算的参数要求能够反映流动强弱情况,进而得到流动差异性,而流速是最能直观地反映油藏流场强弱分布的参数,因而选择渗流速度作为计算参数。研究中以油藏流速为参数计算洛伦兹系数(LRZ),表征油藏流动非均质性。LRZ系数越大,表明流动非均质性越强。

流动非均质性评价参数计算过程为:在油藏内均匀设置监测点,然后计算所有监测点渗流速度,分别计算各渗流速度贡献百分比及其对应监测点数量百分比,以累计渗流速度贡献百分比为纵坐标,以累计监测点数量百分比为横坐标在直角坐标系下绘制曲线,曲线*ACEA*围成的弓形面积与三角形*ACD*面积的比值即为LRZ系数。如图1所示,对于渗流速度完全相同的油藏,该曲线为一条斜率为45°的直线,称为"完全均质线"。

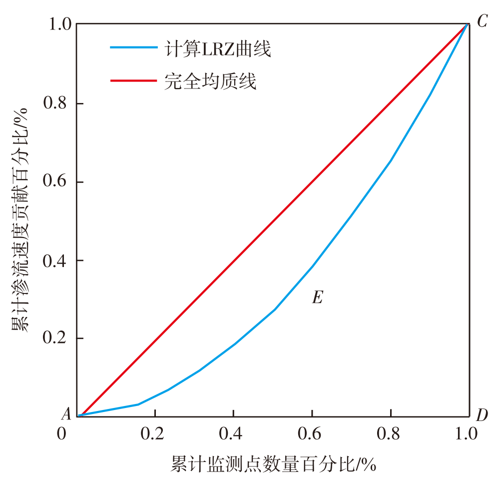


图1　洛伦兹曲线示意图

Fig. 1　Schematic of Lorenz curves

在完全均质线上,洛伦兹系数为0,表明评价对象完全均质;曲线离完全均质线越远,洛伦兹系数越大,评价对象非均质性越强;至折线ADC称为"完全非均质线",洛伦兹系数为1[22-23]。

2.2.2　裂缝等效渗流描述

评价参数选用数值模拟后的流速数据,而低渗油藏一般都采取水力压裂方式开发,给数值模拟过程带来繁重工作量,因此通过理想平板模型和立方定律,得到了裂缝内等效渗流描述方式,从而极大地提高工作效率[24-29]。

1)基质内渗流模型

在基岩系统中,由质量守恒原理得到连续性方程,见式(1),代入运动方程和流体的状态方程,设定边界条件和初始条件,可得到基岩系统完整的数学模型。

$$-\nabla(\rho\boldsymbol{v}) + \rho Q = \frac{\partial(\varphi\rho)}{\partial t} \tag{1}$$

式中:ρ为流体密度,单位kg/m³;$\boldsymbol{v}$为流体的运动速度,单位m/s;Q为在单位时间内单位体积产生或湮没的流体体积,单位m³/s;φ为基岩系统的孔隙度,%;t为时间,单位s。

2)裂缝内渗流模型

实际流体流动系统中,根据动量守恒定律可以得到不可压缩流体运动的基本微分方程[9]:

$$\rho\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = \rho\boldsymbol{F} - \nabla p + \nabla[\mu(\nabla\boldsymbol{v} + \nabla\boldsymbol{v}^{\mathrm{T}})] \tag{2}$$

式中:$\boldsymbol{F}$为单位质量上的质量力,单位m/s²;μ为流体黏度,单位mPa·s;p为压力,单位Pa;T为转置符号。

但式(2)中的裂缝渗流速度难以表征,导致裂缝渗流求解困难,因而进行了裂缝内等效渗流的表征研究。

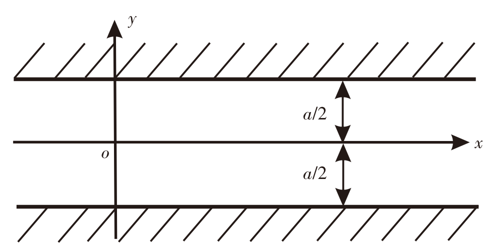
3)裂缝模型简化

水力学研究认为裂缝流量与裂缝开度的3次方成比例,即遵循立方定理(Cubic law),裂缝对油藏渗流能力改善程度与裂缝开度、裂缝密度、流体性质等有关,这样基于立方定理就可以简化裂缝内渗流数学模型,降低数值的模拟难度[30-34]。

假定岩石裂缝是由2片光滑平行板构成的缝隙,即所谓的平行板模型(Parallel Plate Model),缝宽(a)为常数,如图2所示。缝隙中的黏性牛顿流体运动符合Navier-Stokes方程,即:

$$\rho\frac{\mathrm{d}u_i}{\mathrm{d}t} = \rho f_i - \frac{\partial}{\partial x_i}\left(p + \frac{2}{3}\mu\nabla\boldsymbol{v}\right) + \frac{\partial}{\partial x_i}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] \tag{3}$$

式中:u_i、u_j分别为各坐标轴上的分量;f_i为作用在流体上的体积力,单位N;x_i为沿x坐标轴方向位移;y_i为沿y坐标轴方向位移。



注:a为裂缝宽度,单位m。

图2　平行板缝隙理想模型

Fig. 2　Ideal model of parallel plate fracture

基于流体不可压缩,黏性系数(μ)为常数,当流速很小时很显然该模型简化为沿x方向的平行流动,当流动是恒定的,且流速在z方向没有变化,流速为抛物线分布,最终得到:

$$q = -\frac{\rho g a^3}{12\mu}\frac{\mathrm{d}h}{\mathrm{d}x} = -\frac{g a^3}{12\gamma}J_{\mathrm{f}} \tag{4}$$

式中：q 为流量，单位 m^3/s；g 为重力加速度，单位 m/s^2；a 为裂缝宽度，单位m；h 为垂直裂缝面方向的位移，单位m；γ 为流体的动力黏滞系数，单位 m^2/s；J_f 为裂缝内水力梯度，单位m/m。

式(4)即为立方定理(Cubic law)。由裂缝断面流量可求得流体运动的平均速度：

$$\boldsymbol{\nu} = \frac{q}{a} = -\frac{\rho g a^2}{12\gamma} J_f = -K_f J_f \qquad (5)$$

式中：K_f 为渗透系数，单位 m^2。

对于倾斜裂缝，按照类似推导可得：

$$\boldsymbol{\nu} = -\frac{\alpha^2}{12\gamma}(\nabla p + \rho g \nabla D) = -\frac{K_f}{\gamma}(\nabla p + \rho g \nabla D) \qquad (6)$$

式中：D 为流体在倾斜裂缝面的位移，单位m。

从式(2)—式(6)的推导可看出：裂缝系统流动的模式与基岩系统类似，因此其数学模型与基岩系统完全相似，从而得到裂缝内渗流等效描述方式。

2.2.3 参数计算流程化

该研究将数值模拟技术与MATLAB编程相结合，实现了参数计算的程序化及结果的可视化。基于精细三维地质建模及数值模拟工作，可以得到区块压力分布数据，通过MATLAB编程实现压力到流速的转化，并且能够得到直观流速等值线图，最后以流速为变量编程计算可得到单砂体洛伦兹系数，进而反映该平面流动的非均质程度大小，如图3所示。

2.3 建立表征参数标准模板

苏北油田为复杂断块油藏，井网形式以三角形和半反七点井网为主，基于2种井网形式开展了渗流非均质性强弱界限值的研究。

2.3.1 数值模拟模型的设计

首先针对三角形井网、半反七点井网，考虑有无高渗条带、有无裂缝、裂缝角度、高渗条带渗透率等因素分别设计了17、21个方案，研究洛伦兹系数与开发指标关系。2种井网下各方案数值模拟模型示意图见图4。

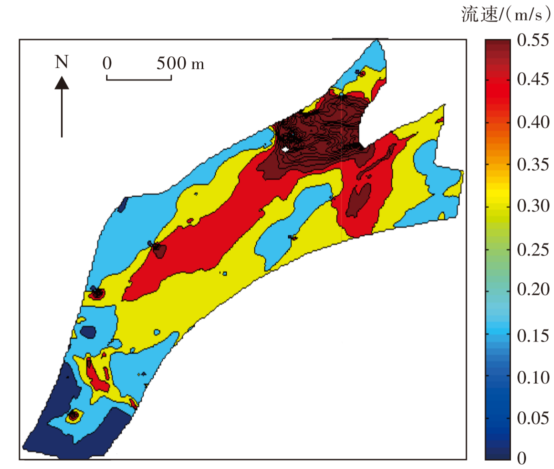
1）对比时间点选取

为选取合适时间点，以三角形井网为例，开展生产年限与洛伦兹系数的关系研究，得到洛伦兹系数随时间的变化规律，图5为统一井网下洛伦兹系数随时间变化曲线。

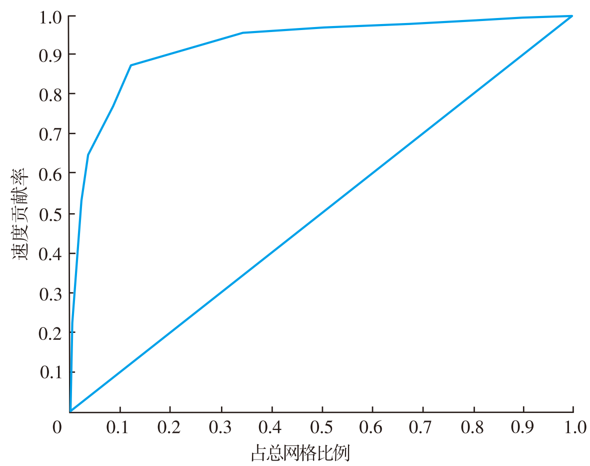
以上研究表明：同一井网、同一生产制度下，不同时刻的洛伦兹系数在某一值附近，因而后续选取生产2 a时对应指标进行对比分析。

2）标准图版建立

基于数值模拟结果，利用MATLAB编程计算各模型



a. 流速分布



b. 洛伦兹曲线

图3 流动非均质性MATLAB编程计算结果示意图

Fig. 3 Schematic of MATLAB programming calculation results for flow heterogeneity

的洛伦兹系数，并建立2种井网形式下采收率–洛伦兹系数标准图版(图6)。

由图6a可知，对于三角形井网，当LRZ小于等于0.94时，二者呈线性关系，采收率随速度非均质性增加而略有增加；但当LRZ大于0.94后，随LRZ增大采收率急剧减小。

由图6b可知，对于半反七点井网，当LRZ小于等于0.96时，二者呈线性关系，采收率随速度非均质性增加而略有减小；但当LRZ大于0.96后，随LRZ增大采收率急剧减小。

3 G7断块流动非均质性评价及流场调整

3.1 G7断块流动非均质性评价

G7断块为苏北典型低渗特高含水油藏，平均渗透率为 46×10^{-3} μm^2，目前含水率为95%，采油速度为0.46%，

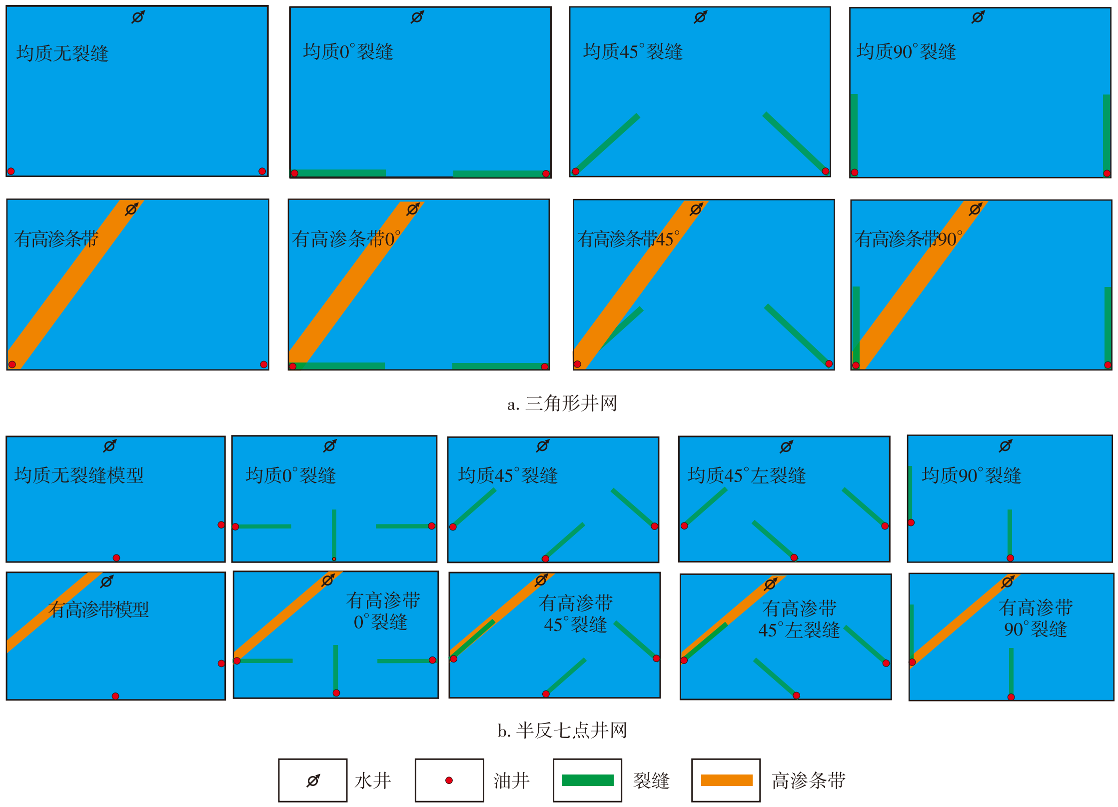


图4 2种井网形式下各方案数值模拟示意图

Fig. 4 Schematic of numerical simulation results for each scheme under two well pattern types

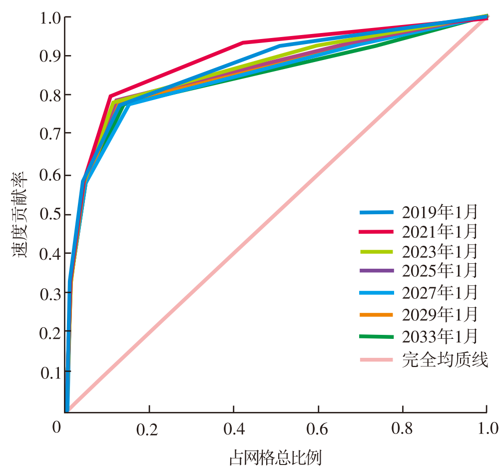


图5 同一井网下洛伦兹系数(LRZ)随时间变化规律

Fig. 5 Variation of Lorenz coefficient (LRZ) with time under the same well pattern

处于低速低效开发阶段。以该断块为例，开展了流动非均质性参数评价及调整对策研究。

3.1.1 流动非均质性小砂体分析

通过评价得到G7断块阜二段第二砂层组的三砂体层系中5个砂体洛伦兹系数小于0.94，因此这些层流动非均质性较小，不作为流场调整的重点。

3.1.2 流动非均质性强砂体分析

流动非均质性较强的层包括阜二段第二砂层组的二

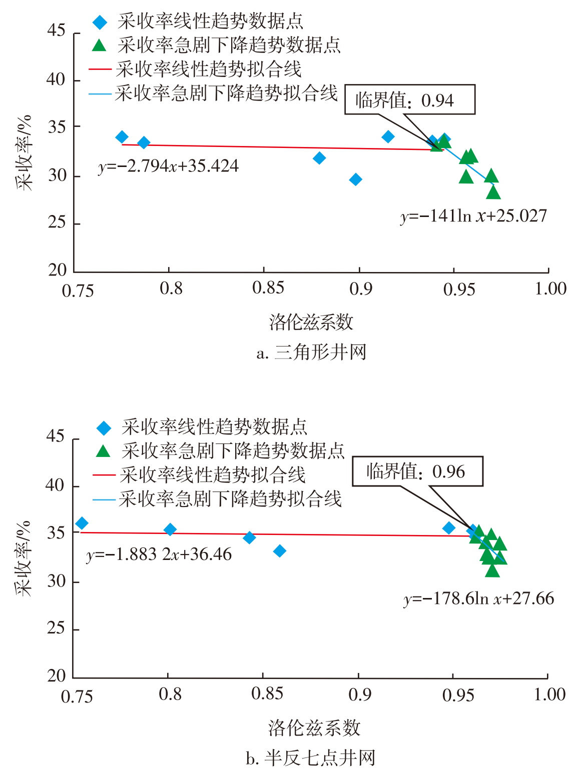
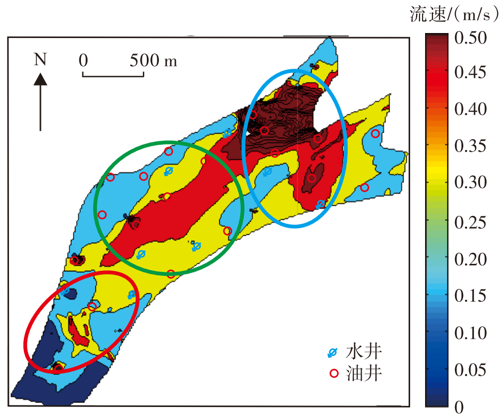


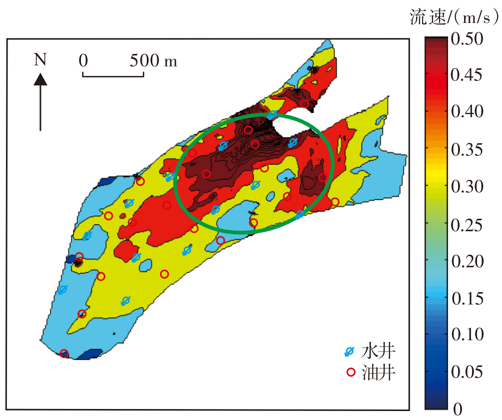
图6 2种井网形式下采收率随洛伦兹系数变化曲线

Fig. 6 Change in recovery rate with Lorenz coefficient under two well pattern types

砂体和阜二段第三砂层组的一砂体，流速分布平面图如图7所示。



a. 阜二段第二砂层组的二砂体流速平面图



b. 阜二段第三砂层组的一砂体流速平面图

图7 苏北盆地金湖凹陷G7断块两强流动非均质性砂体流速平面图

Fig. 7 Flow velocity diagrams for two sand bodies with strong flow heterogeneity in G7 fault block of Jinhu Sag in Subei Basin

阜二段第二砂层组的二砂体,洛伦兹系数为0.949 6,且东部井区存在局部高渗区(图7a中蓝圈区域),中西部渗流较弱(图7a中绿圈区域)。分析产生原因:静态上受储层的非均质性影响,中东部物性好渗流强,西部物性差渗流弱;动态上中部井网不完善,而东部井网较为完善,西部虽然物性较差,但G7-11经过压裂改造加之井网较为完善,因而局部渗流强(图7a中红圈区域)。

阜二段第三砂层组的一砂体,洛伦兹系数为0.954 0,且中东部存在局部高渗区(图7b中绿圈区域)。分析原因:静态上中东部储层非均质性强造成渗流差异大;动态上中东部井网过密及注采制度造成渗流差异大。

3.2 G7断块降低流动非均质性调整策略

3.2.1 井网优化+细分注水,改善平面及纵向渗流差异

不同井网形式对流场及剩余油分布具有较大影响[35-37]。主力砂体阜二段第二砂层组的二砂体、阜二段第三砂层组的一砂体物性好,渗流强度大,主体部位重建井网,拉大井距形成大井网,合理控制注水量;非主力砂体阜二段第三砂层组的五砂体,物性较差,渗流强度小,形成小井网,同时加强注水。方案涉及11口井工作量,如表2所示。实施后主力砂体阜二段第二砂层组的二砂体、阜二段第三砂层组的一砂体构造中部强势流场注采井距在300 m左右,构造西翼及非主力砂体的弱势流场注采井距在250 m左右。方案实施后,2019年累计增油量2 000 t,洛伦兹系数控制在0.900 0左右,渗流差异性变小。井网调整工作量见表2。

3.2.2 流场调整,均衡平面渗流差异

对流动非均质性强井区通过控强扶弱,调整油水井生产制度,达到均衡流场,降低流动非均质性目的。如G7-6井组,控制强势流线G7-2井生产参数,上调渗流低速区G7-1井生产参数,1个月后G7-2井动液面下降,G7-1井动液面上升,且2口井的含水率分别下降4%和2%,井组日增油量3.3 t,取得较好的效果。

表2 苏北盆地金湖凹陷G7断块层系井网调整工作量

Table 2 Well pattern adjustment workload for G7 fault block in Jinhu Sag, Subei Basin

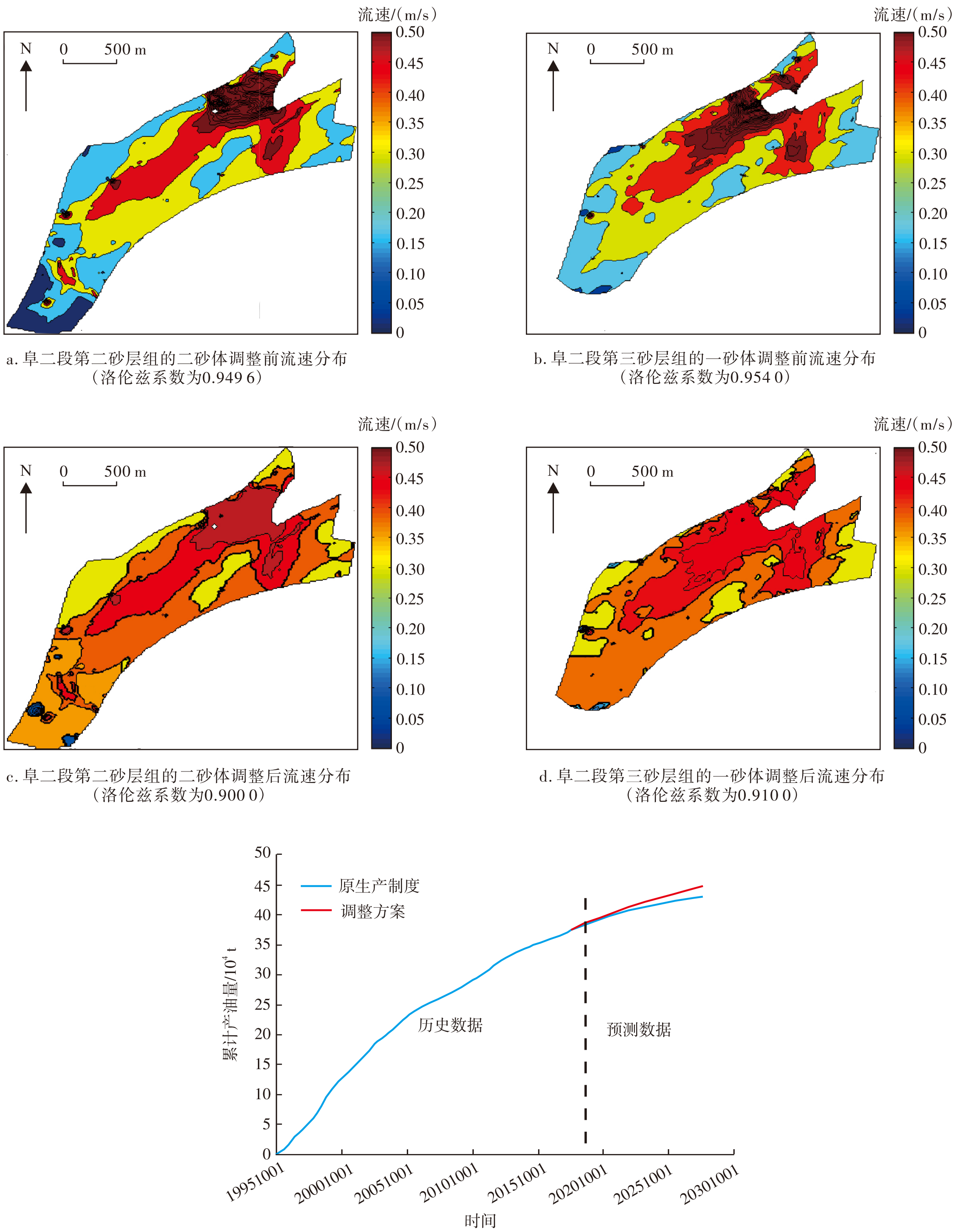
井号	措施类型	措施内容
G7-7	复产	复产
G7-27	调层	补开10-12号层,调层生产阜二段第三砂层组的三、四砂体
CG7-12	动态停	动态关停,拉大井距,改变水线
G7	捞桥塞合采	恢复阜二段第二砂层组的二砂体和第三砂层组的一砂体生产
G7-1	捞桥塞合采	恢复阜二段第二砂层组的二砂体和第三砂层组的一砂体生产
G7-20	补层合采	补开阜二段第二砂层组的二砂体的5号层,与原生产层位合采
G7-34	大修	大修后恢复阜二段第二砂层组的二砂体和第三砂层组的一砂体注水
G7-17	解堵	解堵增注
G7-16	恢复注水	G7-16井阜二段第三砂层组的一砂体原先下死嘴,恢复注水
G7-6	恢复注水	恢复阜二段第二砂层组的二砂体和第三砂层组的一砂体注水
G7-10	调层	调层注水阜三段

3.2.3　开展周期注水,降低流动非均质性

周期注水可以通过压力扰动,引起流场的转向,从而强化非主流线剩余油动用[38],方案选取东翼G7-21、G7-23井组实施交替周期注水,在G7-21井注水期间,G7-23井停注,注水周期为60 d,注水期间强度为连续注水的2倍,强流线上的G7-7井能量得到控制,弱流线油井注水效果得到增强,达到了控水增油目的。

3.3　G7块调整前后开发效果对比

进行调整前后方案对比,阜二段第二砂层组的二砂体和阜二段第三砂层组的一砂体洛伦兹系数分别减小至0.90和0.91,阜二段第三砂层组的五砂体洛伦兹系数增加至0.8。继续生产10 a预计采收率提高1%,累计产油量增加1.70×10^4 t。调整前后主要砂体流场分布及累计产油量对比如图8所示。



a. 阜二段第二砂层组的二砂体调整前流速分布（洛伦兹系数为0.949 6）

b. 阜二段第三砂层组的一砂体调整前流速分布（洛伦兹系数为0.954 0）

c. 阜二段第二砂层组的二砂体调整后流速分布（洛伦兹系数为0.900 0）

d. 阜二段第三砂层组的一砂体调整后流速分布（洛伦兹系数为0.910 0）

e. 累产预测曲线

图8　流场调整前后效果对比及累产预测

Fig. 8　Comparison of flow field adjustment effects before and after, and cumulative production prediction

4 结论与认识

1）选取流速作为计算参数，并引入洛伦兹系数表征流动非均质性，通过编程方法链接数值模拟结果与评价指标计算公式，能够直观、快捷地反映多种因素作用后流场非均质分布情况并进行定量的评价，洛伦兹系数越大流动非均质性越强。

2）对苏北油田常见的三角形和半反七点2种井网形式建立了流动非均质性评价图版，得到划分渗流差异强弱的洛伦兹系数界限分别为0.94和0.96，可方便对实际油藏流动非均质性强弱进行定量判断。

3）对G7断块开展流动非均质性评价，并从井网优化、注采调整及周期注水等方面进行强渗流差异流场的调整。调整前后流动非均质性得到降低，预测10 a采收率提高1%，取得了较好的效果。

4）研究结果表明：流场非均质性评价方法能够准确反映渗流差异，对流场调整及剩余油挖潜具有指导作用。同时，主要研究了苏北断块油藏常见的三角形和半反七点井网渗流强弱界限值，在实际推广应用中应针对具体井网形式重新确定界限值。

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