缝洞型碳酸盐岩油藏开发动态分析方法研究

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摘要：缝洞型碳酸盐岩油藏具有很强的非均质性、各向异性和多尺度特征，传统的砂岩油藏和裂缝型碳酸盐岩油藏的开发动态分析方法难以适用。为了解决塔里木油田缝洞型碳酸盐岩油藏开发动态分析过程中出现的难题，在论证传统开发动态分析方法适用性的基础上，结合缝洞型碳酸盐岩油藏特征、近年来中外的研究成果及笔者的研究经历，分析了各种生产动态分析方法的等效适用条件，重点阐述了三重介质试井和油藏数值模拟方法、数值试井、等效介质油藏数值模拟方法以及离散裂缝方法的理论基础及适用条件，提出一套适合该类油藏开发动态分析方法的研究思路，并应用于现场生产，指导生产实践。

关键词：缝洞型碳酸盐岩油藏 三重介质 数值试井 等效介质 油藏数值模拟 离散裂缝方法
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缝洞型碳酸盐岩油藏的储层类型十分特殊，不同于中东地区和中国东部的裂缝型碳酸盐岩油藏，更不同于常规的孔隙型砂岩油藏。由于缝洞型碳酸盐岩的储层空间具有很强的非均质性、各向异性及多尺度特征[1]，使得这类油藏的油藏描述及开发地质研究很难形成成熟适用的关键技术[2-3]，而对其定量描述的难度则更大。因此，充分利用动静态资料进行油藏开发动态分析，不断深化对油藏特征及其内在规律的认识，研究不同开发阶段的主要矛盾，明确开发潜力，制定合理适用的开发技术政策，是缝洞型碳酸盐岩油藏开发地质和油藏工程研究的重点和难点。

笔者通过对多个碳酸盐岩油藏开发动态分析研究经验的总结，发现传统的基于砂岩油藏的开发动态分析方法很难直接应用于缝洞型碳酸盐岩油藏，目前最成熟的研究思路应从开发机理（如物理模拟实验、渗流机理研究等）入手，并对开发动态分析方法进行修正。由于塔里木油田目前还没有形成相关的系统研究成果或思路，因此，笔者在原有砂岩油藏开发动态分析方法的基础上，结合研究经验及现状，针对缝洞型碳酸盐岩油藏的开发动态分析方法进行了适应性研究和等效方法修正，最后对这些方法的使用和改进提出了意见。

1 方法的适用性

动态分析方法主要包括经验统计类比法、物质平衡法、物理模拟实验、水驱特征曲线、产量递减曲线、试井和油藏数值模拟方法等。缝洞型碳酸盐岩油藏由于具有较强的复杂性和随机性，使部分开发动态分析方法和软件的适用性大为降低。

缝洞型碳酸盐岩油藏采收率标定问题一直是研究工作的难点，目前应用的底水灰岩油藏采收率公式[4]的计算适应性和精度非常低，且除此之外未见其他方法的报道或规范性文件；目前中国常用的经验统计类比法，因很难找到适当的类比对象而导致结果的可行度降低；物质平衡方程中所有高压物性数据和油田水侵量都是压力的函数，而油藏平均压力很难精确确定，同时由于物质平衡法中不包括流动方程且是在储罐模型下导出的，因此，其应用一般需要结合其他分析方法，虽然可用于缝洞型碳酸盐岩油藏单井动态储量的计算，但精度较低。

塔里木油田先后针对轮古7油田及塔中I号气田开展了碳酸盐岩物理模拟实验，但鉴于目前中国实验室的环境等因素影响，模拟结果只能定性分析一些宏观现象和方向性问题。传统的水驱特征曲

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线和产量递减曲线[5]大多针对砂岩油藏回归获得，对于缝洞型碳酸盐岩油藏的实用性和精度较低，笔者在重新统计分析轮古、哈6、英买2等油田100余口油井生产数据的基础上，针对缝洞型碳酸盐岩油藏，提出应根据与实际资料的相关性及应用情况，选择性地应用水驱特征曲线，而产量递减曲线则应根据储层类型和生产阶段进行分析性应用。

试井是油藏动态分析的水动力学方法，目前在对测试数据进行现代试井分析时，很少考虑拟合油井测试前后的压力历史，而且对油藏特殊边界形状、储层物性及流体性质非均质性、渗流特征多样化等复杂油藏特征也未进行相关的描述，用该方法解释碳酸盐岩储层存在许多问题，特别是对储层的认识评价，因而影响油气勘探的效果。三重介质试井解释模型、数值试井方法[6]结合遗传算法、FEBI网格等形成的试井解释新方法，用于缝洞型碳酸盐岩储层试井解释效果较好，并能成功预测储层缝洞的发育及分布[7]。

传统的商业化数值模拟软件Eclipse等只能用于常规的双重介质油藏的研究，对缝洞型碳酸盐岩油藏的数值模拟不能提供很好的支撑。对缝洞型碳酸盐岩油藏数值模拟技术的适应性研究，应采用2种研究思路并行的方法：①以现有成熟软件为基础，通过介质的合理等效和参数的合理赋值，尽可能降低模拟误差，以适应数值模拟的现场应用；②对现有数值模拟技术进行评价，对不适应多重介质数值模拟的部分进行改进，建立三重介质模型，形成改进后的油藏数值模拟软件。

2　三重介质模型及数值试井方法

2.1　三重介质模型

20世纪80年代初，吴玉树等[8]对碳酸盐岩油藏渗流机理进行了研究，并分析了溶洞—裂缝—基岩三重介质渗流模型。塔河和塔里木油田的储层中存在大量与裂缝的早期发育密切相关的溶蚀孔洞，同时裂缝网络又对其起到了很好的沟通作用，从而形成不同级别裂缝与溶蚀孔洞交融的多重介质储集体。为更好地描述这类储层，需引入三重介质模型（图1）。三重介质模型相关参数对复合曲线的影响与双重介质模型类似。二者的主要区别在于三重介质油藏[9]多了一类次生孔隙介质，因此在渗流模型中表现为多了一项代表溶蚀孔洞系统渗流的窜流方程，在样板曲线上则表现为压力导数曲线上多了1个代表溶洞系统窜流的下凹过渡段（图2）。

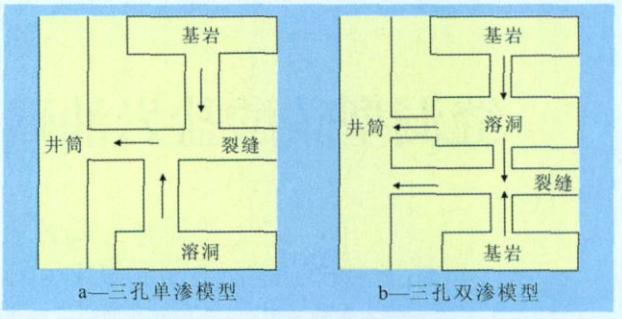


图1　溶洞—裂缝—基岩三重介质模型示意

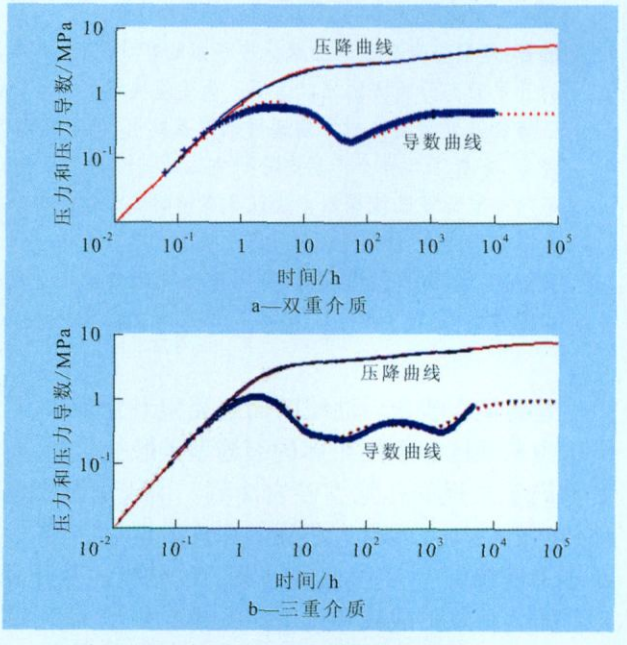


图2　双重介质和三重介质拟稳态双对数对比

2.2　数值试井

数值试井解释方法[6]汲取了油藏数值模拟技术中的油藏特殊边界形状、储层物性及流体性质非均质性、渗流特征多样化等复杂油藏描述技术，同时以有限元法为常用的数值分析方法，实现了对油藏内部不同区域的渗流场分布特征和压力分布特征的精细刻画，结合多口井的并行分析，使井间干扰、注采井网分析等复杂问题得以有效解决。

3　等效介质油藏数值模拟方法

在缝洞型碳酸盐岩油藏的数值模拟中，采用确定性建模和随机建模相结合，综合地震、地质、测井、岩心以及生产动态资料，结合采油指数法、钻时曲线法、岩溶相控建模法[10]进行建模，可以极大地降低不确定性，提高储层建模的精度。

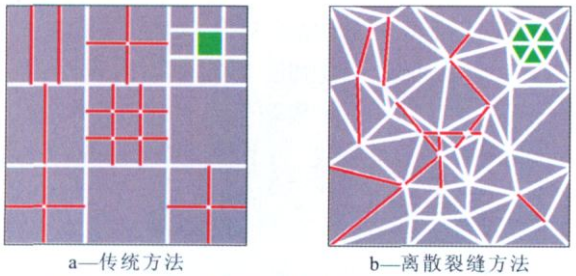
缝洞型碳酸盐岩油藏基质岩块系统的储渗条件差，一般为非有效储层；三重介质油藏模型巨大，单次数值模拟时间一般为十几小时甚至几十小时；

另外，传统的商业化数值模拟软件Eclipse等并未提供对三重介质模型的支持。因此，采用建立等效的裂缝—溶洞型双重介质模型，再将其等效为裂缝—孔隙型双重介质的方法进行模拟，不但可以充分利用现有的数值模拟软件，还可以节约数值模拟计算时间，为提高拟合效率和预测精度提供理论基础。

油藏数值模拟模型的等效，主要在于地质储量、渗透率和渗流方式的等效，可通过弹性储容比、渗透率级差和窜流系数来实现。弹性储容比越小，说明基岩中有较多流体存储，开井生产时产量可能较低，但稳产时间可能较长；反之，说明流体主要储集在裂缝和溶洞中，基岩中的流体可忽略，开井生产时产量可能较大，但稳产时间可能较短，递减较快。渗透率级差大于一定倍数时（具体倍数需进行相应油藏的渗流机理分析和数值模拟机理模型研究），可以直接忽略流体自基质向井筒的流动，否则需要进行等效渗透率的计算。通过裂缝—基质型数学模型和裂缝—溶洞型双重介质数学模型的比较，可得出窜流量的等效计算公式[10]，采用裂缝—孔隙型双重介质来模拟裂缝—溶洞型双重介质。

4　离散裂缝方法

离散裂缝方法是将缝洞的真实形态和分布完全应用到流动模型中，为缝洞型油气藏的数值模拟提供更为精确和直接的解法。在该方法中，裂缝被当作一个等宽的矩形来近似处理，其长度、产状等特征均通过测井资料获得。孔洞被当作一个球形来近似处理，裂缝和孔洞的密度可通过缝洞雕刻数据求出，也可根据测井数据，运用地质统计学方法推算得出。传统方法通过对结构化网格的局部网格加密来模拟裂缝，无法实现裂缝方向的精细和准确的描述，离散裂缝方法采用非结构化网格来处理裂缝问题。通过传统方法和离散裂缝方法获得的网格模型对比（图3）可以看出，离散网格建立的缝洞系统模型更加接近真实情况，从而达到提高油气藏数值模拟的精度的目的。



a—传统方法　　b—离散裂缝方法

图3　传统方法和离散裂缝方法网格模型对比

5　结束语

由于缝洞型碳酸盐岩油藏的复杂性和随机性，难以应用传统的砂岩油藏和裂缝型碳酸盐岩油藏的开发动态分析方法，特别是经验公式，至今未见成熟的计算方法或规范性文件；同时物质平衡法也因为其模型基础和边界条件，不适用于缝洞型碳酸盐岩油藏的计算。经验统计类比法是目前常用的分析方法，其适用性和精度因测试数据和资料收集的完善程度以及油藏工程师的经验而异。

物理模拟实验是缝洞型碳酸盐岩油藏开发机理研究的基础，但是需要在目前定性的基础上作出定量的研究；水驱特征曲线和产量递减曲线应根据具体的储层类型和生产动态，结合渗流机理研究，进行曲线的选择应用。

试井和油藏数值模拟方法是缝洞型碳酸盐岩油藏开发动态研究的前缘和热点，特别是随着塔里木油田缝洞型碳酸盐岩油藏开发，三重介质试井方法及数值模拟研究、数值试井、等效介质油藏数值模拟和离散裂缝方法等动态分析方法逐步形成成熟适用的关键技术，为进一步认识油藏、改造油藏，科学有效地开发油藏提供了重要依据和有力保障。

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cance to further improve the water flooding recovery factor of the fault block oil reservoir in high water cut stage.

Key words: fault block reservoir; layer block; static geological feature; dynamic performance; recovery factor

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Liu Chao, Ma Kuiqian, Chen Jian et al. Research on quantitative characterization of reservoir heterogeneity and adjustments suggestion in LD oilfield. *PGRE*, 2012, 19(5): 88-90.

Abstract: There are some defects in the existing evaluation systems of reservoir heterogeneity such as its unbounded parameters, high subjectivity classification and low degree of quantification. Based on Lorenz curve method, with the new transform process of data, a new parameter named as comprehensive coefficient of heterogeneity is used in reservoir heterogeneity research. This operation is very simple and the parameter has the virtues of strong comparison, quantitative characterization of heterogeneity degree and is applicable for any type of reservoirs. In the comprehensive research of reservoir heterogeneity in LD oilfield, the application result indicates that the level of LD oilfield reservoir heterogeneity is moderate, but the interlayer and horizontal heterogeneity is strong. For the heterogeneity characteristics of LD oilfield, the appropriate development adjustments are carried out: the main development method is directional wells with few horizontal wells or multi-lateral wells supplemented in E_3d^{2U} reservoir. At the same time, the separate stratum development and separated layer and injection process are used in E_3d^{2L} reservoir. It has significant practical guidance in oilfield adjustment and enhanced oil recovery. It is remarkable that the reduction in water cut is 9%, while the daily oil production increased by about 1 000 m^3/d.

Key words: reservoir heterogeneity; Lorentz curve; formation interference; separate stratum development; development adjustments

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Du Dianfa, Wang Yujing, Hou Jiagen et al. Study on water flooding pattern of thin-layered reservoirs with edge and bottom water-case of $K_1h_2^3$ reservoir of Lu9 wellblock in Luliang oilfield. *PGRE*, 2012, 19(5): 91-93.

Abstract: Thin-layered reservoirs with edge and bottom water are rare home and abroad. The water intrusion to oil well in this kind reservoir is very complex. The water cut of the oil well increases fast after the well is put into production, and the recovery factor is low. The production rate declines rapidly, and the ultimate recovery ratio is also very low. Taking $K_1h_2^3$ reservoir of Lu9 wellblock in Luliang oil field as an example, a concept model is built on the base of the whole region history matching. An orthogonal test is introduced to study the sensitive parameters and the water/oil distribution feature of water flooding pattern of the thin-layered reservoir with edge and bottom water. According to the numerical modeling result and dynamic documents of the whole region, five kinds of water flooding patterns are classified, which are injecting water enhanced bottom, injecting water cross-flow, bottom water coning, edge water intruding and compounding. And, the target boundary is given to the patterns. It is presented by the field application that the target boundary is reliable and it can be supplied as the theoretic foundation for the water/oil control measures for this kind of reservoir in the middle and later stage.

Key words: thin-layered; edge and bottom water; numerical simulation; orthogonal test; water flooding pattern

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Cui Chuanzhi, Jiang Hua, Duan Jiehong et al. Reasonable injection rate allocation method of separate-layer water injection wells based on interlayer equilibrium displacement. *PGRE*, 2012, 19(5): 94-96.

Abstract: Affected by the differences of reservoir properties between layers, the interlayer producing situation and interlayer inconsistency of commingled reservoirs have large differences in the long-term process of water flooding. Separate-layer water injection technology is an effective method to ameliorate the contradictions among the high water cut stage layers. The key to the success of separate-layer water injection is to determine the distributional water injection rate according to the reservoir properties and development situations of each layer. This paper presents a method to calculate distributional water injection rate of each layer by use of the Buckley-Leverett displacement theory. This method takes into account of the reservoir physical properties and development situations. The aim of this method is to realize the interlayer equilibrium displacement. The results show that the differences of distributional water injection rate among layers is comprehensively affected by layer thickness, development status and regulatory time etc. And, the calculated distributional water injection rate in the regulatory time can make each layer achieve a balanced flooding state, and can meet the requirements of injection rate allocation of separate-layer water injection wells.

Key words: multilayer reservoir; interlayer contradiction; separate-layer water injection; computation model; equilibrium displacement

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Xiao Yang, Jiang Tongwen, Feng Jilei et al. Study of dynamic analytic method on fractured-vuggy carbonate reservoir. *PGRE*, 2012, 19(5): 97-99.

Abstract: Fractured-vuggy carbonate reservoir has very strong heterogeneous, anisotropic and multi-scale feature. The applicability of traditional development dynamic analytic method of sandstone reservoirs and fractured carbonate reservoir is limited. In order to solve the problems appeared in the process of production dynamic analysis in Tarim oilfield, this paper is based on the applicability of traditional dynamic analytic method, and considering the features of fractured-vuggy carbonate reservoir, as well as the research result in recent years and the author's research experience to analyzes the practical conditions equivalent for various production dy-

namic analysis method, and it focuses on the theoretical basis and applicable conditions of well test data of triple medium reservoir, numerical reservoir simulation of triple medium reservoir, numerical well testing, numerical reservoir simulation of equivalent medium and discrete fracture method. Finally, it proposes the research ideas that are suitable for development dynamic analytic of Tabei fractured-vuggy carbonate reservoir, and it has been used in the field production to guide the production practice.

Key words:fractured-vuggy carbonate reservoir; triple-medium; numerical well testing; equivalent medium; numerical reservoir simulation; discrete fracture method

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Fang Wei, Zhang Juhe, Feng Zihui et al. Geochemical characteristics of reservoir at different injection-production locations in water drive well network-case of North-II-West area in the Saertu oilfield. *PGRE*, 2012,19(5):100-103.

Abstract:Geochemical parameters(eg. remaining oil viscosity, oil displacement efficiency, etc.) of North-II-West area in the Saertu oilfield are obtained through methods of remaining oil viscosity and core analysis. The experimental results show that oil viscosity, mobility, saturation and oil displacement efficiency, etc. of remaining oil are more or less heterogenetic at different injection-production locations in the direction of main stream line of water-flooding, and are controlled by reservoir physical property, injection-production location and time duration of water-flooding, etc. The heterogeneity of reservoir geochemical parameters show increasing trend from the injection wells to the production wells of main steam line, with the increase of oil saturation and decrease of oil displacement efficiency. There is a positive correlation between rock permeability and displacement efficiency and the correlation coefficient increases with increasing permeability. The remaining oil viscosity is weakly correlated with rock permeability that is poorly correlated with oil saturation. With the water-flooding, the remaining oil viscosity and oil displacement efficiency increases while reservoir mobility and oil saturation decreases. Using water-drive at different injection-production locations can exploit some extent of remaining oil potentiality, with the greatest exploitation potentiality being located in those where the mainstream line is close to the production well. However, the polymer flooding will be a better way to exploit remaining oil, and the polymer concentration and viscosity can be determined in function of remaining oil viscosity and the range of controlling mobility ratio of polymer flooding.

Key words:injection-production location; water drive reservoir; heterogeneity; development mode; Saertu oilfield

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Zheng Jian, Li Shunming, Kang Bo et al. Residual oil distribution and technical measures in high water-cut period for light oil reservoir, Wenmi oilfield. *PGRE*, 2012,19(5):104-107.

Abstract:Wenmi oilfield Jurassic Sanjianfang formation contains long oil interval with high variable reservoir feature and low oil water viscosity ratio, therefore, the injection-production network is not perfect. Entering into the high water-cut stage, the oilfield faces problems such as reservoir reserves loss and rapid production decline. Through the sedimentary origin and reservoir anisotropic description, and combined the reservoir water flooding mechanism with the dynamic production and drilling data, as well as the analysis of water flooded zone characteristic and the rule, this area is summarized with respect to the distribution rule of remaining oil. According to the reservoir characteristics, we propose that, in high water cut stage, well pattern reorganization layer system should be optimized based on the reservoir size and abundance of remaining reserves, so as to perfect the injection-production patterns, and maximize the producing efficiency of water flooding. However, the particles or gel for deep profile control system do not improve the performance of less fracture developed zone. In the high water-cut stage, it should focus on the conversion of development scheme for increasing oil displacement agent of swept volume and oil displacement efficiency, moreover, the gas water alternate injection and top gas injection gravity stability drive can greatly improve the oil recovery.

Key words:braided river delta; light-oil reservoir; residual oil distribution; deep profile control; gas injection

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Cai Bo, Ding Yunhong, Lu Yongjun et al. Study and application of new in-fissure fracturing technique for improving stimulated reservoir volume. *PGRE*, 2012,19(5):108-110.

Abstract:The fracturing technique improving stimulated reservoir volume (SRV) brings the soaring development in unconventional gas and oil at home and abroad, it has an important influence for low permeability and low porosity sandstone reservoir. In order to improve the output of post-fracturing, this paper, based on the theory of in-fissure fracturing and network fracturing and through the mechanics and fluid and solid coupling analysis, analyzes two horizontal stresses. Using force closure, and quickly flow-back and multiple treatment, the horizontal stress difference is decreased so as to divert the fracture in short time. Compared with former technique, the new method has the merits of simple and low risk, particular to the high temperature, complicated and difficult treated wells. It can improve the treatment and performance, meanwhile, it extends the method of improving SRV.

Key words:volume fracturing; diverted fracturing; network fracturing; stress field; microseismics technology

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