

# 注水井合理配注方法研究

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**摘要:** 为了更精确地分析油水井在地下的注采关系, 应该确立注水井合理地层压力, 确立注水井各层水量劈分系数, 以及确定生产井产液量来源于各注水井的方向比例系数。通过研究提出了合理配注预测的方法, 并建立了合理配注优化数学模型, 为新老注水井之间的水量劈分提出了新的计算方法, 为油田调整方案的编制提供了理论依据, 最终实现了区块注水井在各层系上的“动态合理配注”。从而最大限度地解决了高含水后期的层间矛盾和平面矛盾, 满足了油田稳产和“稳油控水”的需要。

**关键词:** 合理配注; 合理注采比; 劈分系数; 产液方向比例系数

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## 1 引言

大庆油田进入高含水后期开发阶段以后, 随着井网的加密, 注水开发的层间矛盾和平面矛盾日益加重, 地下情况也越来越复杂。在保证产量的前提下, 如何有效地控制含水, 扩大注水波及体积, 协调井组间、层系间注采平衡、压力平衡是当前所要急需解决的问题。目前, 大庆油田所采用的分层配注方法是以管理人员的生产经验为主的粗放式配水方法, 不能满足注水井精细调整的需要。为此我们开展了注水井合理配注方法研究工作, 以期能进一步改善油田开发效果。

## 2 合理配注方法的建立

### 2.1 注采系统分析及配水原则

随着新井的不断投入生产, 注采关系不断变化, 井网间的注采关系也就越加复杂, 新老注水井各层段的水量如何分配, 这就需要我们以一个合理注水方式来平稳的恢复地下动态平衡, 以获得最大的采收率。

井网二次加密调整后, 在保持层系间总体注采平衡的前提下, 对层系间的注水结构进行了调整。对低含水油层加强注水, 对高含水和高渗透层限制注水或停注; 利用二次加密注水井实现注水量从高含水层向中、低含水层和从老注水井向新注水井的合理转移。在采油井中针对不同层系, 不同含水级别分别采取不同的提液和降水措施, 改善油层动用状况。

由于新、老井存在一定的连通关系, 新注水井投

注的同时进行了新、老井网的注水匹配调整, 为老采油井提供了新的来水方向; 新采油井射开老注水井不吸水层的对应层, 改善了注采对应条件, 从而在新井直接对这类油层动用的同时还改善了老井对这类油层的动用。

确定合理配注必须遵循以下原则:

#### (1) 调整地层压力

确定合理的配注是保持合理地层压力的关键。由物质平衡方程<sup>[1,2]</sup>可得出

$$N_p = NC_i(p_i - p)/e^{C_o(p_i - p)} + (W_i - W_p)e^{-(C_o - C_w)(p_i - p)}B_{wi}/B_{oi} \quad (1)$$

式中  $N_p$ ——累积产油量,  $10^4 t$ ;  $N$ ——原始地质储量,  $10^4$ ;  $W_p$ ——累积产水量,  $10^4$ ;  $W_i$ ——累积注水量,  $10^4$ ;  $B_{oi}$ ——原始地层条件下原油体积系数;  $B_o$ ——目前地层条件下原油体积系数;  $B_{wi}$ ——原始地层条件下水的体积系数;  $B_w$ ——目前地层压力下水的体积系数;  $C_i$ ——地层压缩系数;  $C_o$ ——原油压缩系数;  $C_w$ ——水压缩系数;  $p_i$ ——原始地层压力, MPa;  $p$ ——目前地层压力, MPa。

#### (2) 控制含水上升速度

根据油田开发“稳油控水”的要求, 在区块提液的同时要考虑含水上升速度的问题, 把含水上升率控制到最低。

我们知道含水率的变化是随着采液速度的变化而变化的, 其关系式为

$$V_L = b_0 + b_1 f_w + b_2 f_w \quad (2)$$

式中  $b_0$ 、 $b_1$ 、 $b_2$ ——经验常数;  $V_L$ ——采液速度, %;  $f_w$ ——含水率, %。

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依据采液速度与含水率的关系, 对于高含水井区或者含水上升速度比较快的井区, 就要合理地调整其高含水层的注水量, 控制其采液速度, 以达到全区含水率的最优化

$$f_w = \min \{f_{w1}, f_{w2}, f_{w3}, \dots\} \quad (3)$$

### (3) 产液量的约束

从油田的经济效益出发, 配注值不能无限制的提高, 必须依据油井的生产能力及产液量的大小, 以井组注采平衡为标准来确定配注量的大小。对于低产液的油井, 可以采取一定的措施来增加其生产能力。满足以上的约束条件才能进一步对全区进行合理的配注。

## 2.2 合理配注的确定

要确定全区的合理配注, 首先必须确定全区合理的注采比。通过物质平衡方程可以推导出注水量、产油量、产水量与地层压力变化的关系式

$$a = f_w - \frac{C_t V \Delta p (1 - f_w) - q_o B_o (1 - f_w)}{q_w B_w} \quad (4)$$

式中  $a$ ——注采比;  $C_t$ ——油层综合压缩系数,  $1/\text{MPa}$ ;  $V$ ——油层体积,  $\text{m}^3$ ;  $\Delta p$ ——地层压力增加值,  $\text{MPa}$ ;  $q_o$ ——日产油量,  $\text{t}$ ;  $q_w$ ——日产水量,  $\text{t}$ ;  $B_o$ ——油的体积系数, 无因次;  $B_w$ ——水的体积系数, 无因次。

通过注采比我们可以得到全区的合理配注值

$$q_{iw} = a(q_o + \frac{q_w f_w}{1 - f_w}) \quad (5)$$

由式(5)可得到全区目前阶段的合理配注, 确定全区总的注水量之后, 就需要优化井组之间的合理配注, 结合上述约束条件以及注水井全井射开砂岩厚度来确定单井的合理配注。优化井组之间的合理配注应满足以下几个方面的要求<sup>[3,4,5]</sup>:

### (1) 确定油水井连通关系

确定油水井的连通关系, 即找出注水井与采油井之间的连通情况, 找出注水井连通的对应采油井数。确定连通关系之后, 根据精细地质研究成果, 吸水剖面、产出资料以及油层的物性来确定油水井的各层采液、注水情况。对于油层物性比较好、渗流能力比较高的层、水淹程度比较大的层段, 要控制注水, 对于离老注水井比较近的二次调整油井, 在老注水井都射孔的层段, 要控制老注水井的注水强度, 提高二次调整水井的注水强度, 协调二次调整注水井与老注水井的注水平衡。

### (2) 确定劈分系数

在确定全区合理配注的同时, 一方面要确定二次调整水井的合理配注应该多少, 同时也要调整老注水井段注水量, 要优化这两者的关系, 就需要重新确

定新老注水井之间的劈配关系, 在此引入“劈分系数”这一概念。

在注水开采过程中由于地层的非均质性、井间距离、井间相互位置关系、油水井改造措施、注采井底的流压等因素的影响, 注水井的注入水将以不同的能力分别流向各生产井的方向。对于各生产井对该注水井的注水能力的相对劈分能力以劈分系数这一概念来表示。

$$C_{jik} = \frac{\bar{K}_{jik} \bar{H}_{jik} \Delta p_{jik} Z_{jik} M_{jik} E_{jik} G_{jik} \beta_{jik} a_{ik}}{2 \ln D_{ik}} \quad (6)$$

$$\sum_{i=1}^m \frac{K_{jik} H_{jik} \Delta p_{jik} Z_{jik} M_{jik} E_{jik} G_{jik} \beta_{jik} a_{ik}}{2 \ln D_{ik}}$$

式中  $\bar{K}_{jik}$ ——方向地层系数, 即注水井与该地层系数的平均值;  $\Delta p_{jik}$ ——注水井井底流压与生产井井底流压之差,  $\text{MPa}$ ;  $Z_{jik}$ ——各油井该层与对应注水井的连通状况系数;  $M_{jik}$ ——各油井改层改造措施系数;  $E_{jik}$ ——各油井的开采厚度系数;  $G_{jik}$ ——各油井的渗透率级差系数;  $\beta_{jik}$ ——注水井到各生产井层的渗透率各向异性系数;  $D_{ik}$ ——井间距离,  $\text{m}$ ;  $a$ ——生产井与注水井之间的位置系数,  $a = \sqrt{n \times \theta / 360}$ 。

通过以上公式可以计算注水井到各连通油井的劈分量

$$Q_{iwjik} = Q_{iwjik} C_{jik} \quad (7)$$

### (3) 方向比例系数和产液剖面的确定

对于一口注水井的配注量的大小是周围油井的产液量的大小有关。而这口油井产液量有多少来自于这口注水井, 在这里就要引入比例系数这一概念。所谓方向比例系数, 就是指在某一层上, 该油井在某一口注水井方向上的产液量占全井产液量的比例, 其表达式为

$$R_{pjik} = \frac{Q_{Ljik}}{\sum_{i=1}^n \sum_{j=1}^n Q_{Ljik}} \quad (8)$$

式中  $R_{pjik}$ —— $j$ 层 $k$ 油井在 $i$ 注水井的方向比例系数;  $Q_{Ljik}$ —— $j$ 层 $i$ 水井组 $k$ 油井在 $i$ 水井方向上的日产量,  $\text{m}^3/\text{d}$ ; 其中  $Q_{Ljik}$ 表达式为

$$Q_{Ljik} = (Q_{iwji} - C_t V_{ji} \Delta p_{ji}) C_{jik} \quad (9)$$

式中  $Q_{iwji}$ —— $j$ 层 $i$ 注水井的注水量,  $\text{m}^3/\text{d}$ ;  $C_t$ ——油层综合弹性压缩系数,  $1/\text{MPa}$ ;  $\Delta p_{ji}$ —— $\Delta t$ 时间内 $i$ 注水井 $j$ 层控制区内的压力变化值,  $\text{MPa}$ ;  $V_{ji}$ —— $i$ 水井组 $j$ 油层岩石外表体积,  $V_{ji} = S_{ji} H_{ji}$ ;  $S_{ji}$ —— $i$ 水井组 $j$ 油层面积,  $\text{m}^2$ ;  $H_{ji}$ —— $i$ 水井组 $j$ 油层厚度,  $\text{m}$ 。

从而得到油井的理论产液量为

$$Q_{LK} = \sum_{i=1}^n \sum_{j=1}^n Q_{Ljik} \quad (10)$$

式中  $Q_{LK}$ ——油井的日产量总合;  $m$ 、 $n$ ——总层数和 $k$ 油井对应的总注水井数。

而油井的实际产液量为

$$Q_{LK}^* = (Q_{ok}^* B_o + Q_{wk}^*) \quad (11)$$

为了消除理论产液量与实际产液量的差异,使得理论产液量更加符合实际总产液量,特引入一个“校正系数  $C_k$ ”,其数学表达式为

$$C_k = \frac{Q_{LK}^*}{Q_{LK}} \quad (12)$$

当校正系数获得后,就可以得到比较接近的采油井的实际总产液量的理论公式

$$Q_{LK} = \sum_{i=1}^n \sum_{j=1}^n Q_{Lij} C_k \quad (13)$$

### 3 实例分析

中丁 10-斜水 137 是一口一次调整注水井全井射开砂岩厚度 35.5 m,有效厚度 12.7 m,2002 年 1 月日注水量 156 m<sup>3</sup>,分四层注水,注水层段分别是:萨 II 15 + 16 以上、萨 III 2—萨 III 8—9、葡 II 10、高 I 1 及以下,周围 7 口油井受效,平均单井日产液 96 m<sup>3</sup>,平均日产油 9 t,综合含水 90.6%,平均单井沉没度 403.6 m。为了平稳恢复地层压力,对其水量重新调整。

通过各层段的水量劈分结果可以看出:第一层段主要对其周围连通油井 3 口受效,第二层段主要对其周围连通油井 5 口受效。第三层段主要对其周围连通油井 3 口受效,第四层段主要对其周围连通油井 3 口受效。

在连通的 7 口油井中有两口油井沉没度低于 300 m,通过注水井水量劈分可以看出中丁 10-斜水 137 注水井在一、四层段对这两口油井的水量劈分较多,相邻的注水井对这两个层段的水量劈分较小,从油井产液方向比例和产液剖面可以看出:这两口油井一、四层段产液量主要来源于中丁 10-斜水 137 注水井,但占全井产液方向比例较小。结合精细地质研究,可以看出在一、四层段该井组发育较差,提高注水量对于含水不会有太大的影响。所以 2002 年 2 月对该注水井注水层段重新配水,第一、四层段水量分别由 40 m<sup>3</sup> 上调到 60 m<sup>3</sup>。到 2002 年 4 月这两口油井平均单井日产油上升 2 t,日产液上升 22 t,含水稳定,沉没度平均上升 34 m,达到了较好的效果。

2002 年 8 月初二次调整油井陆续投产后,中丁 10-斜水 137 周围连通油井由 7 口增加到 12 口。随

着受效油井的增加,各层段的水量分配必然不足,针对其连通二次调整油井的射孔特点又一次对该井水量重新调整第一、二、四层段的水量分别由 60 m<sup>3</sup>、40 m<sup>3</sup>、60 m<sup>3</sup> 上调到 80 m<sup>3</sup>、70 m<sup>3</sup>、80 m<sup>3</sup>,以保证二次调整油井的开发效果。

二次调整注水井完井后,即将试注,为了保证新老注水井注水平衡,达到改变注水驱油方向,扩大注水波及体积的目的,中丁 10-斜水 137 在二次调整注水井投产后,全井水量也要重新调整。

通过二次调整油井投产前后的水量劈分对比,可以看出,该注水井在第二、四层段对二次调整油井水量劈分的比较多,而且大部分射孔层段与相邻的二次调整注水井射孔层段重复射孔。所以在二次调整注水井投产后,应对这两个层段的水量下调,增大二次调整注水井在这两个层段的注入强度,保证二次调整油井的开发效果,同时因为改变了注水的波及方向老生产井产量也可以有所增加。因此决定在二次调整水井投产后,降低第二、第四层段的注入强度分别由 70 m<sup>3</sup>、80 m<sup>3</sup> 下调到 50 m<sup>3</sup>、40 m<sup>3</sup>。

### 4 结 论

(1) 油田进入高含水后期,随着井网之间的日益完善,各套层系注水井的匹配调整是必要的。

(2) 在注采完善区域,薄差油层及独立表外油层能够得到很好的动用,并且随着动用程度的提高,井网间、油层间的接替作用逐渐减小。

(3) 合理配注模型的确立,为新老注水井之间的水量劈分提出了新的计算方法,为油田调整方案的编制提供了理论依据。

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powder pellet has been developed for the determination of rare-earth element of deep volcanic rocks in Songliao Basin by Philips PW2400 sequential X-ray Fluorescence Spectrometer. The interelement effect is corrected using scattered line as internal standard. The characteristic parameter of rare-earth element is explained to be a significant symbol of geochemistry in deep stratigraphic correlation. It is used to determine separating degree of magma in different groups, and also determine partial melting, separating and crystallizing degree of each layer. In addition, according to the common distribution of rare-element component in different groups, the characteristic parameter is explained that deep stratum in Songliao Basin and the edge was formed at a similar structural background.

**Key words:** rare-earth element; pressed powder pellet; scattered line as internal standard; X-ray Fluorescence Spectrometry

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#### Research of Reservoir Description and Application for Gao Block17

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**Abstract:** Gao Block17 ( $E_{s_3}^{2+3}$ ) is a typical heterogeneous reservoir with deeper buried depth, longer oil-bearing intervals, and shortage of natural energy. After manual water injecting, the developing effect was not very ideal due to serious interzonal difference. In order to find out dependable evidences regarding development adjustment, comprehensive treatment, and fine water injection for Gao Block17, plenty of reservoir description studies were proceeded involving evaluation to reservoir sensitivity, physical property and heterogeneous characteristic, and microcosmic pore structure category. Reasonable injection intensity, standard of water quality, and measures to corresponding reservoir protection were confirmed based on these studies. It will be very much helpful towards similar heterogeneous reservoirs in improving injection effect.

**Key words:** reservoir description; reservoir characteristic; injection-production intensity; water quality; reservoir protection; Gao Block17

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#### Conglomerate Reservoir Parameters and Remaining Oil Distribution of Block VIII Keshang Group in Kelamayi Oilfield

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**Abstract:** Cray system and neural network technique analysis software is introduced in reservoir layers of block VIII Keshang group, Conglomerate reservoir of Kelamayi oilfield. The software has been used to process 117 wells reservoir formation logging and geological data. The reservoir formation parameters are extracted, assembled and described by applying conglomerate reservoir log interpretation and sedimentary microfacies distribution research achievement, through which the enriched distribution of layers of Keshang group are determined. Accordingly, the development performance is analyzed. The reserve volume and the development status is gained. These provide geological basis for development decision-making of block and improving reservoir development effect.

**Key words:** conglomerate reservoir; formation parameter; description; reserve volume; remaining oil distribution; Keshang Group in Block VIII

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#### Fracture Analysis and Reasonable Injection Pressure Limit Definition of High Pressure Waterflooding Well

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**Abstract:** During the process of high pressure waterflooding in oilfield, there are bends in some water index curves. Mobility analysis and calculation the in-situ stress changes caused by waterflooding are used to define whether the formation is fractured, and to define

the reasonable pressure limit of high pressure waterflooding. Two wells are calculated. The reason of the bend of water index curve is the decrease of in-situ stress caused by waterflooding. It causes the microfracture near the well.

**Key words:** high pressure; waterflooding; fracture; pressure limit

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#### An Application of the Hierarchical Analysis Progress Method in the Tertiary Infilling Optimum Blocks of the La-Sa-Xing Oilfield

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**Abstract:** Based on the comprehensive analyses of adjustable thickness, geologic characters, combined water cut, secondary infilling time and casing damage condition in different blocks in La-Sa-Xing oilfield, using inspection well and secondary infilling production behavior data, this paper makes a optimum ordering of tertiary infilling blocks in La-Sa-Xing oilfield by using the hierarchical analysis progress method. This method provides a theoretical basis for implementing tertiary infilling and adjustment step by step in a planned way in La-Sa-Xing oilfield.

**Key words:** La-Sa-Xing oilfield; late period high water-cut; tertiary infilling; hierarchical structures; optimum blocks

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#### Tapping Remaining Oil Potential in High Water-Cut Layers Using "Approaching Zero Flux Ways"

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**Abstract:** As reservoirs enter the high water-cut stage of development, the most primary formations have been badly flooded. At present, the usual measures are shutting off, profile control, tertiary recovery etc. Basing on the spot practice and the reservoir engineering theory, we take a kind of production method "approaching zero flux" which is mainly used in the high water-cut oil well or the layer. The field application was very successful. It is a new kind of production way and can increase the production of remaining oil efficiently.

**Key words:** waterflooding oilfield; badly water-cut formation; remaining oil; approaching zero flux; field application

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#### A Study of Reasonable Match Injection Method of Waterflooding Well

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**Abstract:** For exactly analyzing the relation of injection-production, the rational formation pressure should be established and the distribution coefficient of all layers of waterflood injection well should be determined and the direction coefficient of fluid output fluid output of producing well rooting in all flooding wells should be given. A reasonable forecast method of match injection was put forward in this paper by series of investigations and the optimization model about reasonable match injection was erected. So a new calculation means was given for water distribution among new and old waterflood injection wells, and a theory gist was offered for weaving the oilfield adjustment project. It realizes dynamic reasonable match in all zone system. It will solve inter-zone and plane conflict mostly to satisfy oilfield stationary production and the requires of firm oil and control water.

**Key words:** reasonable match injection; injection-production ratio; distribution coefficient; the direction proportion coefficient of

fluid output

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### **Predicting Reservoir Absorption Situation Using Fuzzy Comprehensive Judgement Method**

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**Abstract:** Absorption section is a important basic information to analyze remaining oil, but in fact it is impossible to test absorption section for every well. So it is important that according to absorption situation of previous absorption information wells to judge absorption situation of no absorption information wells. In actual work, judging reservoir absorption situation by experience has low accuracy and much work. And because reservoir absorption situation is affected by geology and development factors, it usually can not use quantitative mathematical relation to describe the effect of every factor on reservoir absorption capacity, whereas fuzzy comprehensive judgement method can solve the problem better. By analyzing all kinds of geology and development factors which affect absorption capacity of injection wells, we can select well sandbody type, connection situation with surrounding oil wells' sandbody and wellhead spacing as major factors to judge absorption capacity of injection wells. By establishing corresponding fuzzy factor assembly, we can draw subordinate relation map of absorption situation and all kinds of effect factor and thus obtain absorption situation of each layer in injection wells.

**Key words:** fuzzy comprehensive judgement; prediction; reservoir absorption situation

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### **Non-Cross-Flow Multilayered Reservoir Pressure Performance Distribution Synthesis Research**

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**Abstract:** The Laplace space solution to dimensionless reservoir pressure and dimensionless bottom pressure of variable flow problem, which takes into consideration the effect of three kinds of outer boundary conditions, is studied by using multi-layered reservoir model. A general formula is concluded through deep analysis to solution structure and internal relation among several solutions. The result in this paper is a good help to application software design, and makes well test analysis theory completed than before as well.

**Key words:** multi-layered reservoir; boundary condition; Laplace space solution; general formula

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### **Applied Study on Calculating Formation Pressure**

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**Abstract:** The relationship between formation pressure and casing damage has been studied in Daqing oilfield. Effective ways to determine horizontal high-pressure areas and vertical high-pressure layers are being searching for, which impel casing protection pertinently. Based on the relationship between logging curve and formation pressure differential of new wells, the influence of the variation of pore pressure in natural potential logging is noticed. Methods to calculate pore pressure of the reservoir have been established. In accordance with the investigation of tested pressure data for RFT sub-layer, relative error (absolute value) is 4.9% on average; the maximum value of relative error is 11.6%, the minimum is 0.91%. Oil layers of Saertu II 4 and above layers are analyzed in the west of Nanerqu of Daqing oilfield, horizontal high-pressure areas and vertical high-pressure layers are determined. Key regions and intervals for the prevention and control of casing damage are classified, which provide active guidelines for casing protection.

**Key words:** logging curve; pore pressure; calculation; casing damage

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### **Low Permeability Sandstone Reservoir Imbibition Law Research**

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**Abstract:** With the discovery of more and more low permeable oil fields, the objective of petroleum production is concentrated on the development of low permeable oil fields gradually. Due to poor production and injection capacity of low permeable reservoir, imbibition recovery plays important role in the oilfield development. This paper introduces a new kind of imbibition equipment, and by use of it we studied the reverse imbibition law of low permeable core. Using X-Ray's degree of change checkout apparatus, we studied the core length effect on reverse imbibition performance and ultimate imbibition recovery, as well as the change course of watercut variation for core of different stages during imbibition process. And reach to the following conclusion: adverse imbibition is the main recovery mechanism in fractured low permeable sandstone reservoir; Due to the characteristic of low permeable reservoir, the effectiveness of capillary force is restricted, imbibition is slow, and imbibition recovery is low; the X-Ray's scanning result shows that imbibition speed is quick at the initial stage of imbibition, and the imbibition speed slows down after imbibition frontline arrives the boundary.

**Key words:** low permeable reservoir; imbibition; recovery; saturation

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### **Increasing First Drilling Well Design Level Using the Reservoir Modeling Technique**

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**Abstract:** The Sheng 26 pieces of Shangjia oilfield have a good prospect of development in outer oilfield, how to increase first drilling wells design level then seem to be very important. It is first time that using reservoir modeling method in wells design in outer oilfield, and adopting authenticity insertion and matchable simulation methods evaluates the benefit and the risk block, quantitatively predicts the complicated reservoir characterization. four wells have obtained good results. Investigation of the method on reservoir characterization and modeling in the earlier development and the evaluation period has actual and referenced significance for guiding reservoir research and project design.

**Key words:** stage of earlier period evaluation; reservoir characterization; reservoir modeling; first drilling well

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### **Theoretical Model for a Well with a Finite-Conductivity Vertical Fracture on Constant Bottom-Hole Pressure**

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**Abstract:** A hydraulic fracture is produced by manpower fracture. Now production dynamic of oil-gas wells has become one question of reservoir engineering with fracture. In order to develop economically and reasonably we need to analyze and estimate fractured effect, to predict oil rate. Then transient flow behavior of a vertically fractured well producing at constant bottom-hole pressure is analyzed