基于相似流动替换法预测水平井产量

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摘要:随着水平井技术在油气田开发中运用得日益广泛,准确预测水平井产量变得至关重要。以水平井周围椭球体等压面为基础,将水平井的渗流划分为近井地带若干个椭圆形供给边界中一点汇的渗流问题以及远井地带的线性渗流问题,基于相似流动替换法以及等值渗流阻力法求得水平井产量计算的新公式。通过实例分析以及与Borisov等较为经典的产量公式计算结果相比较,新公式计算结果大,但与实际生产数据的相对误差最小,约为10.09%。分析表明,这是因为新公式推导过程中考虑内部渗流场为一个个椭圆形组成的椭球体,内阻较小,而Borisov等产量公式中将内部渗流场简化为拟圆形组成的圆柱体,内阻较大,使得计算结果与实际生产数据相对误差较大。因此新公式不仅能够准确预测水平井产量,而且符合水平井客观渗流模式。

关键词:水平井产量 相似流动 椭圆形 拟圆形 线性渗流
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自20世纪60年代Merkulov首次提出水平井产量公式[1]以来,中外学者们也纷纷对水平井产量进行了研究,根据不同的假设条件,提出了一系列水平井产量公式[2-10]。Giger等将压力波由水平井井底传播到储层顶底边界的过程等效为拟圆形泄油区域内的渗流问题[3-4],在此基础上,陈元千将椭圆形泄油边界转化为拟圆形驱动边界,将水平井段转化为拟圆形生产坑道,推导出了新的产量公式[8]。笔者认为,作等效为圆形的转化可能会影响产量的预测,且与水平井真实渗流模式不相符,水平井周围的等压面其实为一椭球体,近井地带的渗流为椭球形供给边界中存在一点汇的渗流问题,故而应用相似流动替换法推导了一个新的水平井产量公式,并与实际生产数据进行了对比,以期为水平井渗流机理及产量的研究提供理论依据。

1 物理模型

假设水平井位于顶底封闭、水平方向存在供给边界的各向异性油层中,井筒位于地层中部,流体在地层中的渗流为稳态渗流,流体微可压缩,不考虑井筒中压降及地层污染对水平井产量的影响。在三维空间中,水平井渗流物理模型如图1所示。

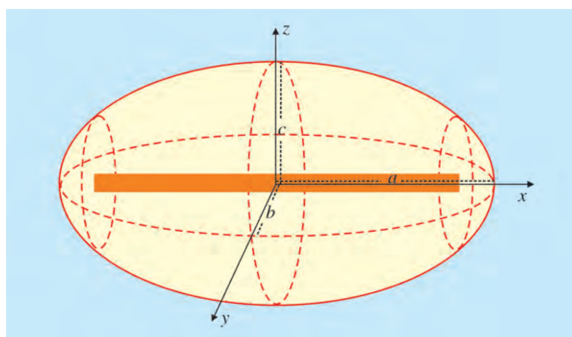

图1 三维空间中水平井渗流物理模型

x,y,z为三维空间中的坐标轴;a为x—y平面椭圆形泄油区域的长半轴长度,m;b为椭球体短半轴长度,m;c为椭球体z方向半轴长度,m

Joshi[4]研究发现,水平井周围的等压面为一个个椭球体(图1),该椭球体等压面的方程为

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}=1 \tag{1}$$

在水平井段任意位置x处,水平井的等压线在y—z平面内均为一条椭圆形曲线(图2)。任一位置x处椭圆的方程为

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$$\frac{y^2}{b^2\left(1-\frac{x^2}{a^2}\right)}+\frac{z^2}{c^2\left(1-\frac{x^2}{a^2}\right)}=1 \tag{2}$$

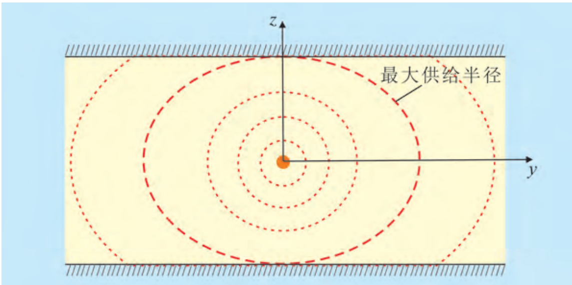

图2 水平井在y—z平面内等压线示意

由图2可以看出，当等压线在z方向达到油层顶、底处时，由于顶底封闭，压力波无法继续传播，z方向等压线消失，则压力波只能沿水平方向传播，随着水平方向距离的增加，等压线的曲率半径越大，即曲率越小，等压线趋于一系列平行直线，因此可以将水平井远井地带的渗流看成线性渗流，而在近井地带，等压线密集，曲率较大，那么近井地带的渗流为椭圆形径向渗流。

2 产量公式推导

2.1 内部渗流场压降公式推导

将压力波由井底传播到顶底边界的这一过程看成是水平井内部渗流场的渗流过程，此时可以得到内部渗流场椭球体供给边界方程中c取值为油层厚度的一半。

在水平井段任一位置x处，y方向和z方向的供给边界分别为

$$b_{\rm p}(x)=b\sqrt{\left(1-\frac{x^2}{a^2}\right)} \tag{3}$$

$$c_{\rm p}(x)=\frac{h}{2}\sqrt{\left(1-\frac{x^2}{a^2}\right)} \tag{4}$$

式中：$b_{\rm p}$为内部渗流场y方向的供给半径，m；$c_{\rm p}$为内部渗流场z方向的供给半径，m；h为油层厚度，m。

选取微元段dx，在y—z平面内的渗流数学模型及内外边界条件为

$$\begin{cases}\frac{\partial^2\Phi}{\partial^2 y}+\frac{\partial^2\Phi}{\partial^2 z}=0\\ \frac{y^2}{b_{\rm p}(x)^2}+\frac{z^2}{c_{\rm p}(x)^2}=1 \qquad \Phi=\Phi_{\rm p}(x)\\ y^2+z^2=r_{\rm w}^{\ 2} \qquad \Phi=\Phi_{\rm w}\end{cases} \tag{5}$$

式中：Φ为油藏中任一点的势，m²/s；$\Phi_{\rm p}$为内部泄油边界处的势，m²/s；$r_{\rm w}$为井筒半径，m；$\Phi_{\rm w}$为井壁处的势，m²/s。

对式(5)直接求解非常困难，目前还没有解析解。刘月田等利用相似流动替换法[11]，将椭圆形区域中含有一点源的位势流动问题等效为距离为H的平行等压直线边界间的点源流动问题。式(5)表示椭圆形供给边界中一点汇的渗流问题，因此根据相似流动替换法可间接得到式(5)的解析解。

由于两等效平行等压直线的距离随x不断变化，式(5)的相似流动替换法转化结果则可写为

$$\begin{cases}\frac{\partial^2\Phi}{\partial^2 y}+\frac{\partial^2\Phi}{\partial^2 z}=0\\ z=\pm H(x) \qquad \Phi=\Phi_1(x)\\ y^2+z^2=r_{\rm w}^{\ 2} \qquad \Phi=\Phi_{\rm w}\end{cases} \tag{6}$$

式中：H为两等效平行等压线间的距离，m；Φ_1为平行等压边界上的势，m²/s。

根据位势叠加原理，式(6)的解析解为

$$\Phi=\frac{{\rm d}q(x)}{4\pi{\rm d}x}\ln\frac{{\rm ch}\frac{\pi y}{2H(x)}-\cos\frac{\pi z}{2H(x)}}{{\rm ch}\frac{\pi y}{2H(x)}+\cos\frac{\pi z}{2H(x)}}+\Phi_1(x) \tag{7}$$

式中：q为水平井地下产油量，m³/s。

式(7)即为椭圆形供给边界中一点汇周围势分布问题的解析解，由于点$(b_{\rm p}(x),0)$与点$(0,c_{\rm p}(x))$位于同一等压线上，且势为内部渗流场供给边界的势$\Phi_{\rm p}$，这2点的势相等，其表达式分别为

$$\Phi_{\rm p}=\frac{{\rm d}q(x)}{4\pi{\rm d}x}\ln\frac{{\rm ch}\frac{\pi b_{\rm p}(x)}{2H(x)}-1}{{\rm ch}\frac{\pi b_{\rm p}(x)}{2H(x)}+1}+\Phi_1(x) \tag{8}$$

$$\Phi_{\rm p}=\frac{{\rm d}q(x)}{4\pi{\rm d}x}\ln\frac{1-\cos\frac{\pi c_{\rm p}(x)}{2H(x)}}{1+\cos\frac{\pi c_{\rm p}(x)}{2H(x)}}+\Phi_1(x) \tag{9}$$

联立式(8)和式(9)可以得到

$$\Phi_1(x)=\Phi_{\rm p}-\frac{{\rm d}q(x)}{2\pi{\rm d}x}\ln\left[\tan\frac{\pi c_{\rm p}(x)}{4H(x)}\right] \tag{10}$$

$$\tan\frac{\pi c_{\rm p}(x)}{4H(x)}={\rm th}\frac{\pi b_{\rm p}(x)}{4H(x)} \tag{11}$$

根据式(11)无法求得$H(x)$的解析解，但可利用图形来研究其变化规律。由$H(x)/c_{\rm p}(x)$与$b_{\rm p}(x)/c_{\rm p}(x)$关系曲线(图3)可见，当$b_{\rm p}(x)/c_{\rm p}(x)>1.5$时，$H(x)/c_{\rm p}(x)$的值趋于恒定，其值为1，而通常情况下，油层中满足$b_{\rm p}(x)/c_{\rm p}(x)>1.5$，因此，文中取$H(x)=c_{\rm p}(x)$。

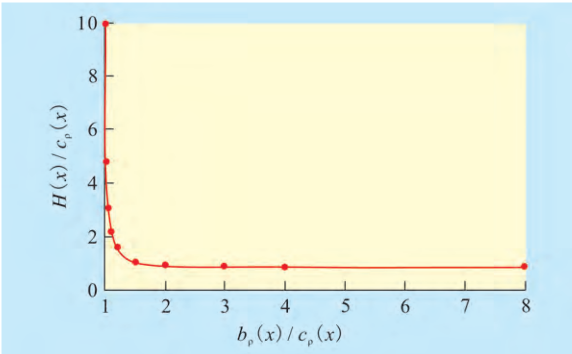

图3　$H(x)/c_\rho(x)$ 随 $b_\rho(x)/c_\rho(x)$ 的变化

将式(10)代入式(7)得到

$$\Phi=\Phi_\rho-\frac{\mathrm{d}q(x)}{2\pi\mathrm{d}x}\ln\left[\tan\frac{\pi c_\rho(x)}{4H(x)}\right]+\frac{\mathrm{d}q(x)}{4\pi\mathrm{d}x}\ln\frac{\mathrm{ch}\frac{\pi y}{2H(x)}-\cos\frac{\pi z}{2H(x)}}{\mathrm{ch}\frac{\pi y}{2H(x)}+\cos\frac{\pi z}{2H(x)}}\tag{12}$$

式(12)即为 $y—z$ 平面内任一点势的计算公式。若在井筒附近，等压线为圆形，且 $y\ll b_\rho(x)$，$z\ll c_\rho(x)$，式(12)可化简为

$$\Phi=\Phi_\rho-\frac{\mathrm{d}q(x)}{2\pi\mathrm{d}x}\ln\left[\tan\frac{\pi c_\rho(x)}{4H(x)}\right]+\frac{\mathrm{d}q(x)}{2\pi\mathrm{d}x}\ln\frac{\pi r}{4H(x)}\tag{13}$$

其中

$$r=\sqrt{x^2+y^2}\tag{14}$$

取 $r=r_w$，得到井壁处势的表达式为

$$\Phi_w=\Phi_\rho-\frac{\mathrm{d}q(x)}{2\pi\mathrm{d}x}\ln\left[\tan\frac{\pi c_\rho(x)}{4H(x)}\right]+\frac{\mathrm{d}q(x)}{2\pi\mathrm{d}x}\ln\frac{\pi r_w}{4H(x)}\tag{15}$$

由此得到内部渗流场的压降公式为

$$\Delta p_1(x)=p_\rho-p_{wf}=\frac{\mu_o}{K_v}\times\frac{\mathrm{d}q(x)}{2\pi\mathrm{d}x}\ln\frac{4c_\rho(x)}{\pi r_w}\tag{16}$$

式中：Δp_1 为内部渗流场压降，Pa；p_ρ 为内部渗流场驱动压力，Pa；p_{wf} 为井底流压，Pa；μ_o 为地层原油粘度，Pa·s；K_v 为油藏垂直方向渗透率，m²。

2.2　外部渗流场压降公式推导

随着等压线离井筒位置越来越远，由于顶底封闭边界的约束，使得压力波只能在水平方向传播，且等压线的曲率越来越小，趋于一系列平行的直线，因此，可以将外部渗流场的渗流看成是线性渗流过程。那么外部渗流场的渗流数学模型及其定解条件为

$$\begin{cases}\dfrac{\partial^2\Phi}{\partial^2 y}=0\\ y=r_e \qquad \Phi=\Phi_e\\ y=r_\rho(x) \qquad \Phi=\Phi_\rho\end{cases}\tag{17}$$

式中：r_e 为油藏水平平面泄油半径，m；Φ_e 为油藏泄油边界处的势，m²/s；r_ρ 为内部渗流场泄油半径，m。

求解该定解问题得到外部渗流场势的分布

$$\Phi=\Phi_e-\frac{\Phi_e-\Phi_\rho}{r_e-r_\rho(x)}(r_e-y)\tag{18}$$

则微元段的产量为

$$\mathrm{d}q(x)=\frac{h(\Phi_e-\Phi_\rho)}{r_e-r_\rho(x)}\mathrm{d}x\tag{19}$$

由于 $r_e\gg r_\rho(x)$，那么外部渗流场的压降为

$$\Delta p_2(x)=p_e-p_\rho=\frac{\mu_o}{K_h}\times\frac{\mathrm{d}q(x)\left[r_e-r_\rho(x)\right]}{h\mathrm{d}x}\approx\frac{\mu_o}{K_h}\times\frac{\mathrm{d}q(x)r_e}{h\mathrm{d}x}\tag{20}$$

式中：Δp_2 为外部渗流场压降，Pa；K_h 为油藏水平方向渗透率，m²；p_e 为油藏驱动压力，Pa。

2.3　水平井产量公式推导

根据式(16)与式(20)，可以得到微元段 dx 的产量公式，对 x 在 $(-L/2,L/2)$ 上积分即可得到整个井段的产量公式，即

$$q=\int_{-L/2}^{L/2}\frac{2\pi K_h(p_e-p_{wf})}{\mu_o\left[\dfrac{2\pi r_e}{h}+\beta^2\ln\dfrac{4c_\rho(x)}{\pi r_w}\right]}\mathrm{d}x\tag{21}$$

式中：L 为水平段长度，m；β 为地层各向异性系数；B_o 为地层原油体积系数。

将式(4)代入式(21)中，并把其化为SI制矿场单位下的地面产量公式为

$$q_{sc}=\frac{0.543K_h(p_e-p_{wf})}{\mu_o B_o}\int_0^{L/2}\frac{\mathrm{d}x}{\dfrac{\pi r_e}{h}+\dfrac{\beta^2}{2}\ln\left(\dfrac{2h}{\pi r_w}\sqrt{1-\dfrac{x^2}{a^2}}\right)}\tag{22}$$

式中：q_{sc} 为水平井地面产油量，m³/d。

3　实例分析

某油田一水平井的基本数据包括：水平段长度为600 m，油层厚度为18 m，水平井筒半径为0.061 m，拟圆形泄油半径为370 m，地层原油粘度为3 mPa·s，原油体积系数为1.13 m³/m³，油藏水平方向渗透率为 1.3×10^{-3} μm²，垂直方向渗透率为 1.29×10^{-3} μm²，油藏驱动压力为17 MPa，水平井井底流压

为9 MPa。

该井投产初期产油量为42 t/d，生产2个月后平均产油量为33.1 t/d，生产6个月后平均产油量为26.3 t/d，1 a之中平均产油量为32.2 t/d，地面原油密度约为0.85 g/cm³，则平均产油量约为37.88 m³/d。

将实例中已知数据代入式(22)，求得产油量为34.06 m³/d。将新推导公式计算结果、水平井经典产量公式计算结果以及实际生产资料进行对比（表1），结果表明，新公式的计算结果比各经典产量公式的计算结果大，但与实际产量相比，相对误差最小，说明新公式在水平井产量预测方面具有较好的实用性。新公式计算产量结果较经典产量公式计算结果大的原因在于内部渗流场的处理上。新公式推导过程中，内部渗流场为一个个椭圆，而各个经典公式的内部渗流场均简化为拟圆形，由于椭圆形渗流场具有泄油面积大，生产压差小等特点[12]，所以内部渗流场阻力较小，这也和水平井实际渗流模式更加符合。

表1 各产量公式计算结果对比

产量公式	产量计算结果/($m^3 \cdot d^{-1}$)	相对误差，%
新推导公式	34.06	10.09
陈元千公式	28.48	24.80
Borisov公式	29.44	22.27
Giger-Resis-Jourdan公式	26.01	31.32
Joshi公式	28.14	25.72
Renard-Dupy公式	29.07	23.25

4 结论

水平井井筒附近等压线大部分呈椭圆形分布，只有很少一部分为圆形，将其看成拟圆形势必违背水平井客观渗流模式，可以利用微元法将水平井井筒附近的渗流分成若干个椭圆形供给边界一点汇的渗流问题，利用相似流动替换法求得任一微元段近井地带的压降方程。

水平井远井地带由于等压线分布较稀疏，因而可以看成线性渗流，利用单向渗流微分方程求得微元段远井地带的压降。

通过实例分析以及与经典水平井产量公式对比，新公式在水平井产量预测方面具有较好的实用性。

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Xiong Jian, Liu Haishang, Zhao Changhong et al. Study on productivity of asymmetrical vertical fracture well in low-permeability gas reservoirs. *PGRE*, 2013, 20(6): 76-79

Abstract: In view of the asymmetrical vertical fracture in the low permeability reservoir after fracturing development, and based on the steady seepage theory, and by means of the conformal transformation method, a prediction model for the finite-conductivity asymmetrical vertical fracture wells is established in the low-permeability gas reservoirs, and the various factors on the gas well productivity are analyzed. The result shows that, under the same bottom-hole pressure, the fracture asymmetry factor has little effect on the productivity of the gas well with asymmetrical vertical fracture. When the fracture conductivity capacity is small, there is great difference in the productivity of the fracture gas well with respect to fracture length or fracture asymmetry factor. And, when the fracture conductivity capacity is high, there is little difference in productivity with respect to variable fracture length or fracture asymmetry factor in gas well. The longer the fracture length, the less the fracture asymmetrical factor, and the greater influence on the fractured gas well productivity.

Key words: low-permeability gas reservoirs; asymmetrical vertical fracture; fracture conductivity capacity; fracture asymmetry factor; productivity forecast

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Li Aifen, Li Huihui, Lv Jiao et al. Experimental study of foam on gas-liquid relative permeability at different temperature. *PGRE*, 2013, 20(6): 80-82

Abstract: There are many researches about the influence of the foam on gas-liquid relative permeability, but the influence of the temperature on foam relative permeability curve needs to be further studied. The curve reflecting the relationship between foam block pressure and gas-liquid flow rate ratio is measured at different temperature in this paper. So, the impact of the gas-liquid flow ratio and temperature on the block pressure is analyzed. The gas-liquid relative permeability curves both with the and without effects of foam are measured by using steady-state method in this paper. On this base, the flow rules of foam at different temperature are also characterized. The results indicate that the higher the experimental temperature, the better the sealing performance. And, both the foam block pressure and the blocking performance of foam can attain the highest degree in the range of gas-liquid flow ratio between 2 and 4. The foam has no effect on the relationship between the liquid relative permeability and the water saturation. The gas relative permeability, however, has a sharp decline under the action of foam. With the experimental temperature, the critical water saturation became higher with the increase of temperature and the moderate values of the gas relative permeability became lower with the increase of temperature.

Key words: temperature; foam; block pressure of foam; steady-state method; gas-liquid relative permeability; critical water saturation

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Yang Hongbin, Pu Chunsheng, Li Miao et al. Laboratory evaluation and field application on profile control of self-adaptive weak gel. *PGRE*, 2013, 20(6): 83-86

Abstract: In response to the problems of fully developed micro-fractures in low permeability oil fields, severely heterogeneous reservoir and the fact that traditional profile control are less effective, the self-adaptive weak gel is developed. The static performance, sealing characteristics and displacement efficiency are evaluated through lab tests. The results show that the self-adaptive weak gel has good temperature-resistant and salt-resistant properties. When the salinity of formation water is 41 811.5 mg/L, the weak gel system can gelatinize rapidly in 38 hours, and the gel strength is 28 549 mPa·s under the condition of 70 ℃. Its plugging ratio is 84.08% and the recovery ratio reaches 12.1%. The field experiments of the well S in Ganguyi oilfeild indicate that the preferred path of water breakthrough of water injection well is controlled after profile control and flooding, and the injection pressure rises, at the same time, the water content of well group fell to 69.16% from 78.51%, and daily fluid production rate increases by 135.14%, while the daily oil production rate increases by 237.5%. The deep profile control technology of self-adaptive weak gel has good adaptability in fractured low permeability oil fields. It can enlarge the sweep volume of injected water and enhance oil recovery factor greatly, so it can provide reference for other similar reservoirs to obtain good performance on water control and oil increment.

Key words: self-adaptive weak gel; profile control; gelation intensity; plugging; micro fractures; Ganguyi oilfield

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Yuan Lin, Li Xiaoping, Sun Fei et al. Deduction of productivity formula for horizontal well with displacement method between two similar flow. *PGRE*, 2013, 20(6): 87-90

Abstract: As the technology of horizontal well had been widely used in the gas and oil fields, the productivity forecast of horizontal wells will be of great importance. Based on the ellipse constant pressure surfaces near the wellbore, the author divides the seepage problem of horizontal well into two parts, one is the problem in several ellipsoidal supply boundary near the wellbore, the other is the linear flow far from the well bore, based on the displacement between two similar flow mode and the law of equivalence percolation resistance, then eventually proposing a new productivity formula of horizontal well. Through case study, the results calculated by new formula has been compared with that calculated by the formulas of Borisov et al, it shows that the new result is more than the results calculated by conventional formulas, meanwhile, the new result has a small relative error compared to the practical oil production by only 10.09%. Analysis shows that this is because the resistance in ellipse drainage area is less than that in pseudo-circular drainage area, and the assumption of pseudo-circular will bring a great relative error. So, we can conclude that the new formula will not only predict the productivity accurately, but also accord with the practical flow mode of horizontal well.

Key words: horizontal well; productivity formula; similar flow; ellipse; pseudo-circular

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Ming Yukun. Electrolytic simulation experiment of multi-stage fracturing horizontal well for water flooding development. *PGRE*, 2013, 20(6): 91-93

Abstract: In order to study the production stimulation mechanism of water flooding by multi-stage fracturing horizontal well, the electrolytic simulation experiment of fractured horizontal well is designed according to the water and electricity resembling principle, and the pressure distribution and the productivity influence factors are studied. The experiment results show that the pressure contour is distributed in parallel in the middle of horizontal which has the fracture, and the fluid flow is unidirectional, it shows that the multi-stage fracturing horizontal well can improve the fluid flow characters and decrease the percolating resistance. The horizontal productivity can be enhanced by increasing the horizontal penetration ratio, the fracture numbers and penetration ratio, the angle between horizontal and fracture. The best parameters are as follows: the horizontal penetration ratio is 0.8, the fracture numbers are 6 (the space between fractures is 91 m), the fracture ratio is 0.25, the angle between the fracture and the horizontal section is 90 degree. The well pattern is staggered line-drive well network, and the ranges of those parameters which have effect on the productivity are 0.032, 0.024, 0.018, 0.018 and 0.004. The field application showed that the productivity of multi-stage fracturing horizontal well is 2 times than that of vertical well, and it is the effective development style for low permeability reservoir.

Key words: multi-stage fracturing; horizontal well; water flooding; electrolytic simulation experiment; productivity

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Cao Gongze, Liu Tao, Ba Yan et al. Microbial flooding after polymer flooding pilot test in N*g*3 of Zhong1 area, Gudao oilfield. *PGRE*, 2013, 20(6): 94-96

Abstract: In order to study the adaptation and effect of microbial flooding after polymer flooding pilot, the test was conducted as pilot project in N*g*3 of Zhong1 area. The indigenous microorganisms are first activated and then filtrated; at the same time, 4 strains of functional bacteria are obtained, the bacteria are mass propagated at the reservoir environment, and the crude oil can be emulsified by the microbe. Meanwhile, the physical simulation experiment is studied under the pressure and temperature of the reservoir, and, the result indicates that the oil recovery is enhanced by 7.8%-8.3% by the bacteria. The field test indicates that the microbe is activated and the concentration of metabolism of acetate may reach 105 mg/L. The production dynamic is improved, and the oil recovery is enhanced by 1.27%, and the recovery factor in the pilot is increased by 4.7% to 57.8%.

Key words: MEOR; post-polymer flooding; pilot test; enhanced oil recovery; Gudao oilfield

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Gao Baoguo, Hua Hui, Ding Wenge et al. Technical treatment in extra-high water cut stage for low permeable reservoir-case study of Yi11 area, Bonan oilfield. *PGRE*, 2013, 20(6): 97-99

Abstract: Due to the serious heterogeneity in plane, interlayer and layer, it is full of imbalances in injection-production pattern, and the production decline reaches 14.8% in Yi11 area of Bonan oilfield, so the technical treatment is needed to ameliorate the decline of the development. The non-stable injection and optimized liquid yielding are adopted to control the water and stabilize oil production in response to the high water cut and serious flooding in the major oil-production layers. Moreover, the water drive producing reserves are produced by improving and completion of well pattern in response to incomplete injection-production pattern. The interlayer problems are resolved by means of layer-oriented injection and plugging of high water cut layer. For the sand body edge and secondary oil-bearing layers, the reservoir reformation, intensive injection, individual layer production are adopted to enhance the reserve utilization. The development effect is remarkably improved. The production decline rate decrease to 4.1% and the recovery factor is further increased from 30.7% to 32%.

Key words: extra-high water cut stage; flow unit; technical treatment; EOR; injection-production completion; Bonan oilfield