分段压裂水平井注水开发电模拟实验

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摘要：为研究分段压裂水平井注水开发增产机理，根据水电相似原理设计了压裂水平井电模拟实验，研究了分段压裂水平井注水开发压力场分布特征和产能影响因素。结果表明，水平井中间有裂缝部分等压线平行分布，渗流方式为单向流，说明分段压裂水平井可通过改善地层渗流方式减小渗流阻力。随着水平段穿透比、裂缝条数（间距）、裂缝穿透比、裂缝与水平段夹角的增大，压裂水平井产能增加；分段压裂水平井注水开发最佳参数组合为：水平段穿透比为0.6~0.8，裂缝条数为6（裂缝间距为91 m），裂缝穿透比为0.25~0.3，裂缝与水平段夹角为90°，井网选用排列交错井网；其对分段压裂水平井产能影响的极差分别为0.030，0.024，0.018，0.018和0.004。矿场应用表明，分段压裂注水开发水平井产能为同条件下直井的2倍，是低渗透油藏的有效开发方式。

关键词：分段压裂 水平井 注水开发 电模拟实验 产能
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胜利油区特低渗透油藏已成为产能建设的重要阵地，水平井分段压裂作为特低渗透油藏开发的有效措施，日益受到重视[1-4]。胜利油区分段压裂水平井平均初期产油量达10 t/d，总体效果较好[5-6]。然而，水平井分段压裂应用中也存在一些问题，如渗流机理认识不清、产能影响因素复杂等，影响了其在矿场的推广应用[7-9]。为此，笔者通过电模拟实验，利用正交试验法，分析了分段压裂水平井注水开发渗流机理和产能影响因素，以期为胜利油区开展分段压裂水平井注水开发产能预测、地质优化设计和井网优化提供技术支持和借鉴。

1 实验装置与步骤

电模拟实验依据的是水电相似原理[10]，实验装置（图1）主要由油藏模拟系统、测试系统和电源系统组成。在油藏模拟系统中，向有机玻璃槽（规格为1 500 mm×1 500 mm×350 mm）装入质量浓度为8%的NaCl溶液模拟储层多孔介质，以铜带模拟供给边界，铜棒（直径为2 mm）模拟井筒，铜片模拟压裂裂缝。电源系统可将220 V交流电转变为安全的电压，输出供给边界和模拟井。测试系统可通过探针在NaCl溶液中的移动，测量平面上各点的电压，并可测定通过模拟井的电流。

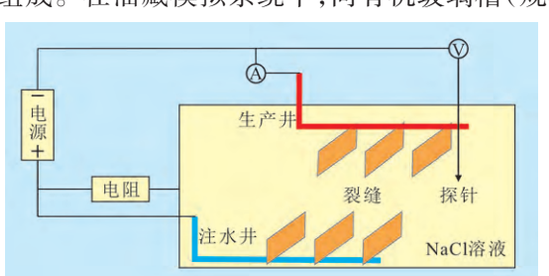

图1 电模拟实验装置示意

实验步骤包括：①对供给边界和模拟的生产井和注水井加上直流稳定电压，测量通过生产井的电流；②以5 cm为1个测点测量模型内各点的电压；③改变井网模型，重复步骤①—②。

2 实验结果

2.1 电压场分布特征

由典型的分段压裂水平井正对井网（图2a）和交错井网（图2b）电压场分布可以看出：①压裂水平井周围等压线以水平井和裂缝为中心总体呈椭圆形分布；②在水平井端部等压线发生弯曲，渗流方式为径向流，而在水平井中间裂缝部位等压线平行分布，渗流方式为单向流，说明分段压裂水平井可通过改善地层渗流方式而减小渗流阻力，从而大幅度提高产能；③靠近裂缝端部的等压线在每条裂缝对应位置发生凸起。

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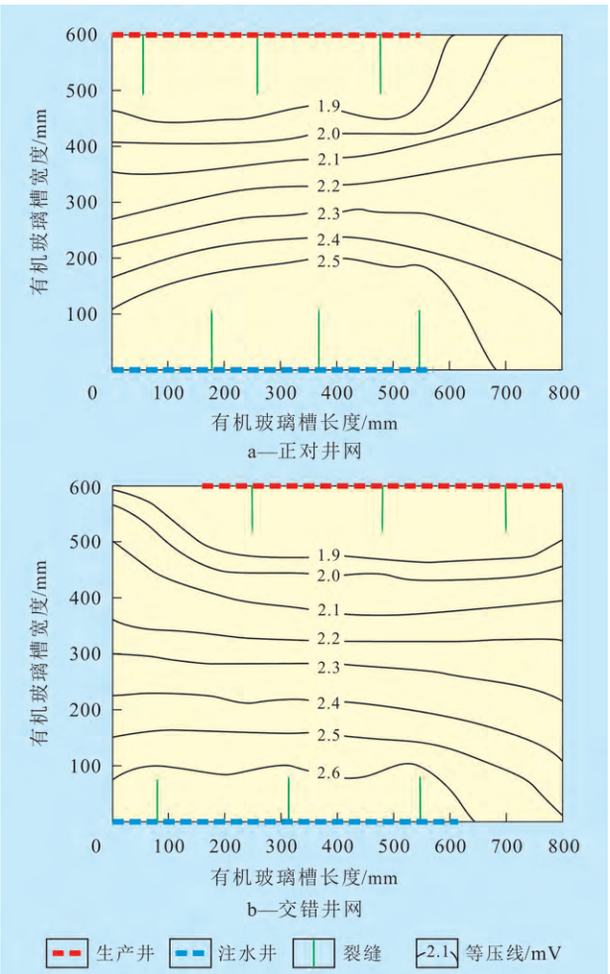

图2　分段压裂水平井电压场分布

2.2　产能影响因素

水平段穿透比　由不同水平段穿透比下产能变化(图3)可看出:①随着水平段穿透比的增大,产能增加,这是因为水平段穿透比增大,单向流的区域范围增大,渗流阻力减小,同时,裂缝间距增大,裂缝间的干扰减弱;②随水平段穿透比增大,产能增幅逐渐变小,当穿透比达到0.8时,增大穿透比产能增幅较小,说明此时整个渗流场以单向流为主,分段压裂水平井的优势已经充分发挥出来。考虑钻井成本,建议水平段穿透比以0.6~0.8为宜。

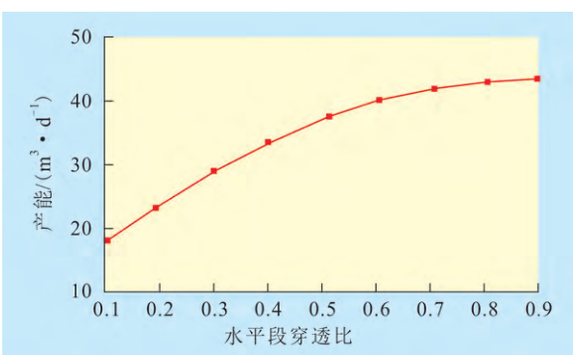

图3　产能随水平段穿透比的变化

裂缝条数　由不同裂缝条数下产能的变化(图4)可知:产能随裂缝数量的增加而增加,但增幅逐渐变小,这是因为随着裂缝条数的增加裂缝间距减小,裂缝间的干扰逐渐增强;当裂缝条数为6时,产能随裂缝条数的增加增幅已很小,考虑压裂经济成本,最优裂缝条数为6,相对应的裂缝间距为91 m。

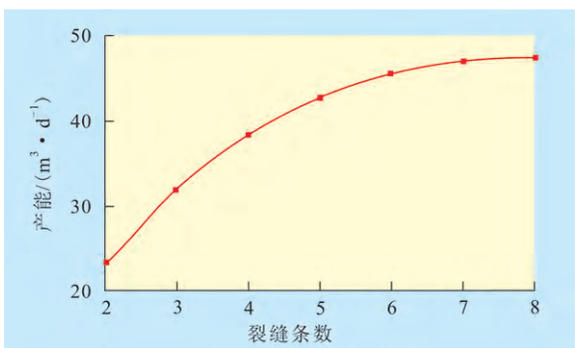

图4　产能随裂缝条数的变化

裂缝穿透比　由不同裂缝穿透比下产能变化(图5)可以看出:压裂水平井的产能随裂缝穿透比的增大而增加,当裂缝穿透比增至0.25时,产能增幅变缓。裂缝穿透比越大,压裂设计技术要求越高,经济成本也越大。同时,裂缝穿透比越大,生产井、注水井裂缝间的距离越短,越容易发生水窜,建议裂缝穿透比为0.25~0.3。

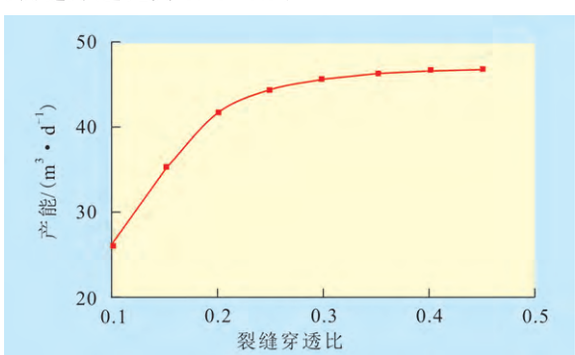

图5　产能随裂缝穿透比的变化

裂缝与水平段夹角　由不同裂缝与水平段夹角下产能变化(图6)可知:裂缝与水平段夹角越大,

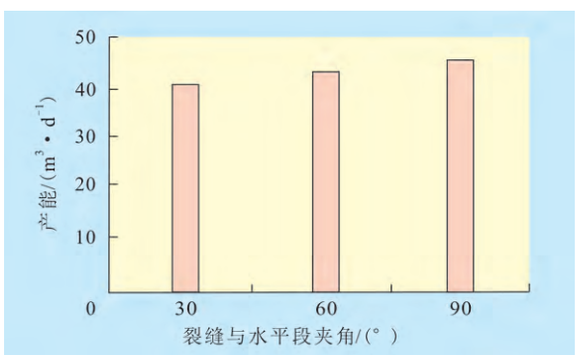

图6　产能随裂缝与水平段夹角的变化

压裂水平井的产能越高，但对产能的影响相对较小。这是因为裂缝与水平段夹角主要影响裂缝的波及面积，裂缝与水平段夹角越大，裂缝直接波及控制的面积越大，渗流阻力越小，产能越高。

井网形式　相同条件下，交错井网的产能为48.84 m^3/d，正对井网的产能为48.16 m^3/d，交错井网产能略高，这是因为交错井网单向流范围比正对井网大，且等压线分布更为均匀，更有利于提高产能。

2.3　产能影响因素敏感性分析

利用正交试验法，对水平段穿透比、裂缝条数、裂缝穿透比、裂缝与水平段夹角、井网形式5个产能影响因素进行正交设计（表1），分析各因素对产能影响的敏感性。

表1　产能影响因素正交试验设计

水平	水平段穿透比	裂缝数/条	裂缝穿透比	裂缝与水平段夹角/(°)	井网形式
1	0.4	2	0.1	30	正对
2	0.5	3	0.15	60	交错
3	0.6	4	0.2	90	正对
4	0.7	5	0.25	30	交错
5	0.8	6	0.3	90	正对

应用正交试验分析理论，计算各影响因素对分段压裂水平井产能影响的极差（图7），结果表明，水平段穿透比、裂缝条数、裂缝穿透比、裂缝与水平段夹角和井网形式对分段压裂水平井产能影响的极差分别为0.030，0.024，0.018，0.018和0.004。

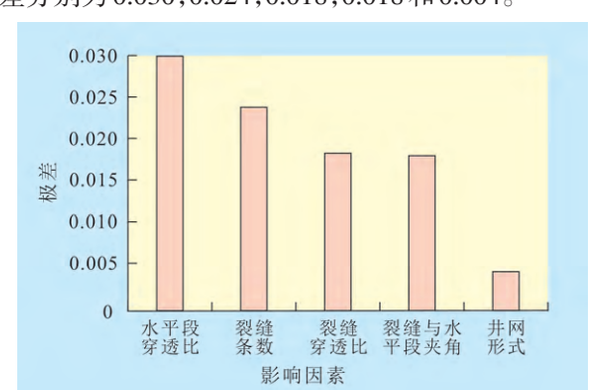

图7　产能影响因素正交试验结果

3　应用实例

樊147块位于正理庄油田东南部，区域构造位置处于金家—正理庄—樊家鼻状构造带东部，为一南高北低的单斜构造，地层倾角为5°～8°。该区块为胜利油区新区产能建设区块，油藏类型为薄互层低渗透构造-岩性油藏，主力储层为沙四段，油藏埋深为2 770 m，储层平均孔隙度为14.6%，平均渗透率为13.9×10^{-3} μm^2。樊147-平2井水平段长度为684 m，2008年9月分3段压裂投产，监测水平段中部裂缝缝长为317 m，趾端缝长为250 m。该井投产初期产液量为19 t/d，产油量为15 t/d，为周围直井的2倍。至2011年12月，产液量为18.7 t/d，产油量为10.2 t/d，累积产油量为1.59×10^4 t，与直井相比开发优势明显。

4　结论

分段压裂水平井注水开发时，压裂水平井周围等压线以水平井和裂缝为中心总体呈椭圆形分布，水平井中间有裂缝部位等压线平行分布，渗流方式为单向流，说明分段压裂水平井可通过改善地层渗流方式而减小渗流阻力。当水平段穿透比为0.8、裂缝条数为6（裂缝间距为91 m）、裂缝穿透比为0.25、裂缝与水平段夹角为90°且选用交错井网时，开发效果最佳。实例应用表明，分段压裂水平井注水开发产能为同条件下直井的2倍，是低渗透油藏有效的开发方式。

参考文献：

[1] 唐汝众，温庆志，苏建，等.水平井分段压裂产能影响因素研究[J].石油钻探技术，2010，38(2)：80-83.
[2] 王聪.胜利油区致密砂岩油藏水平井开采技术[J].油气地质与采收率，2013，20(3)：86-88.
[3] 曲占庆，赵英杰，温庆志，等.水平井整体压裂裂缝参数优化设计[J].油气地质与采收率，2012，19(4)：106-110.
[4] 李勇明，翟锐，高瑞民，等.水平井多段压裂后压力递减分析[J].油气地质与采收率，2012，19(4)：66-70.
[5] 樊冬艳，姚军，姚婷，等.基于自适应遗传算法的压裂水平井参数优化[J].油气地质与采收率，2011，18(5)：85-88.
[6] 陈汾君，汤勇，刘世铎，等.低渗致密气藏水平井分段压裂优化研究[J].特种油气藏，2012，19(6)：85-87.
[7] 周德华，焦方正，葛家理.裂缝网络油藏水平井开发电模拟实验研究[J].石油实验地质，2003，25(2)：216-220.
[8] 魏建光，汪志，张欣.裂缝参数对压裂水平井产能影响规律分析及重要性排序[J].水动力学研究与进展，2009，24(5)：631-639.
[9] 牟珍宝，袁向春，朱筱敏.低渗透油藏压裂水平井产能计算方法[J].现代地质，2009，23(2)：337-340.
[10] 吴晓东，隋先富，安永生，等.压裂水平井电模拟实验研究[J].石油学报，2009，30(5)：740-743.

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lem 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

Cao Gongze, Research Institute of Oil Production Technology, Shengli Oilfield Company, SINOPEC, Dongying City, Shandong Province, 257000, China

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