超低渗透油藏注水方式研究

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摘要: 从超前注水的机理入手，结合数值模拟与实际动态，对比了不同注水时机下油水井间的压力剖面，优选了超低渗透油藏的注水时机，并在最优注水时机下，分析了不同注水方式对地层压力波及范围的影响；基于超低渗透油藏具有启动压差大、应力敏感性强、孔喉细小等特性，分析了不同超前注水方式下油井和水井压力升幅和压力波及范围，在岩石不破裂的情况下，进行不同超前注水方式的筛选与组合，反阶梯温和注水能够得到最优的开发效果。以长庆油田 BMZ 区块为例，进行了不同注水方式的开发效果分析，当采用反阶梯温和注水时，预测平均单井产油量在前 20 个月都明显高于非超前注水。

关键词: 超低渗透油藏 超前注水 阶梯注水 温和注水 反阶梯温和注水 压力剖面
中图分类号: TE341　**文献标识码:** A　**文章编号:** 1009－9603（2012）04－0078－03

超前注水即在油井投产前进行注水，将能量波及时间和进程提前，在储层能量尚未降低时补充地层能量[1－3]，能有效解决因储层变形、原油脱气、驱动能量不足造成的超低渗透油藏产能低、下降快的难题[4－6]。长庆油田最早提出超前注水，并将这一技术应用于现场[7]，开发效果明显，单井产能高于同类区块。超低渗透储层的启动压差大、压力敏感性强，虽然进行了一些渗流规律的研究及开发实践[8]，但超低渗透油藏超前注水开发理论还有待完善。

1　注水时机优选

超低渗透油藏具有岩性致密、渗透率低和应力敏感性强等特点，注采井之间的压降漏斗比常规油藏的更为陡峭，再加上应力敏感性的影响，对近井地带储层物性会造成不可恢复的破坏[9]。在开发制度相同的情况下，对比了不同注水时机开发 1 a 后储层中压降漏斗的形状。超前注水的配注量为 20 m^3/d，超前注水 3 个月；同步注水的配注量为 20 m^3/d，注采同步；滞后注水的配注量为 20 m^3/d，滞后注水 3 个月。

在油井开发 3 个月前开始注水，开发 1 a 后，注采井间的压力较高（图 1），可有效避免应力敏感性对储层的伤害。随着注水时机的不断延后，地层压力逐渐下降，降低了在超低渗透油藏中的有效波及体积，开发效果变差。

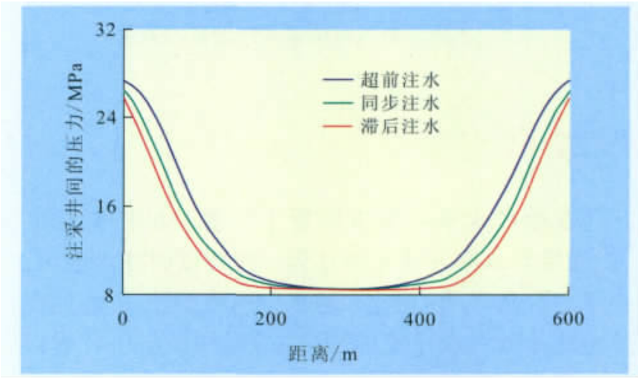

图 1　不同注水时机注采井间的压力分布

通过数值模拟对比不同注水时机的采出程度（图2）发现，超前注水可提高投产初期的采出程度。

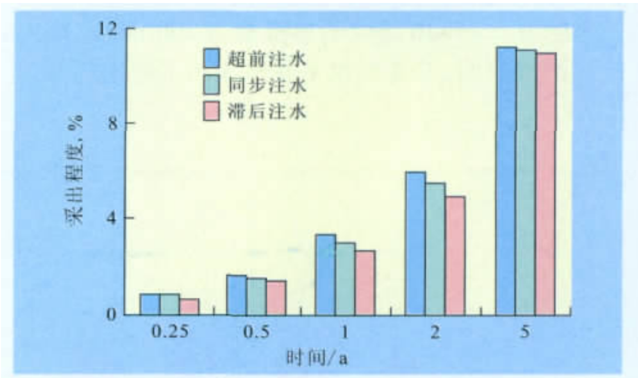

图 2　不同注水时机采出程度随时间的变化

收稿日期: 2012－05－11。
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基金项目: 国家科技重大专项“鄂尔多斯盆地大型岩性地层油气藏勘探开发示范工程”（2008ZX05044），国家科技重大专项“海上稠油水驱及注聚开发方式下不同井型生产能力与注入能力评价方法研究”（2011ZX05024－002－006）。

当开发时间为 2 a 时，超前注水采出程度提高幅度最大; 5 a 后，3 种注水方式的采出程度趋于相同。结合现场与模拟分析认为，超前注水可有效提高超低渗透油藏的初期产能。

2　注水方式优化

在超前注水研究中，通常以平均地层压力的升幅作为超前注水压力的评价标准，注水后储层压力升高到原始地层压力的 105% ~110% 即认为超前注水对储层压力的改善是有效的，但是注水后近注水井地带地层压力往往较大，而油井井底压力升幅小，故平均地层压力升幅不能反映地层中压力的分布情况[10-11]。因此，引入压力波及系数，即压力波及的储层体积与油藏体积的比值，作为超前注水对储层压力改善程度的评价标准，压力波及系数能更好地反映储层压力的分布情况。

2.1　阶梯注水

模型采用菱形反九点井网，直井注水，压裂直井采油，井距为 485 m，排距为 135 m，裂缝穿透比为 0.5，分别设计正阶梯注水、恒速注水和反阶梯注水 3 种注水方式，注水时间为 3 个月。正阶梯注水每个月的配注量分别为 15，20 和 25 m^3/d; 恒速注水的配注量为 20 m^3/d; 反阶梯注水每个月的配注量分别为 25，20 和 15 m^3/d。

通过对比发现，采用反阶梯注水时，油井井底压力升幅最大，恒速注水和正阶梯注水次之; 超前注水结束时，反阶梯注水注水井底压力最低，便于开发后注水的进行，而正阶梯注水注水井井底压力过高，易导致微裂缝的开启，不利于后续开发。

由阶梯注水时的压力波及系数计算结果可知，反阶梯注水的压力波及系数较大，能够达到 77%，压力波及范围最广; 恒速和正阶梯注水的压力波及系数分别为 72% 和 65%，压力范围较小，导致压力场分布不均。

2.2　温和及强化注水

在超前注水配注量相同的情况下，对比温和注水和强化注水对压力波及范围的影响。其中，温和注水的配注量为 15 m^3/d，注水 4 个月; 强化注水的配注量为 30 m^3/d，注水 2 个月。

在累积配注量相同的条件下，由不同注水方式下油藏压力的变化(图 3) 可知: 注水越温和，注水井周围的压力越低，压力分布标准偏差越小，超前注水对于油藏压力的改善效果越好，油井受效程度越高。

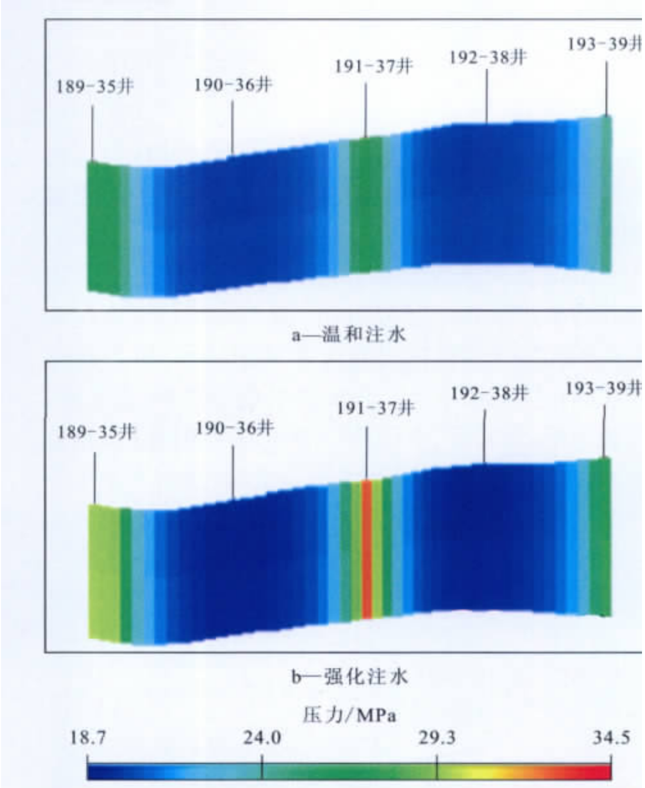

图 3　温和和强化注水油藏压力分布

对于特低渗透储层，当采用强化注水时，地层压力场分布就会更不均匀，会突破破裂压力导致天然裂缝开启，因此应采用温和注水提高压力传播面积，抑制天然微裂缝开启。

2.3　最优注水方式

由反阶梯注水前提下温和注水(反阶梯温和注水) 的井底压力分布(图 4) 可知: 油井井底压力升幅由大到小依次为反阶梯温和注水、温和注水、反阶梯注水; 注水井井底压力升幅由大到小依次为反阶梯注水、温和注水、反阶梯温和注水。反阶梯温和注水进一步提高了油井的压力升幅，对开发超低渗透油田具有一定的优势，压力波及范围高达 90%，因此推荐超低渗透油藏采用反阶梯温和注水。

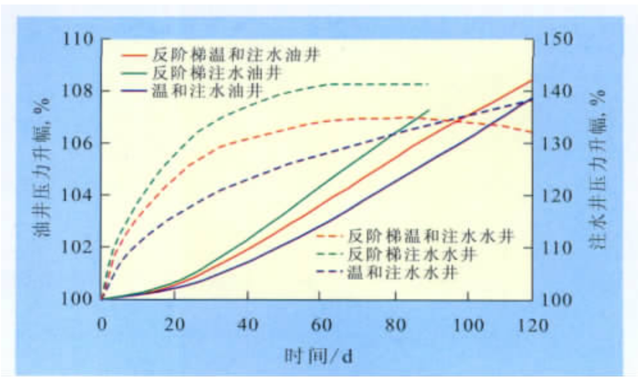

图 4　不同注水方式下油井和注水井井底压力分布

3 现场应用

以长庆油田 BMZ 区块为例，选取该区块储层物性和有效厚度相近的井进行对比分析(299 口超前注水井与 157 口非超前注水井)。

BMZ 区块恒速超前注水与非超前注水所对应油井的平均单井产油量对比(图 5)表明，恒速超前注水的初期产油量明显高于非超前注水，可以提高区块的初期产油量。非超前注水在生产 15 个月后，产量平稳，递减慢，中后期产能和恒速超前注水相差不大；当采用反阶梯温和注水方式时，预测平均单井产油量在前 20 个月都明显高于非超前注水和恒速超前注水。

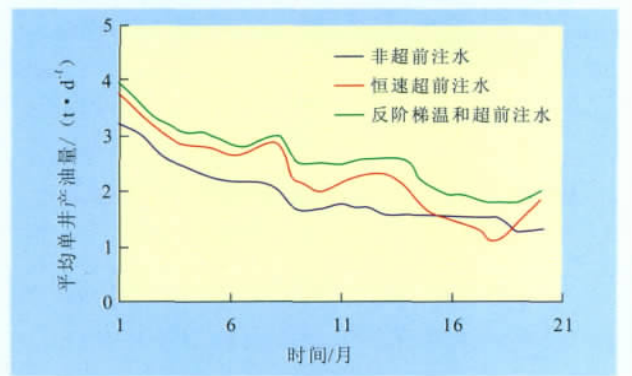

图 5 长庆油田 BMZ 区块平均单井产油量

综合对比 BMZ 区块不同超前注水方式下的含水率发现，反阶梯温和注水与恒速超前注水和非超前注水相比，不仅有效降低了含水率，且大幅度提高了油田的初期产能，具有较广阔的应用前景。

4 结论

通过对比不同注水时机下地层压力与产能，发现超前注水可以使注采井间的压降漏斗更为平缓，随着注水时机的不断延后，地层压力逐渐下降，降低了超低渗透油藏的有效波及体积，开发效果变差。

针对超低渗透油藏储层物性差、平面非均质性强、超前注水能量波及范围有限的特点，对比了多种超前注水方式，发现反阶梯注水优于恒速注水和正阶梯注水，温和注水优于强化注水。组合实验结果表明，反阶梯温和注水的开发效果最好，既能有效提高油井井底压力，又能降低注水井井底压力，是开发超低渗油藏最有效的方式。

以长庆油田 BMZ 区块为例，发现超前注水的初期产油量明显高于非超前注水，但中后期产油量和超前注水相差不大。当采用反阶梯温和注水时，平均单井产油量比恒速超前注水有了进一步的提高，同时有效降低了含水率，因此采用反阶梯温和注水开发超低渗透油藏具有较广阔的应用前景。

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Liu Shun, He Heng, He Yanxiang et al. Data processing correlation on stress sensitivity experiment for low-permeability reservoirs. *PGRE*, 2012,19(4):71-73.

Abstract: Stress sensitivity presents in low-permeability reservoirs. Choose 17 blocks low-permeability cores to stress sensitivity experiment according to SY/T 5358-2010 standard. The Darcy law equation and power-law non-linear percolation equation are adopted to analyze the experimental data. The parameter of power-law non-linear percolation equation is regressed from the relations between rate and stress gradient derived from other 8 blocks experimental cores. The results show that the peripheral pressure numbers are greater and the permeability number reduces less. Also, the conclusion can be achieved that the reduced ratio of permeability number from the two correlated calculated methods is nearly same. But, the permeability number based on power-law percolation method is quadruple to Darcy law method. So, the power-law non-linear percolation equation suggests to be used to data analysis in low-permeability reservoir.

Key words: low-permeability reservoirs; stress sensitivity; Darcy law; power-law non-linear percolation; pressure gradient

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Liu Yongge, Liu Huiqing, Pang Zhanxi et al. Study on nitrogen foam anti-water-cresting by double horizontal wells for bottom water heavy oil reservoir. *PGRE*, 2012,19(4):74-77.

Abstract: By means of numerical simulation, below the producing horizontal well, another horizontal well is placed to put off water cresting. When water cresting reached up to the height of producing horizontal well, we shut in the producing horizontal well and inject nitrogen foam into the horizontal well below. After two days'soaking, the upper horizontal well is opened to produce again. This process can be repeated for many times. The results of numerical simulation show that the development efficiency by double horizontal wells is much better, and the effect of water cresting can be alleviated greatly comparing to injecting nitrogen foam and producing oil only by a single well. The development style, distance away from the bottom water, length, liquid producing rate and the moment of injecting nitrogen foam are optimized by simulation. After optimization, the quantity and amplitude of incremental oil can reach up to 19,000 cubic meters and 48.7% respectively.

Key words: horizontal well; foam; bottom water heavy oil reservoir; water cresting; numerical simulation

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Li Nan, Cheng Linsong, Chen Hongquan et al. Study on water injection in ultra low permeability reservoir. *PGRE*, 2012,19(4):78-80.

Abstract: This article starts from the mechanism of advanced water injection, combining with the numerical simulation and actual production data, it contrasts the pressure profiles between the water injection well and oil well under the different water injection timing, then, optimizes the water injection timing in ultra low permeability reservoirs, and under the optimal water injection timing, it analyzes the effect on transmission of pressure by different ways of advanced water injection. Based on low permeability reservoirs property of start-up pressure gradient, stress the sensitive, thin pore throats, we analyze the effect on the lifting amplitude of oil wells, water wells and reservoir pressure by the different ways of advanced water injection. At the condition of the maximum of spread coefficient and under the rock breakdown pressure, screening and combining different ways of advanced water injection, we found that, it could be able to get the best development performance in ultra low permeable reservoir by anti-step mild water injection. Taking Changqing BMZ oilfield as example, the development effect has been analyzed under different water injection, and we evaluated the development effect of the method of anti-step mild water injection, which has certain directive significance to make the technology policy.

Key words: ultra low permeability reservoir; advanced water injection; stepped injection; mild injection; anti-step mild water injection; pressure profile

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Wang Jian. Study on technical policy limits of layer recombination in edge water fault block reservoir. *PGRE*, 2012,19(4):81-83.

Abstract: Fault block reservoir possesses the characteristics of many oil-bearing strata, serious heterogeneity. In addition, for the layers in the edge water fault block reservoirs, their oily strip width and edge water body multiples are different. The combination of the layers with different oily strip width and edge water body multiples have great impact on the development effect of the development unit. Therefore, in addition to considering the policy limits of permeability differences and oil viscosity differences, such the policy limits as oily strip width differences and edge water body multiples differences should be considered during the layers recombination. In this paper, the effect of the combination of different layers with oily strip width differences and edge water body multiples differences on the reservoir performance is analyzed. And, the policy limits of oily strip width differences and edge water body multiples differences are set up. The research result was applied to the actual fault block reservoir development, and achieved good results.

Key words: edge water reservoir; layer recombination; oil stripe width; water body multiples; policy limits

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