常规稠油油藏水驱开发初期可动凝胶调驱效果
——以华北油田泽70断块为例

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摘要：常规稠油油藏原油粘度较高，水驱开发效率较低，导致最终采收率不高。为探索改善常规稠油油藏水驱开发效果的新技术，开展了可动凝胶调驱技术改善稠油开发效果的可行性研究，结果表明，在油田开发初期这是一种有效的开发方式。针对华北油田泽70断块常规稠油油藏水驱开发特征，在开发初期开展了可动凝胶调驱先导试验，并推广到整个区块。应用可动凝胶调驱1 a后，注入压力明显提高，吸水剖面得到改善，生产井含水率上升速度得到有效控制，综合含水率由47.5%下降到37.4%，采油速度由0.82%提高到2.1%，阶段累积增产油量为12 787 t，提高采收率为1.58%，取得了较好的增油降水效果。

关键词：稠油 水驱开发 可动凝胶 流度控制 数值模拟
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近年来，在新发现的储量中，常规稠油油藏所占的比重越来越大。常规稠油油藏原油粘度较高，在水驱开发过程中，中低含水期含水率上升快，水驱油效率较低，最终采收率仅为20%左右，且大部分可采储量(80%左右)在高含水期采出，耗水量较大，注水利用率较低[1－3]。因此，如何改善此类油藏的水驱开发效果，提高中低含水期的采出程度，是开发面临的主要任务。通过华北油田泽70断块水驱开发早期可动凝胶调驱先导试验，分析了可动凝胶调驱在常规稠油油藏水驱开发中的应用效果和经验。

1 试验区概况

1.1 地质特征

华北油田泽70断块是一个受岩性因素影响的多层砂岩构造油藏，原油粘度较高，属于常规稠油。主要含油层位是古近系东营组三段(Ed_3)，油层中部埋深为2 400 m，含油面积为2.1 km^2，石油地质储量为517.2×10^4 t。Ed_3属于河流相沉积，储层物性和油层连通性均较好，平均孔隙度为20%，平均渗透率为300×10^{-3} μm^2，Ⅰ类油层连通率为79.4%，但储层非均质性较强，平面和纵向渗透率级差分别为31.6和34.8。纵向上，储层物性自下而上逐渐变好；平面上，沉积微相决定了储层物性分布规律，主河道地区物性好，河口砂坝地区物性相对较差。

泽70断块地面原油密度为0.917 8～1.010 4 g/cm^3，平均地层原油粘度为165.6 mPa·s，凝固点为16～40 ℃，含蜡量为1.56%～12.4%，胶质沥青质平均含量为50.47%，原油饱和压力低，为1.4 MPa，气油比为7.76 m^3/t，具有高体积质量、高粘度、高沥青质和高凝固点的特点。地层水矿化度为2 372～15 163 mg/L，Cl^-质量浓度为4 340 mg/L，水型以$NaHCO_3$型和$CaCl_2$型为主。

1.2 水驱开发特征

含水率上升快 泽70断块2001年12月投入注水开发，油井明显见效，油井见水后含水率上升较快。到2003年1月，综合含水率为48.5%，比2001年底上升了28.5%，全油藏月含水率上升速度大于2%的油井占66.7%。

地层能量和单井产量下降快 从油藏整体看，平均单井产液量、产油量和平均动液面呈持续下降趋势。其中平均单井产液量由初期的11 t/d降至2003年1月的9.4 t/d，平均单井产油量由8.5 t/d降至3.4 t/d，油藏平均动液面由－400 m降至－923 m，平均月下降7.7 m。

油层动用程度低 由于储层非均质性较强，层间矛盾突出，油层动用程度较低。全油藏Ⅰ类油层动用程度为33.4%，Ⅱ类油层动用程度为20.5%。

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根据 2 口井吸水剖面资料统计，吸水强度大于 1.5 $m^3/(d \cdot m)$ 的主力吸水层共 7 层 32.8 m，相对吸水量为 63%；而吸水强度小于 1 $m^3/(d \cdot m)$ 的低吸水层共 4 层 26 m，相对吸水量为 17.4%。

水驱效率低　泽 70 断块油水粘度比高达 550，含水率上升较快，水驱波及体积和采出程度均较低，水驱开发效果较差。油藏综合含水率为 50% 时，采出程度仅为 7.77%；综合含水率为 70% 时，采出程度仅为 9.87%。可见，油藏绝大部分可采储量将在高、特高含水期采出。

2　可动凝胶调驱先导试验

可动凝胶调驱技术是在聚合物驱和堵水调剖基础上发展的新的提高采收率方法，具有流度控制和深度调剖的作用，实现了对注水井中高渗透层的动态封堵，在加强调整注水剖面的同时，增加了一定的驱替功能[4-6]。

2.1　可动凝胶配方及调驱方案设计

在水驱开发研究的基础上，针对泽 70 断块的高温特点开展了可动凝胶室内配方体系研究和可动凝胶调驱先导试验。结果表明，聚合物 KYP 的增粘性、耐温和溶解性均较好，交联剂 HT2002A 和 HT2002B 的耐温性能较好，聚合物和交联剂采用清水配制，聚合物和交联剂之比为 2∶1，成胶能力较强，能够满足泽 70 断块高温油藏的调驱需要。

首先在地面配制可动凝胶溶液，然后注入地层，进行可动凝胶调驱。采用数值模拟方法对注入体系进行了优化设计，最终确定采用三级段塞注入方式[7-8]（表 1）。

表 1　试验区注入参数

段塞	化学剂质量浓度/($mg \cdot L^{-1}$)			单井注入量/m^3		总注入量/m^3	注入时间/d
	聚合物 KYP	交联剂 HT2002A	交联剂 HT2002B	泽 70-50 井	泽 70-5 井		
前置段塞	1 000	1 500	600	850	650	1 500	21
主段塞	800	1 200	500	10 500	7 500	18 000	188
接替段塞	600	1 000	400	3 250	2 250	5 500	58

先导试验区石油地质储量为 81×10^4 t，数值模拟结果表明，试验区含水上升较快，水驱效率较低，预测水驱最终采收率为 19.7%。注入了 0.030 8 倍孔隙体积的可动凝胶段塞，预测中心区含水率最大下降幅度为 27.6%，最终累积增油量为 3.28×10^4 t，提高采收率为 4.05%，投入产出比为 1∶2.48。

2.2　方案实施及效果分析

2003 年 1 月 10 日可动凝胶调驱先导试验正式开始实施，到 2003 年 9 月 13 日施工结束，转入后继水驱开发。调驱段塞累积注入可动凝胶溶液 2.5×10^4 m^3，整体上 100% 完成了方案设计注入量。

2.2.1　注入压力提高

调驱前后对比，泽 70-5 井注入压力由 7 MPa 上升到 19 MPa，注入量由 30 m^3/d 上升到 70 m^3/d，而视吸水指数则由 4.3 $m^3/(d \cdot MPa)$ 下降到 3.7 $m^3/(d \cdot MPa)$。泽 70-50 井注入压力由 14.5 MPa 上升至 19 MPa，注入量由 40 m^3/d 上升到 50 m^3/d，而视吸水指数则由 2.8 $m^3/(d \cdot MPa)$ 下降到 2.63 $m^3/(d \cdot MPa)$。可动凝胶调驱明显提高了注入压力，其原因主要包括 2 方面：①可动凝胶大幅度提高了注入体系的粘度，原油与驱替液的流度比明显降低，减少了驱替液锥进，扩大了波及体积；②可动凝胶在一定程度上封堵了高渗透层，启动了中低渗透层，高渗透层的吸水能力降低，中低渗透层的吸水能力大幅提高，而中低渗透层的注入压力明显高于高渗透层的注入压力[9]。

2.2.2　纵向吸水剖面得到改善

调驱前后对比，泽 70-5 井的主力吸水层相对吸水量由 45.7% 增加至 59%，中渗透层的相对吸收量由 5.1% 增加至 22.3%。泽 70-50 井的主力吸水层相对吸水量由 54.4% 增加至 64.4%，中渗透层的相对吸收量由 9.7% 增加至 24.1%。这表明可动凝胶溶液启动了中渗透层，扩大了后继水驱在中渗透层的波及体积，吸水剖面得到了明显改善[10-11]。

2.2.3　产量增加

注入可动凝胶后，生产井均有不同程度的见效，试验区生产状况明显好转。主要表现为：单井产油量上升了 0.5～0.7 t/d，单井含水率下降了 2%～10%，单井动液面平均上升了 132 m。全区产液量由 35.6 t/d 上升到 72.1 t/d，产油量由 18.7 t/d 上升到 45.1 t/d，综合含水率由 47.5% 下降到 37.4% 左右，采油速度由 0.82% 上升到 2.1%。按

递减法计算,到 2006 年 1 月可动凝胶基本失效时,阶段累积增产油量为12 787 t,提高采收率为1.58%,取得了较好的增油降水效果[11]。

2.3　开发指标对比

油田实际生产曲线与预测曲线基本吻合(图1)。到 2006 年 1 月,实际采收率为 9.12%,比预测结果高 0.16%。出现差别的主要原因是试验区部分生产井在 2004 年 8 月采取了提液措施,而预测方案没有考虑产量变化的影响。这说明可动凝胶调驱设计方案比较符合油田实际。

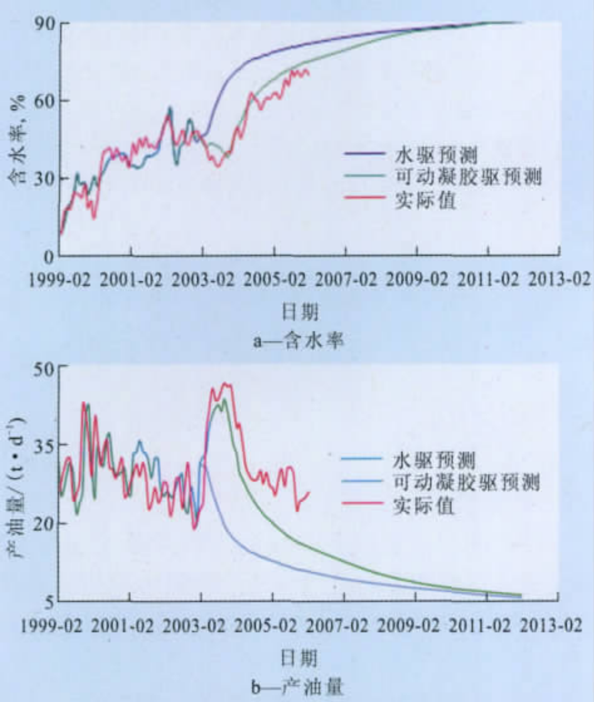

图 1　先导试验区含水率和产油量预测与实际曲线对比

3　结论

华北油田泽70断块的油藏温度和地层水矿化度都较高。采用的高温可动凝胶调驱体系在该油藏条件下有较好的成胶性能,注入压力上升明显,稳定性达 2 a 以上。

可动凝胶调驱能有效抑制稠油油藏的含水上升速度,减缓注入水的突进,提高波及体积。实施可动凝胶调驱后,试验区综合含水率下降了 10.1%,阶段累积增油量为 12 787 t,提高采收率为 1.58%。由此表明,在常规稠油油藏水驱开发早期实施多轮次的可动凝胶调驱可明显改善稠油油藏开发效果。

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Cr^{3+} and carboxyl group in polyacrylamide molecules. The simulation dynamic cross-linking experiment results show that the polymer gel can generate cross-linking under the flowing state of the porous medium, the initial cross-linking time is 7-8 h, and the final cross-linking time is about 70 h. The block coefficient of polymer gel during migration is as follows: the distribution in unconsolidated sand tube is increased with the rise of injected pore volume multiple; the main block is located at the entrance, the blocking strength is increased with the rise of the depth in system migration; from the pressure index of the former four manometry sections of the sand filling tube, the pressure coefficient of each section is increased to different degrees, which indicates that the polymer gel has good transport blocking ability.
Key words: gel; porous media; dynamic cross-linking; migration; blocking
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Yang Shengjian, Wang Jialu, Diao Haiyan et al. Application performance of mobile gel in earlier stage of water flooding for conventional heavy oil field-case of Ze 70 block, Huabei oilfield. *PGRE*, 2012, 19(2): 57-59.

Abstract: The oil viscosity in conventional heavy oil reservoir is very high, and the oil recovery of water-flooding is very low. The study of the feasibility of using mobile gel in-depth fluids diversion to improve the performance of water-flooding in conventional heavy oil reservoir is carried out. The result indicates that the mobile gel in-depth fluids diversion is an effective approach to improve the performance of water-flooding for the development of conventional heavy oil field. According to the feature, oil recovery of water-flooding is very low in Ze 70 complex-faulted block, the pilot test of mobile gel in-depth fluids diversion in early stage is carried out in order to improve the result of water-flooding, and then it is extended to the whole block. After one-year injection, injection pressure rises obviously and injection profile is improved, moreover, the ascending velocity of water-cut is controlled and the water cut declines to 37.4% from 47.5%, while the producing rate rises to 2.1% from 0.82%, the recovery factor is 4.05% higher than that of water-flooding, and the input-output ratio is 1:2.48. The result of the pilot is satisfied.
Key words: conventional heavy oil; water-flooding; flowing gel; in-depth fluids diversion; numerical simulation
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Liu Lili, Yang Shuren, Wang Lihui et al. The numerical calculation about the stress and deformation of residual oil in the micropore. *PGRE*, 2012, 19(2): 60-63.

Abstract: In order to analyze the stress and deformation of residual oil film in the micro pore that is affected by the visco-elasticity of the fluid and the wettability of the rock, and the hydrodynamics displacement mechanism is explored from the viewpoint of hydrodynamics, which is that the residual oil film is displaced by the elasticity of polymer solution. The viscoelastic fluid flow equation is established in the micro pore by choosing continuity equation, momentum equation, the upper convected Maxwell constitutive equation, the flow field is obtained by using the method of numerical analysis, and the stress and deformation, which polymer solution acts on the residual oil film in different wettability of the rock surface, are calculated. The results show that: the normal deviatoric stress acting on the residual oil film, which is affected by viscoelastic driving fluid, has the abrupt change compared to that of inelastic driving fluid, meanwhile, the higher the visco-elasticity of polymer solution, the greater the normal deviatoric stress acts on the residual oil-film, the higher the deformation; for the different wettability of the rock, the deformation of the residual oil film on oil wet surface is slightly larger than that of the water wet surface, which lays the foundation for the next calculation of the stress, deformation and breakup of residual oil about the special boundary conditions.
Key words: micro pore; residual oil film; stress; deformation; viscoelasticity
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Du Dianfa, Hou Jiagen, Li Dongdong et al. Deliverability formulas for vertical-horizontal well pattern in low permeability oil reservoir. *PGRE*, 2012, 19(2): 64-66.

Abstract: Because of low permeability and high starting pressure gradient in low permeability oil reservoir, the final oil recovery is very low and the development performance is poor if it is exploited with conventional well pattern. But, the development result will be encouraging with the help of vertical-horizontal well pattern. However, only few papers have discussed the deliverability formulas for vertical-horizontal well pattern in low permeability oil reservoir. Considering this problem, the deliverability formula of a single well in the center of horizontal isopachous formation is established based on the flow characteristics of low permeability oil reservoir in this paper. Then, the deliverability formulas of conventional oil reservoir including five-spot pattern, seven-spot pattern and nine-spot pattern are derived by means of equivalent flowing resistance method. In this step, the flowing resistance is divided into three parts. At last, based on the first two aspects, deliverability formulas for vertical-horizontal well pattern in low permeability oil reservoir are confirmed. The example shows that the formulas are simple, correct as well as efficient.
Key words: low permeability reservoir; starting pressure gradient; vertical-horizontal well pattern; deliverability formulas; equivalent flowing resistance method
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Xu Mengya, Liao Xinwei, He Yifan et al. Study on productivity analysis of fractured horizontal wells based on different completion methods in tight gas reservoir. *PGRE*, 2012, 19(2): 67-71.

Abstract: Based on the geologic characteristics of tight gas reservoir, three tight gas reservoir-fractured horizontal wellbore coupling models are derived by Green functions and Newman product principle. The models consider different completion methods and the interferences from fractures and horizontal wellbore. The example shows that under the same conditions of reservoir and