聚合物凝胶体系在孔隙介质中交联及运移封堵性能研究

张建华
(中国石化股份胜利油田分公司 技术发展处,山东 东营 257001)

摘要:聚合物凝胶体系是由部分水解聚丙烯酰胺和XL有机铬交联剂交联而成。采用ESEM 2020型环境扫描电镜、聚合物凝胶动态交联和渗流规律实验装置及不同规格的填砂管模型对聚合物凝胶体系的微观交联机理、在孔隙介质中动态交联性能及在岩心中的封堵运移性能进行了研究。实验结果表明,聚合物分子在微观上呈星状结构排列,而聚合物凝胶在微观上呈链状分形结构,是Cr^{3+}与聚丙烯酰胺分子中的羧基交联的结果。动态交联实验结果表明,聚合物凝胶体系在孔隙介质中流动状态下可发生交联,初始交联时间为7~8 h,最终交联时间约为70 h。聚合物凝胶体系在运移过程中,从填砂管前4个测压段的压力指数来看,各段压力系数均有不同程度的上升,说明聚合物凝胶体系具有良好的运移封堵能力;其在填砂管中的封堵系数随着注入孔隙体积倍数的增大而增大;但随着体系运移距离的增加,封堵能力降低。

关键词:聚合物凝胶 孔隙介质 动态交联 运移 封堵
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随着油田开发的不断深入,研究人员逐渐认识到实现深部调剖、提高波及系数是提高原油采收率的技术关键[1]。聚合物驱仅靠改善流度比提高波及系数不足以达到深部调剖。要实现深部调剖,调剖剂必须优先封堵孔隙介质中的大孔道,并且能深入到孔隙介质的深部。目前常用的深部调剖剂为高分子类调剖剂,主要有聚合物和聚合物凝胶。聚合物凝胶[2-6]是目前研究和应用最多的深部调剖剂,但其在现场使用过程中出现交联性能差异较大、不同区块应用效果差别大等问题[7-11]。为此,笔者利用环境扫描电镜、聚合物凝胶动态交联和渗流规律实验装置及不同规格的填砂管等,对聚合物凝胶体系在孔隙介质中的交联及运移封堵性能进行了研究。

1 实验器材及方法

1.1 实验器材

实验试剂包括:相对分子质量为$1\ 800\times10^4$~$2\ 100\times10^4$的部分水解聚丙烯酰胺(HPAM)、XL有机铬交联剂、孤岛油田东区污水、地层产出砂及自来水等。

实验设备主要包括:ESEM 2020型环境扫描电镜、DV-Ⅲ布什粘度计、聚合物凝胶动态交联和渗流规律实验装置。实验装置由供液泵、中间容器及保温套、恒温箱、填砂管模型、控制系统、油水两相自动计量仪、压力及压差自动采集系统、工业控制计算机等组成。

用自来水配制质量浓度为5 000 mg/L的HPAM母液,用孤岛油田东区污水将HPAM母液稀释至2 000 mg/L,加入质量浓度为600 mg/L的XL有机铬交联剂,搅拌均匀后即得到聚合物凝胶体系,其在剪切速率为8.6 s^{-1}时的初始粘度为28 mPa·s。

收集孤岛油田东区地层产出砂,对其按粒径进行分级处理,按照不同粒径、比例及粘土含量,制作成孔隙度为26%~32%、渗透率为2~4 μm^2的填砂管。2个填砂管的直径均为38 mm,长度分别为5.6和30 m。

1.2 实验方法

聚合物凝胶体系动态交联时间评价方法 实验

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作者简介:张建华,男,工程师,从事油田开发方面的研究。联系电话:13864747327,E-mail:zhangjh.slyt@sinopec.com。
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采用长度为 5.6 m 的填砂管，在填砂管上沿程布置了 11 个精度为 0.1 级的压差传感器，其测量值对应为 $\Delta p_1, \Delta p_2, \cdots, \Delta p_{11}$。在 65 ℃条件下，将填砂管抽真空饱和地层水，测量孔隙度和渗透率；岩心参数合格后，以 4.5 mL/min 的恒定速度注入聚合物凝胶体系，进行动态循环交联实验。实验过程中适时记录各压差传感器压差值并检测填砂管出口各产出液粘度。将剪切速率为 8.6 s^{-1} 时聚合物凝胶经多孔介质出口粘度为初始粘度的 1.5 倍时的时间定义为初始交联时间，注入压力保持平稳时的时间定义为最终交联时间。

聚合物凝胶体系运移封堵性能评价方法　采用长度为 30 m 的填砂管，根据组合填砂管的实际情况和实验需要，沿程布置了 9 个测压点，将 30 m 的填砂管分成 10 段（0 ~ 1.28，1.28 ~ 2.99，2.99 ~ 3.83，3.83 ~ 5.54，5.54 ~ 8.09，8.09 ~ 11.2，11.2 ~ 15.8，15.8 ~ 20.6，20.6 ~ 25.4 和 25.4 ~ 30 m）。在 65 ℃条件下，将填砂管抽真空饱和地层水，测量孔隙度和渗透率；岩心参数合格后，以 4.5 mL/min 的恒定速度，依次注入 0.15 倍孔隙体积的聚合物凝胶体系主段塞、0.05 倍孔隙体积的 2 000 mg/L 聚合物保护段塞和后续水驱段塞。笔者引入了封堵系数和压力指数 2 个概念，以评价聚合物凝胶体系的运移封堵能力。

封堵系数的表达式为

$$F_s(x) = \frac{\xi_2(x) - \xi_1(x)}{\xi_1(x)} \tag{1}$$

式中：$F_s(x)$ 为 x 处的封堵系数；x 为距注入端的距离，m；$\xi_2(x)$ 为注入调剖剂后 x 处的压力指数，MPa · s/m^2；$\xi_1(x)$ 为注入调剖剂前 x 处的压力指数，MPa · s/m^2。

通过记录 x 处的压力指数，将其代入式（1），可计算 x 处的封堵系数。

压力指数的表达式为

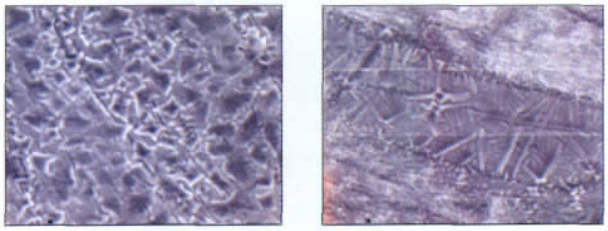
$$\xi(x) = \frac{dp}{dx} \times \frac{1}{v} \tag{2}$$

式中：$\xi(x)$ 为 x 处的压力指数，MPa · s/m^2；dp/dx 为 x 处的压力梯度，MPa/m；v 为渗流速度，m/s。

2　实验结果与分析

2.1　聚合物凝胶体系微观交联机理的新认识

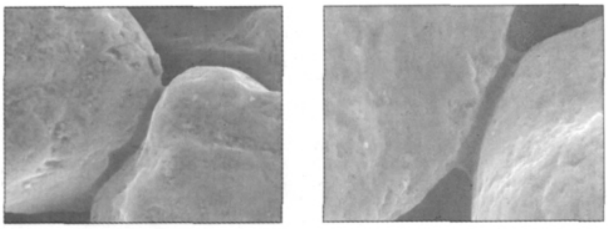
观察环境扫描电镜下聚合物溶液和聚合物凝胶体系的微观结构（图 1）发现，2 000 mg/L 聚合物溶液呈较均匀的星状结构，聚合物凝胶体系呈条带状的链状结构，可以明显看出星状聚合物分子相互连接形成的局部结构，交联基为羧基。而孙卫等[7-9]认为，聚合物分子的交联反应是以 Cr^{3+} 羟配聚合物为核心而进行的，聚合物聚集体尖端容易与 Cr^{3+} 接触并发生交联，并以此为生长点，形成链状分形结构。这与笔者的认识有所不同。



a—2 000 mg/L聚合物溶液　　b—聚合物凝胶体系

图 1　环境扫描电镜下聚合物溶液和聚合物凝胶体系的微观结构（250 倍）

由不同放大倍数的微观结构图片（图 2）可清楚看出，聚合物凝胶体系在孔隙介质中流动时可发生很好的交联，形成聚合物凝胶颗粒，且颗粒间具有良好的粘连性。



a—500倍　　b—1 000倍

图 2　动态交联后聚合物凝胶体系不同放大倍数时的微观照片

2.2　动态交联时间

聚合物凝胶体系在孔隙介质中运移时，不断受到剪切，并且在多孔介质中一直存在吸附现象，会不同程度地影响聚合物凝胶体系的交联时间。因此，聚合物凝胶体系动态交联时间是评价其性能最有效的参数之一。为了表征聚合物凝胶体系交联后造成其体系粘度上升的程度，定义了等效无量纲粘度，它是聚合物凝胶体系流经填砂管各取样口的产出液粘度与聚合物凝胶体系的初始未交联粘度的比值。

实验结果表明（图 3），聚合物凝胶体系的动态初始交联时间为 7 ~ 8 h，聚合物凝胶体系在流动过程中发生交联，最终交联时间为 70 h。随着运移距离的增加，受剪切和吸附的影响也逐渐增大，聚合物凝胶体系的初始交联时间和最终交联时间均延长。

聚合物凝胶体系静态初始交联时间一般为 4 h，动态初始交联时间比其延长了近一倍；静态最终交

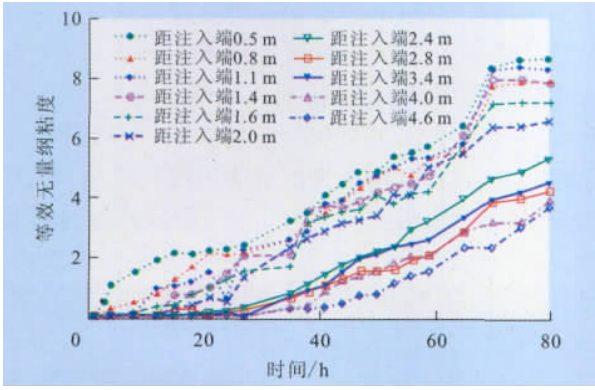


图 3　剪切速率为 8.6 s^{-1} 时聚合物凝胶在孔隙介质中动态交联等效无量纲粘度

联时间一般为 8 h，则动态最终交联时间延长约 9 倍。可见聚合物凝胶体系的动态初始交联时间和最终交联时间均比静态交联时间长。

2.3　运移封堵能力

从图 4 可知，距注入端 8.09 m 后各测压点的压力很小，为此仅对 8.09 m 之前数据进行分析。由于前置液聚合物质量浓度较低，经过吸附和剪切损失后，其粘度变得更小，所以注入主段塞时，调剖剂可以均匀推进。当注入量为 0.04 倍孔隙体积时，距注入端 0 ~ 1.28 m 段的测压点开始起压，1.28 ~ 2.99 m 段的压力指数开始增加；当注入量为 0.1 倍孔隙体积时，2.99 ~ 3.83 m 段的压力指数开始增加；当注入量为 0.15 倍孔隙体积时，主段塞注入结束，注入深度为 4.5 m，填砂管注入端的前 4 个测压段的压力指数均依次升高，而 5.54 ~ 8.09 m 测压段的压力指数增加缓慢。整体来看，主要封堵位置在 0 ~ 1.28 m，并且1.28 ~ 2.99，2.99 ~ 3.83和3.83 ~ 5.54 m 段的压力系数均有不同程度的上升，说明聚合物凝胶体系具有良好的运移能力。

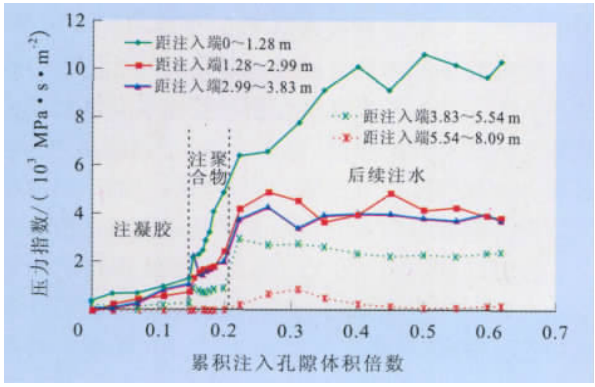


图 4　聚合物凝胶体系运移动态曲线

根据注入量与孔隙体积计算推测，聚合物凝胶体系主段塞的长度应为 4.5 m，顶替段塞长度为 1.5 m。若顶替段塞能推动主段塞以整体段塞方式运移，主段塞在填砂管中的实际位置应在距注入端 1.5 ~ 6 m。实验结束后，实际观测到聚合物凝胶体系的位置在距注入端 0 ~ 5.54 m，表明聚合物凝胶体系在向深部运移时没有保持整体段塞方式。

从图 5 可以看出，封堵系数在填砂管中的分布随注入孔隙体积倍数的增加而增大。在不同注入量下，距注入端 0 ~ 5.54 m 段的封堵系数较大，而大于 5.54 m 后封堵系数很小。分析聚合物凝胶体系在填砂管各段的封堵系数后可知，聚合物凝胶体系在距注入端 0 ~1.28 m 段的封堵程度占整个封堵系数的 50.26%，封堵效果较好；在距注入端 1.28 ~2.99，2.99 ~3.83，3.83 ~ 5.54 和 5.54 ~ 8.09 m 各段的封堵程度分别占整个封堵系数的 18.90%，18.32%，11.51%和 1.01%；大于 8.09 m 后未产生有效封堵。这说明随着运移距离的增加，封堵能力降低。

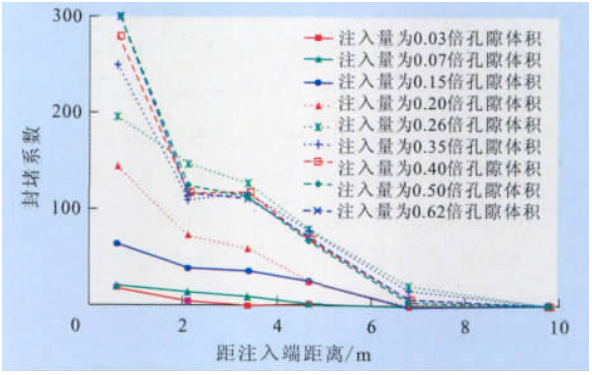


图 5　聚合物凝胶体系封堵系数动态曲线

3　结论

利用环境扫描电镜得到的聚合物溶液和聚合物凝胶体系的微观结构照片显示，聚合物溶液呈较均匀的星状结构，聚合物凝胶体系呈条带状的链状结构，可知星状聚合物分子相互连接形成的局部结构，交联基为羧基。

动态交联实验结果表明，聚合物凝胶体系在孔隙介质中流动状态下可发生交联，与静态交联相比，初始交联时间延长，达到最终交联的时间则更长。

聚合物凝胶体系在运移过程中，填砂管前 4 段的压力系数均有不同程度的上升，说明聚合物凝胶体系具有良好的运移能力；封堵系数在填砂管中的分布随注入孔隙体积倍数的增加而增大；随着运移距离的增加，封堵能力降低。

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表 1　油膜变形后润湿角对比　　(°)

驱替液	亲油岩石表面油膜		亲水岩石表面油膜		中性润湿岩石表面油膜	
	前进角	后退角	前进角	后退角	前进角	后退角
水	124.23	31.53	154.14	53.79	147.22	30.88
W_e 为 0.1 的聚合物溶液	165.24	15.54	158.38	21.65	162.96	15.83
W_e 为 0.2 的聚合物溶液	170.39	7.97	168.91	10.35	170.19	8.89

4　结论

由连续性方程、运动方程、本构方程联立组成的流动方程是非线性方程，边界条件也非常复杂，所以采用数值计算方法进行求解。计算结果表明：聚合物溶液的粘弹性对残余油膜的受力和变形有显著的影响。聚合物溶液的粘弹性越强，对残余油膜的作用力越大，非对称性越明显，更易于使油膜变形，继而破裂，最终从母体上分离出小油滴；对于不同润湿性的岩石，亲油岩石表面的油膜比亲水的变形更大。

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concentration is greater than 1 500 mg/L, as the concentration increasing, the increasing rate of plugging rate decreases.
Key words: pore scale; elastic microspheres; profile control and flooding; maximum deforming migration pressure gradient; plugging efficiency
Lei Guanglun, School of Petroleum Engineering, China University of Petroleum (East China), Qingdao City, Shandong Province, 266555, China

Zhang Guangqing, Liu Wei, Li Jing et al. Experimental study on the factors influencing the blocking ability of foam. *PGRE*, 2012, 19(2): 44-46.

Abstract: A uniform design method is implemented to study the affecting factors relevant to foam blocking ability in lab. And, two empirical formulae of foam resistance factor and foam residual resistance factor are established with five factors: permeability, gas to liquid ratio, injection volume, injection rate and concentration of foam stabilizer. The results indicate that these formulae have a high accuracy whose error is less than 15%. Permeability and gas to liquid ratio are the most influential factors of foam blocking ability. As the rise of permeability and gas to liquid ratio, the blocking ability is improved first and then reduced. After the injection of foam, gas phase saturation increases rapidly in the core, but decreases in the phase of following water injection accompanying with fluctuation. When 6 PV water is injected, gas phase saturation can still be kept at 45%.
Key words: foam; blocking ability; uniform design; gas phase saturation; correlation analysis
Zhang Guangqing, Oil Production Engineering Department, Shengli Oilfield Company, SINOPEC, Dongying City, Shandong Province, 257000, China

Sun Jianfang. Study and application on HDNS technology to develop shallow and thin super heavy oil reservoirs. *PGRE*, 2012, 19(2): 47-49.

Abstract: Chunfeng heavy oil field is located in Junggar basin, western China. Ground degassing viscosity is commonly higher than 5×10^4 mPa · s. The depth of the heavy oil play ranges from 400 to 500 m underneath with 2-6 m of net pay. Porosity is about 30% and permeability ranges from $5\ 000\times10^{-3}$ to $6\ 000\times10^{-3}\ \mu m^2$. Traditional development techniques such as steam-injection using vertical well are not effective due to tremendous heat losses, limited heat radius within thin layers and low drainage energy. In this study, it shows that super heavy oil is non-Darcy flow in porous media. In order to improve steam quality and enhance steam sweep efficiency, new techniques combing horizontal well assisted steam injection with N_2 and solvent are proposed to develop this kind of heavy oil reservoirs. Study also shows that high efficient solvent may decrease the viscosity of the heavy oil around wellbore and increase injection steam quality; meanwhile, N_2 assisted steam injection may increase the volume of injection steam, enhance the drainage energy, and decrease heat losses around wellbore and make steam reach overburden effectively. By means of plug injection of solvent and N_2 assisted by horizontal wells, super heavy oil may be recovered effectively. Moreover, well patterns, the extendibility of horizontal well steam flooding and economic-technique limits are studied. Based on the research, related thermal chemical techniques are successfully developed. Those techniques are proved to be very effective for the development of shallow and thin super heavy oil reservoirs.
Key words: super heavy oil; horizontal well; dissolver; N_2; Chunfeng oilfield; Junggar basin
Sun Jianfang, School of Energy Resources, China University of Geosciences (Beijing), Beijing City, 100083, China

Dong Xiaohu, Liu Huiqing, Zhang Hongling et al. Experimental and simulation study of hot-water flooding of heavy oil reservoirs after steam injection. *PGRE*, 2012, 19(2): 50-53.

Abstract: Steam injection is the main development mode for heavy oil reservoirs now. With the accelerating of exploitation, a great number of heavy oil reservoirs have reached the later stage of steam injection development. Poor effect on steam injection has gradually become the important problem of heavy oil reservoirs development. Using the experimental and simulation method, this paper aims at the residual oil of thermal production, and studies the alternative mode of heavy oil reservoirs after steam injection. We establish the models of converting into hot-water flooding under different temperature and different moment. The models of water alternative steam process and nitrogen foam hot-water flooding have also been set up. Then, we also establish the numerical models with different layer height, different rhythm and different heterogeneity. Results indicate that converting into hot-water flooding with 120 ℃ when the recovery of steam injection is 22% will get a great recovery performance. The reservoirs with a reverse rhythm where the layer thickness is greater than 5 m and the coefficient of variation less than 0.4 converting into hot-water flooding can yield a good recovery.
Key words: heavy oil reservoirs; steam flooding; hot-water flooding; sweep efficiency; coefficient of variation
Dong Xiaohu, MOE Key Laboratory of Petroleum Engineering, China University of Petroleum (Beijing), Beijing City, 102249, China

Zhang Jianhua. Study of crosslinking and transport blocking properties of polymer gel system in porous media. *PGRE*, 2012, 19(2): 54-56.

Abstract: The polymer gel is a cross-linking system consisted of partially hydrolyzed polyacrylamide HPAM solution and organic chromium (Cr^{3+}) crosslinker. ESEM2020 type environmental scanning electron microscopy, polymer gel dynamic crosslinking and seepage law experimental setup and unconsolidated sand model with different specifications are adopted for studying micro-cross-linked mechanism of polymer gel system dynamic cross-linking performance in porous media and transport blocking properties in rock cores. The experimental results show that the polymer molecules are arranged in star-shaped structure at the microcosmic view, and the polymer gel shows chain-like fractal structure microscopically, which is the result of cross-linking between

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

Zhang Jianhua, Technology Development Department, Shengli Oilfield Company, SINOPEC, Dongying City, Shangdong Province, 257000, China

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

Yang Shengjian, Research Institute of Petroleum Exploration and Development, Beijing City, 100083, China

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

Liu Lili, Department of Fluid Mechanics, North East Petroleum University, Daqing City, Heilongjiang Province, 163318, China

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

Du Dianfa, College of Geosciences, China University of Petroleum (Beijing), Beijing City, 102249, China

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