低渗透油藏直井水平井联合井网产能公式

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摘要：低渗透油藏具有渗透率小、存在启动压力梯度等特点，采用常规井网开采最终采收率低且开发效果差，而采用直井水平井联合井网开采该类油藏具有独特的优势，但对考虑启动压力梯度的低渗透直井水平井联合井网产能公式的论述较少。首先，根据低渗透油藏渗流特征，考虑启动压力梯度，确定了水平均质等厚地层中心 1 口生产井径向渗流时的产能公式；然后，利用等值渗流阻力法，将渗流阻力分成 3 部分：井网中心水平井在垂直方向上的渗流阻力、从生产坑道到水平井的渗流阻力以及从供给边缘到生产坑道的渗流阻力，推导出常规油藏直井水平井五点法、七点法及九点法联合井网的产能公式；最后，以低渗透直井产能公式和常规油藏联合井网产能公式为基础，将两者结合，得到了低渗透油藏直井水平井五点法、七点法以及九点法联合井网产能公式。矿场实例证实，所建产能公式简单易用、准确有效。

关键词：低渗透油藏 启动压力梯度 联合井网 产能公式 等值渗流阻力法
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目前，将渗透率低于 $50\times10^{-3}\ \mu m^2$ 的油藏称为低渗透油藏，并将其进一步分为低渗透油藏(渗透率为 $10\times10^{-3}\sim50\times10^{-3}\ \mu m^2$)、特低渗透油藏(渗透率为 $1\times10^{-3}\sim10\times10^{-3}\ \mu m^2$)和超低渗透油藏(渗透率为 $0.1\times10^{-3}\sim1\times10^{-3}\ \mu m^2$)3 类[1]。

由于启动压力梯度的存在[2]，低渗透油藏中流体的渗流不符合达西渗流规律[3]。近年来，随着低渗透油藏探明储量的增加，对该类油藏非线性渗流特征的研究逐渐引起重视[4]，但对于直井水平井联合井网产能计算的论述较少。另外，大量文献在推导产能公式时将水平方向渗透率与垂直方向渗透率按相等处理，这与实际情况偏差较大。为此，笔者首先根据低渗透油藏的渗流特征，确定了水平均质等厚地层中心 1 口井的产能公式；然后，利用等值渗流阻力法[5]，根据水电相似原理，且假设水平方向渗透率与垂直方向渗透率不同，推导出常规油藏直井水平井联合井网产能公式；最后，以前两者为基础，得到了低渗透油藏直井水平井联合井网产能公式。

1 渗流特点

流体通过多孔介质时，固液界面之间存在着固体分子与流体分子之间的作用力，在其作用下，多孔介质孔隙表面会形成一个流体吸附滞留层，称为边界层。低渗透油藏孔隙半径小，基本与吸附滞留层的厚度在同一数量级上，甚至更小。因此，要使吸附滞留层的流体参与流动，必须有足够的能量克服固液界面分子力作用。边界层是细小孔隙中的流体流动具有启动压力以及低渗透渗流不符合达西渗流的主要原因之一[6-8]。

考虑启动压力时，低渗透油藏的渗流方程[9]为

$$\begin{cases} v=-\dfrac{K}{\mu_o}\mathrm{grad}\,p\left(1-\dfrac{G}{|\mathrm{grad}\,p|}\right) & |\mathrm{grad}\,p|>G \\ v=0 & |\mathrm{grad}\,p|\leqslant G \end{cases} \tag{1}$$

式中：v 为渗流速度，cm/s；K 为地层渗透率，μm^2；μ_o 为地层原油粘度，mPa·s；p 为压力，10^{-1} MPa；G 为启动压力梯度，10^{-1} MPa/cm。

当渗流为径向流时，渗流方程为

$$\begin{cases} v=\dfrac{K}{\mu_o}\left(\dfrac{\mathrm{d}p}{\mathrm{d}r}-G\right) & \dfrac{\mathrm{d}p}{\mathrm{d}r}>G \\ v=0 & \dfrac{\mathrm{d}p}{\mathrm{d}r}\leqslant G \end{cases} \tag{2}$$

式中：r 为径向渗流半径，cm。

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2　直井产能公式

假设地层水平均质等厚，边界定压且渗流为单相稳态，油藏中心 1 口生产井的渗流方程由渗流综合微分方程、内边界条件和外边界条件三者构成，其表达式分别为

$$\frac{1}{r}\times\frac{\partial}{\partial r}\left[r\left(\frac{\partial p}{\partial r}-G\right)\right]=0\qquad\frac{\partial p}{\partial r}>G \tag{3}$$

$$r\left(\frac{\partial p}{\partial r}-G\right)\bigg|_{r=r_w}=\frac{q\mu_o}{2\pi Kh} \tag{4}$$

$$p(r)\,|_{r=r_e}=p_e \tag{5}$$

式中：r_w为油井半径，cm；q 为地层条件下生产井的产量，cm^3/s；h 为地层厚度，cm；r_e为供给半径，cm；p_e为供给压力，10^{-1} MPa。

将式(3)积分后代入式(4)，可得

$$r\left(\frac{\partial p}{\partial r}-G\right)=\frac{q\mu_o}{2\pi Kh} \tag{6}$$

将式(4)积分后代入式(5)，可得

$$p(r)=p_e-\frac{q\mu_o}{2\pi Kh}\ln\frac{r_e}{r}-G(r_e-r) \tag{7}$$

式中：$p(r)$ 为地层中任一点的压力，MPa。

由式(7)可得生产压差为

$$\Delta p=p(r)-p_{wf}=\frac{q\mu_o}{2\pi Kh}\ln\frac{r}{r_w}+G(r-r_w) \tag{8}$$

式中：Δp 为生产压差，10^{-1} MPa；p_{wf}为生产井井底压力，10^{-1} MPa。

式(6)中的 $G(r-r_w)$ 为启动压力梯度引起的附加压降，其值为启动压力梯度与渗流距离的乘积。

整理式(8)，并代入式(5)，可得均质等厚地层中心 1 口生产井的产能公式为

$$q=\frac{p_e-p_{wf}-G(r_e-r_w)}{\dfrac{\mu_o}{2\pi Kh}\ln\dfrac{r_e}{r_w}} \tag{9}$$

为了便于应用等值渗流阻力法，整理式(9)，将阻力写在分母上[10]，可得

$$q=\frac{p_e-p_{wf}}{\dfrac{\mu_o}{2\pi Kh}(1+G_r)\ln\dfrac{r_e}{r_w}} \tag{10}$$

其中

$$G_r=\frac{2\pi Kh(r_e-r_w)}{q\mu_o} \tag{11}$$

3　直井水平井联合井网产能公式

3.1　常规油藏

一个有界均质各向同性水平等厚地层布井的面积注水系统，均可以生产井为中心，划分成多个既相互独立又相互依存的单元，每个单元由 1 口水平井和 j 口直井组成。定义五点法井网正方形的边长、七点法井网六边形两对边的距离以及九点法井网正方形边长为井网特征尺度(图 1)。

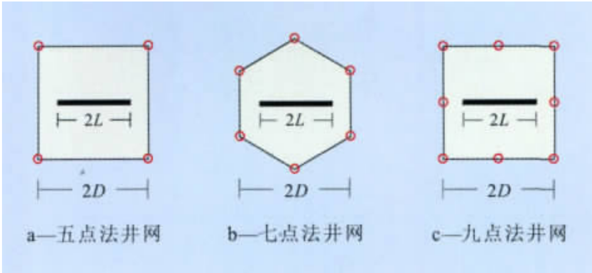

图 1　直井水平井联合井网常用井网单元示意

D 为井网特征尺度之半，cm；L 为水平井段半长，cm

在活塞式水驱油和水油流度比为 1 的情况下，根据水电相似原理，将渗流阻力分为水平井在垂直方向上的渗流阻力、从生产坑道到水平井的渗流阻力及流体从供给边缘流向生产坑道的渗流阻力 3 部分[11]，其表达式分别为

$$R_1=\frac{\mu_o}{4\pi LK_Z}\ln\frac{h}{2\pi r_w} \tag{12}$$

$$R_2=\frac{\mu_o}{2\pi K_H h}\ln\frac{a+\sqrt{a^2-L^2}}{L} \tag{13}$$

$$R_3=\frac{\mu_o}{2\pi mK_H h}\ln\frac{r_e}{jr_w} \tag{14}$$

式中：R_1为水平井在垂直方向上的渗流阻力，mPa·s/(μm^2·cm)；K_Z为地层垂直渗透率，μm^2；R_2为从生产坑道到水平井的阻力，mPa·s/(μm^2·cm)；K_H为地层水平渗透率，μm^2；a 为椭圆渗流区的半长轴，cm；R_3为流体从供给边缘流向生产坑道的渗流阻力，mPa·s/(μm^2·cm)；m 为注水系统的注水井数与生产井数之比；j 为井网单元的注水井数。

当 $r_e\approx a$ 且 $a>>L$ 时，式(11)可简化为

$$R_2=\frac{\mu_o}{2\pi K_H h}\ln\frac{2r_e}{L} \tag{15}$$

则直井水平井联合井网的产能公式为

$$q=\frac{\Delta p}{\frac{\mu_o}{2\pi K_H h}\left(\frac{1}{m}\ln\frac{r_e}{jr_w}+\ln\frac{2r_e}{L}+\frac{K_H}{K_Z}\frac{h}{2L}\ln\frac{h}{2\pi r_w}\right)} \tag{16}$$

当流度比不为 1 时，可用束缚水饱和度下的油相流度代入式(12)—式(16)中计算产量[12]。

对于五点法井网，$r_e=\sqrt{2}D$，$m=1.0$，$j=4$；七点法井网，$r_e=\frac{2}{\sqrt{3}}D$，$m=2.0$，$j=6$；九点法井网，$r_e=\sqrt{2}D$，$m=3.0$，$j=8$[11]。代入式(14)，分别得到常规油藏五点法、七点法和九点法井网的产能公式分别为

$$q_{C1}=\frac{\Delta p}{\frac{\mu_o}{2\pi K_H h}\left(\ln\frac{\sqrt{2}D}{4r_w}+\ln\frac{2\sqrt{2}D}{L}+\frac{K_H}{K_Z}\frac{h}{2L}\ln\frac{h}{2\pi r_w}\right)} \tag{17}$$

$$q_{C2}=\frac{\Delta p}{\frac{\mu_o}{2\pi K_H h}\left(\frac{1}{2}\ln\frac{D}{3\sqrt{3}r_w}+\ln\frac{4D}{\sqrt{3}L}+\frac{K_H}{K_Z}\frac{h}{2L}\ln\frac{h}{2\pi r_w}\right)} \tag{18}$$

$$q_{C3}=\frac{\Delta p}{\frac{\mu_o}{2\pi K_H h}\left(\frac{1}{3}\ln\frac{\sqrt{2}D}{8r_w}+\ln\frac{2\sqrt{2}D}{L}+\frac{K_H}{K_Z}\frac{h}{2L}\ln\frac{h}{2\pi r_w}\right)} \tag{19}$$

式中：q_{C1}，q_{C2} 和 q_{C3} 分别为常规油藏五点法、七点法和九点法井网水平井在地层条件下的产量，cm^3/s。

3.2 低渗透油藏

根据式(8)，将常规油藏直井水平井联合井网产能公式推广到低渗透油藏中，得到五点法、七点法和九点法井网的产能公式分别为

$$q_{L1}=\frac{\Delta p}{\frac{\mu_o}{2\pi K_H h}\left(\ln\frac{\sqrt{2}D}{4r_w}+\ln\frac{2\sqrt{2}D}{L}+\frac{K_H}{K_Z}\frac{h}{2L}\ln\frac{h}{2\pi r_w}\right)}-\frac{(\sqrt{2}D-4r_w)\ln\frac{\sqrt{2}D}{4r_w}+\left(\sqrt{2}D-\frac{L}{2}\right)\ln\frac{2\sqrt{2}D}{L}+\left(\frac{h}{2\pi}-r_w\right)\ln\frac{h}{2\pi r_w}}{\frac{\mu_o}{2\pi K_H h}\left(\ln\frac{\sqrt{2}D}{4r_w}+\ln\frac{2\sqrt{2}D}{L}+\frac{K_H}{K_Z}\frac{h}{2L}\ln\frac{h}{2\pi r_w}\right)}G \tag{20}$$

$$q_{L2}=\frac{\Delta p}{\frac{\mu_o}{2\pi K_H h}\left(\frac{1}{2}\ln\frac{D}{3\sqrt{3}r_w}+\ln\frac{4D}{\sqrt{3}L}+\frac{K_H}{K_Z}\frac{h}{2L}\ln\frac{h}{2\pi r_w}\right)}-\frac{\left(\frac{2D}{\sqrt{3}}-6r_w\right)\ln\frac{D}{3\sqrt{3}r_w}+\left(\frac{2D}{\sqrt{3}}-\frac{L}{2}\right)\ln\frac{4D}{\sqrt{3}L}+\left(\frac{h}{2\pi}-r_w\right)\ln\frac{h}{2\pi r_w}}{\frac{\mu_o}{2\pi K_H h}\left(\frac{1}{2}\ln\frac{D}{3\sqrt{3}r_w}+\ln\frac{4D}{\sqrt{3}L}+\frac{K_H}{K_Z}\frac{h}{2L}\ln\frac{h}{2\pi r_w}\right)}G \tag{21}$$

$$q_{L3}=\frac{\Delta p}{\frac{\mu_o}{2\pi K_H h}\left(\frac{1}{3}\ln\frac{\sqrt{2}D}{8r_w}+\ln\frac{2\sqrt{2}D}{L}+\frac{K_H}{K_Z}\frac{h}{2L}\ln\frac{h}{2\pi r_w}\right)}-\frac{(\sqrt{2}D-8r_w)\ln\frac{\sqrt{2}D}{8r_w}+\left(\sqrt{2}D-\frac{L}{2}\right)\ln\frac{2\sqrt{2}D}{L}+\left(\frac{h}{2\pi}-r_w\right)\ln\frac{h}{2\pi r_w}}{\frac{\mu_o}{2\pi K_H h}\left(\frac{1}{3}\ln\frac{\sqrt{2}D}{8r_w}+\ln\frac{2\sqrt{2}D}{L}+\frac{K_H}{K_Z}\frac{h}{2L}\ln\frac{h}{2\pi r_w}\right)}G \tag{22}$$

式中：q_{L1}，q_{L2} 和 q_{L3} 分别为低渗透油藏五点法、七点法和九点法井网水平井在地层条件下的产量，cm^3/s。

4 实例应用

某油田 Y 区块区域构造属于济阳坳陷沾化凹陷五号桩次级洼陷东斜坡，整体为东高西低的单斜构造，地层倾角为 9°～18°，南、北 2 个方向均受断层控制，向东地层超覆尖灭。Y 区块采用五点法井网，其物性参数包括：生产压差为 5 MPa，地层原油粘度为 3 mPa·s，地层水平渗透率为 $18.9\times10^{-3}\ \mu m^2$，地层垂直渗透率为 $3.4\times10^{-3}\ \mu m^2$，油井半径为 10 cm，井网特征尺度之半为 200 m，水平井段半长为 100 m，油层厚度为 12 m，启动压力梯度为 1.6 Pa/cm，地层原油的体积系数为 1.1，地面脱气原油的密度为 $0.867\ g/cm^3$。

将以上各参数值代入直井水平井联合井网五点法产能公式，得到水平井在油层条件下的产量为 $237.48\ cm^3/s$，转化为地面条件下的产油量为 16.17 t/d，而实际测得的产油量为 15.33 t/d，误差为 5.48% 左右，可见该公式准确有效。

5 结束语

根据水电相似原理，利用了等值渗流阻力法，以井网单元为研究单位，推导了低渗透油藏直井水平

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产气量随裂缝条数的增加而增加，在非稳态阶段，裂缝中的产气量相近; 在拟稳态阶段，裂缝之间存在相互干扰，产气量呈“U”型分布。对于特定地层，裂缝条数存在最优值。

考虑致密气藏储层特征，推荐采用射孔完井的压裂水平井进行生产，在研究中必须考虑裂缝之间的干扰现象，压裂设计时应该适当扩大水平段两端的压裂规模，裂缝模式选用均匀间距，“U”型布局(即两端长，中间短)更为合理。

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井联合井网五点法、七点法和九点法的产能公式，为多口直井水平井联合布井提供了产能预测的新方法。此方法与保角变换等方法相比，过程简单，便于理解。且与其他文献不同，将地层的水平渗透率和垂直渗透率按不相等处理，计算结果更接近真实情况。此公式中使用的各项参数均为油藏平均值，对于非均质性较强的油藏，需要更加准确的产能公式。

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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