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水平井多段压裂后压力递减分析

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摘要：目前水平井多段压裂的应用越来越多，但是现有的压裂压力递减分析方法都是针对单条水力裂缝的。由于水平井多段裂缝闭合时，流体流动特征与直井单条裂缝具有明显不同，针对直井单条裂缝的压裂压力递减分析方法不适用于水平井多段压裂。考虑水平井多段裂缝闭合时的压力变化特点，对多段裂缝强制闭合与裂缝自然闭合进行了分析，建立了多段裂缝同时闭合的压力递减模型和裂缝参数解释方法，编制了水平井多段压裂后压力递减分析解释软件，并进行了实例分析。模拟结果表明，压力递减分析方法可以解释出水平井多段压裂的重要裂缝及储层参数，实例应用结果表明，由所建模型模拟出来的裂缝参数解释结果可靠，对水平井水力压裂理论的发展以及指导现场施工都有重要的意义和参考价值。

关键词：水平井多段压裂 多缝闭合 压力递减模型 裂缝参数 解释方法
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近年来，水平井多段压裂技术在全世界范围内得到了广泛应用，因此需要一种针对水平井多段裂缝的压后诊断技术来对施工效果进行分析评价。现有的压裂压力递减分析方法都是针对单条水力裂缝的，而水平井多段裂缝闭合时流体流动特征与直井单条裂缝相比有很大区别，并且水平井多段裂缝的几何形态有其特殊性，所以不能利用以往的相关技术来对水平井多段裂缝进行有效分析。因此，笔者针对水平井多段压裂后压力递减规律进行了研究，以期为多段裂缝的参数解释提供参考。

1 限流法压裂裂缝闭合过程

限流法压裂[1]施工停泵的一瞬间，在不考虑井筒续流效应下，各段裂缝停止进液，此时各段裂缝缝口压力可以看作瞬间达到平衡。由于各裂缝缝口处于一个连通的水力系统，在裂缝自然闭合过程中，各缝口的压力变化始终保持一个连通水力系统的压力关系；而对于裂缝强制闭合情况，则要考虑由于排液而引起的水平段沿程压降。多段裂缝的闭合压力各不相同，闭合压力大的裂缝最先闭合，随着井筒内压力逐步下降其他裂缝相继闭合。

水平井多段裂缝闭合分析的特殊性主要是由多段裂缝同时闭合造成的，常规压力递减分析理论不适用于水平井多段压裂闭合分析的原因主要有4点：①水平井多段裂缝闭合时，几条裂缝叠加在一起的压降特点与1条裂缝闭合时不同。前者在停泵时井筒中液体不再流动，此时各条裂缝缝口的压力瞬时达到平衡，造成压力不连续变化，破坏了常规压降分析中压降方程的连续性，这是单条裂缝压降分析法不能直接用于多段裂缝同时闭合的主要原因之一。②各段裂缝的施工时间不同，且其滤失系数、缝长、缝高和闭合压力也不同，不能用统一的压降方程将其联系起来。③考虑压裂后放喷情况，水平井多段压裂后，裂缝的返排液流动状态不同于单条裂缝。在多段裂缝中，压裂液径向流入井筒，从水平井趾端到跟端，井筒中的流量逐渐变大，其流动特征为水平段变质量流。各段裂缝之间也会呈现不同流态，可能从开始的层流发展到下一段的紊流，所以其沿程压降的计算不同于直井。④水平井多段压裂后的压力递减分析与常规压力递减分析不同，不能看作为一个反问题求解。与单条裂缝分析相比，多段裂缝的不同参数组合，如不同缝长、缝宽和滤失系数的组合可能会得到同一条压力递减曲线，因此不能利用

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常规的分析方法。

2　压降模型

在水平井多段裂缝闭合过程中，虽然各段裂缝的施工时间、改造规模、岩石物性等参数不同，使得其压裂液滤失速度不同，但每条裂缝的滤失规律是相同的，可以分别计算每条裂缝的滤失体积，进而得到各段裂缝缝口压力的递减规律，最后根据水平井多段裂缝之间连通水力学系统的压力关系，得到多段裂缝同时滤失时的井口压降规律[2]。

2.1　压裂液滤失体积的计算

综合考虑油藏边界条件、地层条件以及压裂液性质对滤失体积的影响，对单条裂缝的压裂液滤失体积建立数学模型。在裂缝中取微小的三维单元体(微元体)[3]，流体从微元体的左边流进，从右边流出(图 1)。

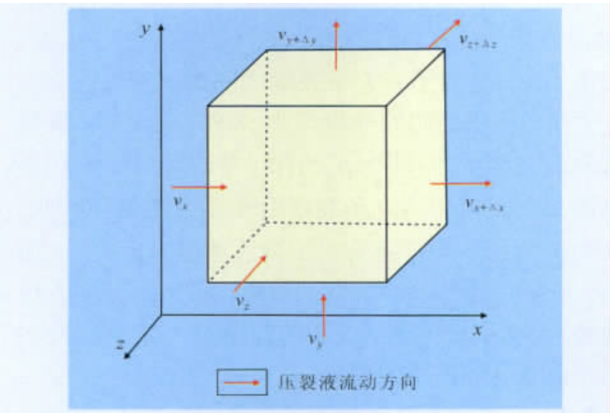

图 1　裂缝微小三维单元体示意

v_x，v_y 和 v_z 分别为某时刻压裂液沿 x，y 和 z 轴进入微元体的流量，m^3/min；$v_{x+\Delta x}$，$v_{y+\Delta y}$ 和 $v_{z+\Delta z}$ 分别为同一时刻压裂液沿 x，y 和 z 轴流出微元体的流量，m^3/min

根据质量守恒定律和达西定律，可以推导出该时刻 x 和 y 轴方向流入和流出的压裂液质量差[4-5]为

$$\frac{\partial}{\partial x}\left(\rho\frac{K_d}{\mu}\times\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left(\rho\frac{K_d}{\mu}\times\frac{\partial p}{\partial y}\right)=\phi\frac{\partial\rho}{\partial p}\times\frac{\partial p}{\partial t}+\rho\frac{\partial\phi}{\partial p}\times\frac{\partial p}{\partial t}\tag{1}$$

式中：ρ 为压裂液密度，kg/m^3；K_d 为地层渗透率，μm^2；μ 为压裂液的粘度，mPa · s；p 为压力，MPa；ϕ 为岩石孔隙度；t 为时间，min。

考虑流体微可压缩性与岩石孔隙的压缩性，可得

$$C_1=\frac{1}{\rho}\times\frac{\partial\rho}{\partial p}\tag{2}$$

$$\phi=\phi^0\left[1+C_R(p-p^0)\right]\tag{3}$$

式中：C_1 为流体的压缩系数，MPa^{-1}；ϕ^0 为压力为 p^0 时的岩石孔隙度；C_R 为岩石的压缩系数，MPa^{-1}；p^0 为某一参考压力，MPa。

由式(1)—式(3)推导出压裂液在地层中的渗流方程为

$$\nabla\cdot\left[\frac{K_d}{\mu}\nabla p\right]=C_f\phi\frac{\partial p}{\partial t}\tag{4}$$

式中：C_f 为岩石综合压缩系数，MPa^{-1}。

模型封闭外边界、定压外边界及内边界条件分别为

$$\begin{cases}\left.\dfrac{\partial p}{\partial y}\right|_{y=L_y}=0\\ \left.\dfrac{\partial p}{\partial x}\right|_{x=L_x}=0\end{cases}\tag{5}$$

$$\begin{cases}p|_{y=L_y}=p_i\\ p|_{x=L_x}=p_i\end{cases}\tag{6}$$

$$p|_{x\leq L_f}=p_f\qquad(y=0)\tag{7}$$

式中：L_y 为对裂缝进行网格划分后沿 y 轴方向的几何长度，m；L_x 为对裂缝进行网格划分后沿 x 轴方向的几何长度，m；p_i 为地层压力，MPa；L_f 为单条裂缝长度，m；p_f 为裂缝压力，MPa。

压裂液滤失模型初始条件为

$$p|_{t=0}=p_i\tag{8}$$

$$\left.\frac{\partial p}{\partial x}\right|_{x=0}=0\qquad y\in(0,L_y)\tag{9}$$

$$\left.\frac{\partial p}{\partial y}\right|_{y=0}=0\qquad x\in(L_f,L_x)\tag{10}$$

对裂缝进行网格划分，并建立差分方程，式(4)—式(10)构成五对角方程组，可以采用强隐式方法求出各网格点的压力。

单位时间内压裂液的滤失体积为

$$q=4\sum_{i=1}^{m}\frac{K_d}{\mu}\times\frac{p_f-p_i}{\Delta y_1}l_{xi}h\tag{11}$$

式中：q 为单位时间内压裂液的滤失体积，m^3/min；i 为多段压裂中的某条裂缝；m 为多段压裂裂缝的总数；p_i 为裂缝第 i 个网格内的压力，MPa；Δy_1 为 y 方向上第 1 排网格的长度，m；l_{xi} 为 x 方向上裂缝的网格长度，m；h 为滤失缝高，m。

单条裂缝的总滤失体积为

$$V_{loss}^{n}=V_{loss}^{n-1}+4\sum_{i=0}^{m}\frac{K_d}{\mu}\times\frac{p_f-p_i}{\Delta y_1}l_{xi}h\tag{12}$$

式中：V_{loss}^{n} 为停泵后 t_n 时刻压裂液的总滤失体积，m^3；V_{loss}^{n-1} 为停泵后 t_{n-1} 时刻压裂液的总滤失体

积，m^3。

根据不同裂缝内的压力可得到单位时间内每条裂缝压裂液的总滤失体积。在裂缝闭合过程中，各段裂缝的滤失体积随缝口压力而变化，t_1 到 t_{n-1} 时刻的缝口压力值已经求出，则 t_n 时刻的裂缝压裂液滤失体积仅为该时刻裂缝压力的函数，即

$$V_{\mathrm{loss}}^{n} = f_{\mathrm{loss}}(p_{\mathrm{f}}^{n}) \tag{13}$$

式中：p_{f}^{n} 为停泵后 t_n 时刻的裂缝压力，MPa；t_n 为停泵后的某时刻，min。

2.2　裂缝强制闭合过程中压力递减模型

根据体积平衡原理，压裂后强制返排时裂缝体积的变化量等于返排液体积与返排时刻起的压裂液总滤失体积之和，即

$$\Delta V_{\mathrm{f}} = V_{排} + V_{\mathrm{loss}} \tag{14}$$

式中：ΔV_{f} 为裂缝体积的变化量，m^3；$V_{排}$ 为压裂液的返排体积，m^3；V_{loss}为返排时刻起的压裂液总滤失体积，m^3。

2.2.1　压裂液的返排体积

不同时刻压裂液的返排体积为

$$V_{排} = \int_0^t 1.414 \times 10^3 \pi r^2 \rho^{-0.5}\left(1+\xi-\frac{r^4}{R^4}\right)^{-0.5}\left[p(t)-p_0\right]^{0.5}\mathrm{d}t \tag{15}$$

式中：r 为井口放喷油嘴的半径，m；ξ 为局部阻力系数，其值为0.5；R 为井筒半径，m；$p(t)$ 为排液过程中的井口压力，MPa；p_0 为标准大气压，MPa，其值为0.1。

压裂液的返排体积随水平段跟端压力的变化而变化，其为裂缝压力的函数，即

$$V_{排} = f_{排}(p_{\mathrm{f}}) \tag{16}$$

由于各段裂缝的参数不同，压裂液的返排体积不同，根据各段裂缝缝口处沿井筒方向的压力变化率来分配各段裂缝的返排流量，某段裂缝的压裂液返排流量为

$$Q_i = Q\frac{\left(\dfrac{\partial p}{\partial x}\right)_i}{\sum\limits_{i=1}^{m}\dfrac{\partial p}{\partial x}} \tag{17}$$

式中：Q_i 为第 i 条裂缝的压裂液返排流量，m^3/min；Q 为总的压裂液返排流量，m^3/min。

2.2.2　沿程压降

由于水平井水平段较长，压裂液的返排流量较大，因此破胶液沿水平井筒流动的沿程压降不能被忽略[6]。水平井趾端到跟端的流量逐渐变大，流动特征为水平段变质量流。水平段的压力损失分为壁面剪切应力造成的摩阻压力损失、动量变化造成的加速压力损失及重力压力损失[7]，2条裂缝之间的压降为

$$\Delta p_{ij} = \Delta p_{\mathrm{w}j} + \Delta p_{\mathrm{acc}j} + \Delta p_{\mathrm{h}j} \tag{18}$$

其中

$$\Delta p_{\mathrm{w}j} = f_j\frac{\rho_j v_j^{\,2}}{2D}\Delta L_j \tag{19}$$

$$\Delta p_{\mathrm{acc}j} = p_{1j} - p_{2j} = \rho_{2j}v_{2j}^{\,2} - \rho_{1j}v_{1j}^{\,2} \tag{20}$$

$$\Delta p_{\mathrm{h}j} = \rho g \Delta h_j \tag{21}$$

式中：Δp_{ij}为压裂液返排过程中第 j 条裂缝与第 $j+1$ 条裂缝之间的井筒沿程压降，MPa；$\Delta p_{\mathrm{w}j}$为第 j 条裂缝与第 $j+1$ 条裂缝之间的井筒摩阻压力损失，MPa；$\Delta p_{\mathrm{acc}j}$为第 j 条裂缝前后的加速压力损失，MPa；$\Delta p_{\mathrm{h}j}$为第 j 条裂缝与第 $j+1$ 条裂缝之间的重力压力损失，MPa；f_j 为沿程摩阻系数；ρ_j 为压裂液密度，kg/m^3；v_j 为压裂液的流速，m/s；D 为井筒直径，m；ΔL_j 为第 j 条裂缝与第 $j+1$ 条裂缝之间的井筒长度，m。p_{1j}为第 j 条裂缝前的井筒压力，MPa；p_{2j}为第 j 条裂缝后的井筒压力，MPa；ρ_{2j}为第 j 条裂缝后的压裂液密度，kg/m^3；v_{2j}为第 j 条裂缝后井筒中的流体流速，m/s；ρ_{1j}为第 j 条裂缝前的压裂液密度，kg/m^3；v_{1j}为第 j 条裂缝前井筒中的流体流速，m/s；g 为重力加速度，m/s^2；Δh_j 为第 j 条裂缝与第 $j+1$ 条裂缝所在层位射孔孔眼的垂直距离，m。

2.2.3　闭合期裂缝体积的变化量

从停泵起某个时刻裂缝体积的变化量[8-10]为

$$\Delta V_{\mathrm{f}} = \frac{\pi(1-\gamma^2)H_{\mathrm{f}}L_{\mathrm{f}}}{E}\times\left[p_{\mathrm{f}}(t_0)-p_{\mathrm{f}}(t_n)\right]\begin{bmatrix}H_{\mathrm{f}}\\L_{\mathrm{f}}\end{bmatrix}\begin{matrix}PKN\text{ 模型}\\KGD\text{ 模型}\end{matrix} \tag{22}$$

式中：γ 为岩石的泊松比；H_{f} 为井筒端裂缝缝高，m；E 为岩石的杨氏模量，MPa；$p_{\mathrm{f}}(t_0)$ 为停泵时的缝口压力，MPa；t_0 为压裂停泵时刻，min；$p_{\mathrm{f}}(t_n)$ 为停泵 t_n 时刻的缝口压力，MPa。

拟三维裂缝模型的体积变化量[11]为

$$\Delta V_{\mathrm{f}} = \frac{\pi(1-\gamma^2)}{2E}H_{\mathrm{f}}^{\,2}L_{\mathrm{f}}M\left[p_{\mathrm{f}}(t_0)-p_{\mathrm{f}}(t_n)\right] \tag{23}$$

式中：M 为拟三维裂缝模型缝高与储层厚度的相关比值。

由式(23)看出，某时间段裂缝体积的变化量是该时刻井底压力的函数。

2.3　裂缝自然闭合过程中的压力递减模型

裂缝自然闭合时，返排液量为 0，不考虑返排液沿程的压力损失，井口压力递减规律只受裂缝内压裂液滤失的影响。根据压裂液体积平衡原理，裂缝自然闭合的体积变化量等于停泵后压裂液的滤失体积，即

$$\Delta V_{\mathrm{f}} = V_{\mathrm{loss}} \tag{24}$$

裂缝体积变化量以及压裂液滤失体积的计算方法与前面的裂缝强制闭合时的计算方法相同。

3　裂缝参数的解释方法

3.1　曲线自动拟合方法的提出

对裂缝相关参数的解释可以采用数值分析中的函数逼近法来对水平井多段压裂停泵后的压力数据进行分析[12]。根据前面建立的水平井多段压裂后压力递减模型，编制出压力递减分析软件，其中实际的压力数据表示为 $Testing\_p(i)$，$i=1,2,\cdots,N$，i 为时间步；不同裂缝、地层参数组合下的拟合压力表示为 $Simu\_p(i,j)$，j 为不同的拟合压力曲线，共有 k 条，$j=1,2,\cdots,k$。计算机按照预先给定的参数自动计算出不同裂缝尺寸与相关参数下的一系列拟合压力曲线，然后对比所有拟合压力曲线与实际压力曲线的误差平方和，误差函数 $ERR(j)$ 值最小时所对应的拟合压力曲线即为最佳拟合曲线，即

$$\mathrm{Min}ERR(j) = \min_{j=1,2,\cdots,k} \sum_{i=1}^{N} [Testing\_p(i) - Simu\_p(i,j)]^2 \tag{25}$$

3.2　参数解释模型

3.2.1　裂缝的几何尺寸

根据曲线拟合方法，可以得出当误差函数最小时的缝长组合，即为模型解释出的多段裂缝的几何尺寸。

3.2.2　综合滤失系数

对水力裂缝采取了网格划分，计算了各条裂缝的不同微元体分布，且考虑压裂液滤失系数随裂缝位置与滤失时间变化而变化的情况，综合滤失系数表示为

$$C_{\mathrm{L}}(x) = \frac{-\dfrac{1}{C_{\mathrm{c}}(x)} + \sqrt{\dfrac{1}{C_{\mathrm{c}}^2(x)} + \dfrac{4}{C_1^2(x)}}}{\dfrac{2}{C_1^2(x)}} \tag{26}$$

式中：$C_{\mathrm{L}}(x)$ 为综合滤失系数，$\mathrm{m/min^{1/2}}$；$C_{\mathrm{c}}(x)$ 为受地层流体压缩性控制的滤失系数，$\mathrm{m/min^{1/2}}$；$C_1(x)$ 为受压裂液粘度控制的滤失系数，$\mathrm{m/min^{1/2}}$。

3.2.3　闭合压力

闭合压力的计算可参考文献[13]中的计算方法。根据经验公式计算出裂缝闭合压力，进而在设定的计算精度下拟合该闭合压力，避免由人为因素造成的可能误差，从而得到了较准确的闭合压力。

3.2.4　压裂液效率

水平井多段压裂的压裂液效率是停泵时各段裂缝的体积之和与施工期间注入压裂液体积之比。通过该方法求出的停泵时刻各段裂缝的缝长、缝宽与缝高，计算出各段裂缝的体积之和，从而求出压裂液效率，即

$$\eta = \frac{\sum_{i=1}^{m} V_{\mathrm{f}i}}{Qt_0} \tag{27}$$

式中：η 为压裂液效率；$V_{\mathrm{f}i}$ 为停泵时某段裂缝体积，$\mathrm{m^3}$；Q 为压裂时的泵注排量，$\mathrm{m^3/min}$。

4　实例分析

根据建立的压降解释模型以及裂缝参数解释方法，编制了水平井多段压裂后压力递减分析解释软件，并应用此软件进行实例分析。某油田 X－1 井采用限流法压裂出 2 条横向裂缝，第 1 条裂缝的压裂目的层深度为 3 015～3 021 m，地应力差为 8 MPa，岩石杨氏模量为 36 000 MPa，泊松比为 0.21；第 2 条裂缝的压裂目的层深度为 3 081～3 086 m，地应力差为 7 MPa，岩石杨氏模量为 36 700 MPa，泊松比为 0.27；2 个目的层裂缝间水平段距离为 421 m，压裂液用量为 143 $\mathrm{m^3}$，施工排量为 3.0～6.5 $\mathrm{m^3/min}$，压裂液压缩系数为 0.000 436 $\mathrm{MPa^{-1}}$，压后排液油管直径为 6.20 cm，放喷油嘴直径为 3 mm，井口停泵压力为 30.27 MPa。压裂停泵后立即强制排液。

利用编制的软件得出的结果为：第 1 条裂缝的缝长为 76.2 m，缝宽为 3.82 mm，缝高为 9.3 m，储层闭合压力为 51.5 MPa；第 2 条裂缝的缝长为 61.5 m，缝宽为 3.55 mm，缝高为 7.2 m，储层闭合压力 52.2 MPa；压裂液滤失系数为 12.54×10^{-4} $\mathrm{m/min^{1/2}}$，压裂液效率为 24.3%。

利用所编制的软件可输出这 2 条裂缝在不同几何尺寸组合下的一系列拟合压力曲线，选取其中 3 条压力曲线来分析模型计算出的压力递减情况(图

2)。其中模拟压力 p_1 曲线是上述最终计算结果的拟合压力曲线，其对应的裂缝参数为最终模型的输出结果，而模拟压力 p_2 和 p_3 曲线是裂缝参数不符合实际的 2 条拟合压力曲线。由模型输出的 p_2 情况下，第 1 条裂缝的缝长为 61.5 m，缝宽为 3.23 mm，缝高为 8.2 m；第 2 条裂缝的缝长为 55.7 m，缝宽为 3.01 mm，缝高为 6.7 m。由模型输出的 p_3 情况下，第 1 条裂缝的缝长为 80.5 m，缝宽为 2.76 mm，缝高为 7.3 m；第 2 条裂缝的缝长为 42.6 m，缝宽为 2.39 mm，缝高为 5.1 m。

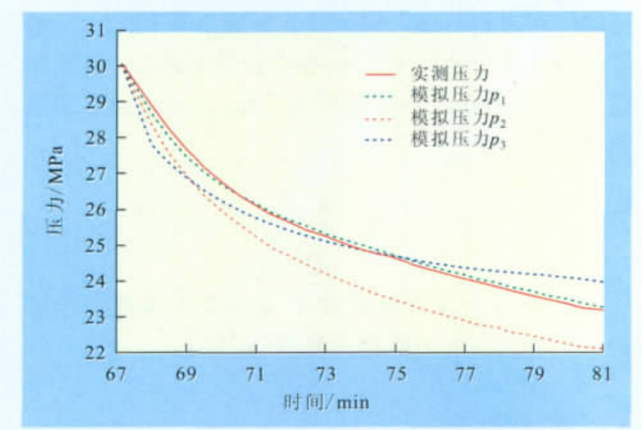

图 2　X－1 井 2 条裂缝不同几何尺寸下的拟合压力曲线

由图 2 可以看出，模拟出来的裂缝缝长符合压前评估，因为该井采用限流法压裂，且 2 个压裂目的层条件相差不大，第 1 层最先压开，施工时间长，因此缝较长；第 2 层其次压开，施工时间短，缝长也短。模型解释出的压降曲线较好地拟合出停泵后最初一段时间压力下降较快的现象，体现了压裂施工后沟通了近井地带微裂缝，使裂缝压力扩散较快，与实际情况吻合。而图中的这几条曲线显示压力降落速度都较快，这是由于压裂后强制排液造成的。

5　结束语

水平井多段压裂裂缝与井身结构的特点决定了常规压裂压力递减分析方法不能用于水平井多段压裂的压力递减分析。压后强制返排条件下，不能忽略水平段的沿程压降损失；通过所建立的多段裂缝同时闭合时的压力递减分析模型，提出了适用于水平井多段压裂后压力递减的曲线拟合法，能很好地计算出多段裂缝的几何参数以及其他相关参数。实例分析表明，建立的压力递减模型和解释方法能有效地应用于现场水平井多段压裂后裂缝评估以及施工评价。

参考文献：

[1] 王琴，张士诚，陈浩东．限流压裂工艺技术研究[J]．重庆科技学院学报：自然科学版，2009，11(1)：41－43.

[2] 虞建业，沈飞，顾庆宏，等．水平井射孔参数对压裂起裂压力的影响[J]．油气地质与采收率，2011，18(1)：105－107，110.

[3] 葛家理．油气藏渗流力学[M]．北京：石油工业出版社，1982.

[4] 李勇明，纪禄军，郭建春．压裂液滤失的二维数值模拟[J]．西南石油学院学报，2000，22(2)：43－45.

[5] 吴忠宝，胡文瑞，宋新民，等．整体水力压裂油藏裂缝—油藏耦合数值模拟研究[J]．油气地质与采收率，2009，16(2)：70－73.

[6] 罗天雨，赵金洲，郭建春．薄层多层压裂的拟三维模型及应用[J]．特种油气藏，2005，12(6)：60－64.

[7] 程林松，兰俊成．考虑水平井筒压力损失的数值模拟方法[J]．石油学报，2002，23(1)：67－71.

[8] Khristianovic S A，Zheltov Y P. Formation of vertical fracture by meand of highly viscous liquids[C]. Proceeding of the Fourth World Petroleum Congress，Section Ⅱ，1955.

[9] 王立军，张小红，马宁，等．压裂水平井裂缝与井筒成任意角度时的产能预测模型[J]．油气地质与采收率，2008，15(6)：73－75.

[10] Gertsma J，Dekerk F. A rapid method of predicting width an extent of hydraulically induced fractures[J]. SPE 2458，1969：63－72.

[11] Palmer I D，Craig H R. Modeling of asymetric vertical growth in eongated hydraulic fracture and appdication to first MWX stimulation[J]. SPE 12879，1984：36－43.

[12] 任勇，郭建春，赵金洲，等．酸化压裂井停泵压力三维分析模型和解释方法[J]．石油勘探与开发，2006，33(5)：634－637.

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欢迎广大科技人员踊跃投稿

Shi Xian, Li Zhaomin, Liu Chengwen et al. New productivity prediction model for sand control wells by cyclic steam stimulation. ***PGRE*****, 2012, 19(4): 56-58.**

Abstract: There are many productivity prediction models for heavy oil wells with cyclic steam stimulation, but these models have little consideration on effects of sand control measures for the productivity, however, sand control measures are necessary for heavy oil stimulation, which result in some errors in calculation of the productivity. This paper presents a new productivity two zone model which considers the interaction of steam stimulation and sand control, and this model also combines the gravity override effect and the rheological behavior of heavy oil, then, it gives an actual example. Comparing with conventional models, the heating radius calculated through new model are greater and the calculation error is approximately 5%, which proves its validity. Based on negative power exponent of the heating radius hypothesis, the new model should not consider the heating area, shape and the influence of the reservoir thickness. The computing workload for new model is small and it is easy to use, which can provide plan for the productivity prediction for sand control well with thermal recovery.

Key words: cyclic steam stimulation; heating radius; sand control; skin factor; productivity prediction

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Huo Gang, Fan Xiao. Numerical simulation study on displacement mechanism of flue gas assisting steam huff and puff. ***PGRE*****, 2012, 19(4): 59-61.**

Abstract: Study on multi-phase and multi-component seepage mechanism for mixing flue gas assisting steam huff and puff is of great significance for understanding the change of seepage physical field different to conventional steam huff and puff and improving the thermal recovery results. In this paper, multi-phase and multi-component anisothermal numerical model is built for reservoir numerical simulation, in order to systematically study the phase change rule of flue gas, steam and crude as well as the variable phase seepage characteristics of multi-component system. The results show that, mixing flue gas injection can increase the steam quality in oil layer effectively. The dissolution and expansion of flue gas significantly extend the crude viscosity reduction range. Meanwhile, CO_2 dissolution in flue gas can decrease oil-water interfacial tension effectively and increase the microscopic displacement efficiency.

Key words: flue gas; cyclic steam stimulation; multi-phase and multi-component; seepage mechanism; numerical simulation; heavy oil

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Li Guoyong, Ye Shengjun, Feng Jiansong et al. Research and application of water-control and oil-enhance for horizontal wells CO_2 huff and puff in complex fault-block reservoir. ***PGRE*****, 2012, 19(4): 62-65.**

Abstract: Horizontal wells are the main development mode in Jidong Nanpu onshore shallow complex fault-block reservoir. Most horizontal wells have entered the high water cut stage. The reasons caused abnormal raise of water cut includes tectonic, well trajectory, production system and impact of external fluid. The mechanism of water-control and oil-enhance for horizontal wells CO_2 huff and puff includes expansion of the crude oil volume, reduction of the viscosity, and extraction for light hydrocarbon, according to the prediction of CO_2 minimum miscibility pressure, laboratory analysis of fluid output and reservoir simulation. We determine the single well injection, injection rate, soaking time and other parameters based on the optimization of process design. Implementation of 32 wells and related technical experiments show that, it achieved significant results in water-control and oil-enhance, and shows a good prospect for field promotion.

Key words: complex fault-block reservoir; horizontal well; CO_2 huff and puff; minimum miscibility pressure; water control

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Li Yongming, Zhai Rui, Gao Ruimin et al. Study of pressure decline on horizontal well after multiple-stage fracturing. ***PGRE*****, 2012, 19(4): 66-70.**

Abstract: At present, the application of horizontal well multiple-stage fracturing becomes more and more popular. However, the existing model of pressure decline analysis aims primarily at single fracture. There are great differences in the flow performance of fluids between multiple-stage fractures and single fracture during the fracturing closure process. The model of pressure decline analysis aiming at single fracture does not apply to the horizontal well multiple-stage fractures. Taking into account of the pressure change with the situation about the horizontal well multiple-stage fractures closure, this paper analyzes forced and natural closure of horizontal well after multiple-stage fracturing, and then establishes curve fitting method of related pressure decline model and fracturing parameters interpretation based on the pressure drop features while multiple-stage fractures are closing simultaneously, than we compiled the software about pressure decline analysis of horizontal well multiple-stage fracturing, and it has been used for the case analysis. The results show that this analytical method can explain some important parameters of fracture and reservoir, and the result is reliable, also it is of great significance and reference value to the development of horizontal well fracturing theory and fracturing operation.

Key words: multistage fracturing horizontal well; multi-fracture closure; pressure decline model; fracture parameter; interpretation method

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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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