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低渗透气藏不对称垂直裂缝井产能预测

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摘要:针对低渗透气藏压裂后产生的不对称垂直裂缝,基于稳定流理论,利用保角变换,推导了低渗透气藏有限导流不对称垂直裂缝井产能的预测模型,通过实例分析了多种因素对不对称垂直裂缝井产能的影响。结果表明:在井底流压相同的条件下,裂缝非对称率对不对称垂直裂缝井产能影响较小;当裂缝导流能力较小时,不同裂缝长度或裂缝非对称率对气井产能影响程度差异较大,当裂缝导流能力较大时,不同裂缝长度或裂缝非对称率对气井产能影响程度差异较小;裂缝越长,裂缝非对称率越小,对气井产能影响程度越大。

关键词:低渗透气藏 不对称垂直裂缝 裂缝导流能力 裂缝非对称率 产能预测

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一般气井压裂后将在较深的地层中形成垂直裂缝,并改变地层的渗流条件[1],使得压裂前后产能预测模型不同。针对低渗透气藏垂直裂缝井产能评价方面的研究较多,汪永利等提出了多种气藏垂直裂缝井产能计算模型[2-12],这些模型的假设前提均为垂直裂缝是关于井筒对称的,然而由于受地层非均质性影响易形成不对称垂直裂缝。目前,关于不对称垂直裂缝井的研究较少,Cinco等研究了各种渗流模式下非对称率对压力动态的影响[13-14],曹宝军等推导了裂缝无限导流能力下,压裂裂缝不对称产能模型[15]。笔者根据前人的研究成果,基于稳定流理论,应用保角变换,推导了低渗透气藏有限导流不对称垂直裂缝井产能的预测模型,并在此基础上分析了产能的影响因素。

1　产能预测模型

不对称垂直裂缝井产能预测模型的基本假设包括:①压裂裂缝为垂直裂缝,沿井眼呈不对称分布;②裂缝导流能力有限;③气藏和裂缝中均为单相流,气藏中气体流动符合达西渗流定律,裂缝中气体流动符合高速非达西渗流;④不考虑地层流体的垂向流动及裂缝附近的污染,且气藏上下封闭。

利用保角变换,将 z 平面的流动区域映射为 w 平面宽为 π 的矩形区域(图1),z 平面中线段 AB 表示裂缝,点 o 表示井筒,垂直裂缝沿井筒呈不对称分布。保角变换后 z 平面中裂缝 AB 将映射为 w 平面的 $A'B'$,z 平面中的井筒点 o 映射为 w 平面的点 H。此时,在 z 平面内垂直压裂井的复杂渗流将转化为在 w 平面的单向渗流(图1)。在 w 平面上的渗流阻力可认为由基质单向渗流阻力(外阻)和裂缝渗流阻力(内阻)2部分组成。保角变换公式[2-4,10,12]为

$$z-\frac{L_l-L_s}{2}=\frac{L_l+L_s}{2}\times\frac{e^{w}+e^{-w}}{2} \tag{1}$$

式中:z 为 z 平面上的复变函数,m;L_l 和 L_s 分别为 z 平面井筒两端的长、短裂缝的长度,m;w 为 w 平面上的复变函数,m。

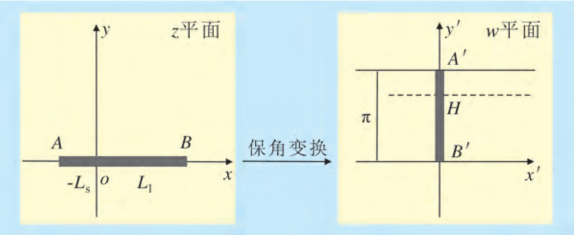

图1　不对称垂直裂缝井保角变换示意

当裂缝导流能力无限时,可认为 w 平面上基质渗流为单向流,结合达西定律,可得低渗透气藏不对称垂直裂缝井的产能为

$$Q_{sc}=\frac{\pi K_i h Z_{sc} T_{sc}\left[m\left(p_e\right)-m\left(p_{wf}\right)\right]}{T p_{sc}\ln\frac{4r_e}{L_l+L_s}} \tag{2}$$

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其中

$$m(p)=\int\frac{2p}{\mu Z}\mathrm{d}p \tag{3}$$

式中：Q_{sc} 为标准状态下的气井压裂后产能，$\mathrm{m^3/d}$；K_{i} 为气藏基质渗透率，$10^{-3}\ \mu\mathrm{m}^2$；h 为气藏的厚度，m；Z_{sc} 为标准状态下压缩因子；T_{sc} 为标准状态下温度，K；m 为拟压力函数，$\mathrm{MPa^2/(mPa\cdot s)}$；$p_{\mathrm{e}}$ 为供给压力，MPa；p_{wf} 为井底流压，MPa；T 为气藏温度，K；p_{sc} 为标准状态下压力，MPa；r_{e} 为泄气半径，m；p 为压力，MPa；μ 为压力 p 时气体的粘度，mPa·s；Z 为压力 p 时的压缩因子。

当裂缝导流能力有限时，在 w 平面上的渗流包括基质渗流和裂缝渗流，基质流向裂缝渗流时，可认为裂缝的导流能力是无限的。取 w 平面裂缝中微元体，由质量守恒定律知，流出单元体的质量与流进单元体的质量相等（不考虑流体压缩性），即

$$-\frac{\partial(\rho_{\mathrm{g}}v)}{\partial y'}\times\frac{1}{2}W_{\mathrm{f}}=\rho_{\mathrm{g}}v_{\mathrm{r}} \tag{4}$$

其中

$$\rho_{\mathrm{g}}=\frac{M_{\mathrm{air}}\gamma_{\mathrm{g}}p}{ZRT} \tag{5}$$

$$v=\delta\frac{K_{\mathrm{f}}}{\mu}\times\frac{\mathrm{d}p}{\mathrm{d}y'} \tag{6}$$

$$v_{\mathrm{r}}=\frac{K_{\mathrm{i}}\left[m(p_{\mathrm{e}})-m(p)\right]}{\mu\ln\dfrac{4r_{\mathrm{e}}}{L_{\mathrm{l}}+L_{\mathrm{s}}}} \tag{7}$$

式中：ρ_{g} 为地层气体密度，$\mathrm{kg/m^3}$；v 为裂缝的渗流速度，m/s；y' 为裂缝在 y' 方向上的长度，m；W_{f} 为裂缝宽度，m；v_{r} 为气藏基质流向裂缝的渗流速度，m/s；M_{air} 为空气相对分子质量；γ_{g} 为气体相对密度；R 为气体常数；δ 为非达西流的修正系数；K_{f} 为裂缝渗透率，$10^{-3}\ \mu\mathrm{m}^2$。

由式（4）—式（7）可得

$$\frac{\mathrm{d}^2m(p)}{\mathrm{d}y'^2}-\frac{2K_{\mathrm{i}}}{\delta W_{\mathrm{f}}K_{\mathrm{f}}}\times\frac{1}{\ln\dfrac{4r_{\mathrm{e}}}{L_{\mathrm{l}}+L_{\mathrm{s}}}}m(p)=-\frac{2K_{\mathrm{i}}}{\delta W_{\mathrm{f}}K_{\mathrm{f}}}\times\frac{1}{\ln\dfrac{4r_{\mathrm{e}}}{L_{\mathrm{l}}+L_{\mathrm{s}}}}m(p_{\mathrm{e}}) \tag{8}$$

式（8）即为二阶常系数非齐次线性微分方程，可对其进行求解。在 w 平面 y' 轴上，当 $0\leqslant y'\leqslant H$ 时，边界条件为：当 $y'=0$ 时，$\dfrac{\mathrm{d}m(p)}{\mathrm{d}y'}=0$；当 $y'=\arccos\dfrac{L_{\mathrm{s}}-L_{\mathrm{l}}}{L_{\mathrm{l}}+L_{\mathrm{s}}}$ 时，$m(p)=m(p_{\mathrm{wf}})$。该边界条件与式（8）可构成定解，求解可得

$$m(p)=m(p_{\mathrm{e}})-\frac{m(p_{\mathrm{e}})-m(p_{\mathrm{wf}})}{\mathrm{e}^{nH}+\mathrm{e}^{-nH}}\left(\mathrm{e}^{ny'}+\mathrm{e}^{-ny'}\right) \tag{9}$$

其中

$$n=\sqrt{\frac{2K}{\delta W_{\mathrm{f}}K_{\mathrm{f}}\ln\dfrac{4r_{\mathrm{e}}}{L_{\mathrm{l}}+L_{\mathrm{s}}}}} \tag{10}$$

$$H=\arccos\frac{L_{\mathrm{s}}-L_{\mathrm{l}}}{L_{\mathrm{l}}+L_{\mathrm{s}}} \tag{11}$$

在 w 平面 y' 轴上，当 $H\leqslant y'\leqslant\pi$ 时，边界条件为：当 $y'=\pi$ 时，$\dfrac{\mathrm{d}m(p)}{\mathrm{d}y'}=0$；当 $y'=\arccos\dfrac{L_{\mathrm{s}}-L_{\mathrm{l}}}{L_{\mathrm{l}}+L_{\mathrm{s}}}$ 时，$m(p)=m(p_{\mathrm{wf}})$。该边界条件与式（8）可构成定解，求解可得

$$m(p)=m(p_{\mathrm{e}})-\frac{m(p_{\mathrm{e}})-m(p_{\mathrm{wf}})}{\mathrm{e}^{nH}+\mathrm{e}^{n(2\pi-H)}}\left(\mathrm{e}^{ny'}+\mathrm{e}^{n(2\pi-y')}\right) \tag{12}$$

根据达西定律，由式（9）和式（12）可得低渗透气藏有限导流时不对称垂直裂缝井产能的计算式为

$$Q_{\mathrm{sc}}=\frac{\delta K_{\mathrm{f}}W_{\mathrm{f}}hZ_{\mathrm{sc}}T_{\mathrm{sc}}}{2p_{\mathrm{sc}}T}\times\left\{\frac{\left[m(p_{\mathrm{e}})-m(p_{\mathrm{wf}})\right]m}{\mathrm{e}^{nH}+\mathrm{e}^{-nH}}\left(\mathrm{e}^{nH}-\mathrm{e}^{-nH}\right)+\frac{\left[m(p_{\mathrm{e}})-m(p_{\mathrm{wf}})\right]m}{\mathrm{e}^{nH}+\mathrm{e}^{n(2\pi-H)}}\left(\mathrm{e}^{nH}-\mathrm{e}^{n(2\pi-H)}\right)\right\} \tag{13}$$

其中

$$\delta=\left(1+\frac{\beta_{\mathrm{g}}\rho_{\mathrm{g}}K_{\mathrm{f}}v}{\mu}\right)^{-1}=\left(1+\frac{\beta_{\mathrm{g}}M_{\mathrm{air}}\gamma_{\mathrm{g}}P_{\mathrm{sc}}K_{\mathrm{f}}Q_{\mathrm{sc}}}{2T_{\mathrm{sc}}R\mu W_{\mathrm{f}}h}\right)^{-1} \tag{14}$$

式中：β_{g} 为气体紊流系数，$\mathrm{m^{-1}}$，其计算方法参考文献[16]。

可利用牛顿迭代法对式（13）进行求解。在求解中压缩因子的计算采用D-A-K方法[17]，天然气粘度的计算采用Lee关系式[18]，拟压力函数计算式为

$$m(p)=\sum_{i=1}^{n}\left(\frac{p_i}{\mu_iZ_i}+\frac{p_{i-1}}{\mu_{i-1}Z_{i-1}}\right)\times(p_i-p_{i-1}) \tag{15}$$

式中：n 为积分区间（0，p）分成的区间段数；i 为积分区间（0，p）的任意小段；p_i 为第 i 小段的压力，MPa；μ_i 为第 i 小段的气体粘度；Z_i 为第 i 小段的气体压缩因子。

为了便于分析裂缝不对称对垂直裂缝井产能影响程度，引入裂缝非对称率来度量裂缝的不对称性，其计算式为

$$\alpha=\frac{L_{\mathrm{s}}}{L_{\mathrm{l}}} \tag{16}$$

式中：α 为裂缝非对称率。

为了定量描述裂缝非对称率对垂直裂缝井产能影响程度，引入产能影响程度，其计算式为

$$\varepsilon = \frac{Q_{\rm sym} - Q_{\rm asym}}{Q_{\rm sym}} \times 100\% \tag{17}$$

式中：ε 为产能影响程度，%；$Q_{\rm sym}$ 为对称垂直裂缝井产能，$\rm m^3/d$；$Q_{\rm asym}$ 为不对称垂直裂缝井产能，$\rm m^3/d$。

2 影响因素敏感性分析

以某气藏为例，对影响因素敏感性进行分析，其相关参数包括：原始气藏压力为30 MPa，厚度为6.5 m，供给半径为800 m，井径为0.1 m，气藏渗透率为3.6×10^{-3} μm²，气体相对密度为0.65，裂缝非对称率为0.4，裂缝长度为400 m，裂缝渗透率为2 μm²，缝宽为0.005 m。

2.1 裂缝非对称率

由裂缝非对称率对气井IPR曲线的影响（图2）可知，裂缝非对称率对不对称垂直裂缝井产能影响较小。当裂缝非对称率为0.8，0.6和0.4时，对应的无阻流量比对称垂直裂缝井的无阻流量分别降低了0.033%，0.196%，0.621%。

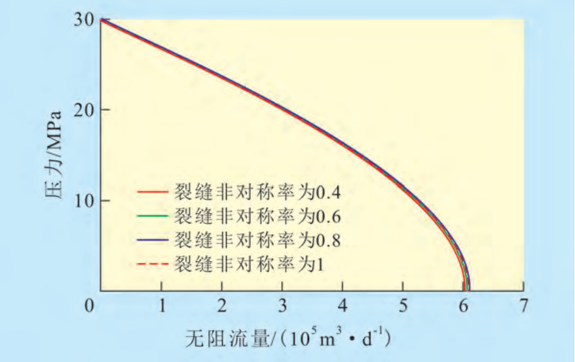

图2 裂缝非对称率对气井IPR曲线的影响

由不同裂缝非对称率下裂缝导流能力与气井产能影响程度的关系（图3）可知，裂缝非对称率对气井产能影响程度随着导流能力增大而逐渐减弱；当裂缝导流能力较小时，裂缝非对称率越小，其对气井产能影响程度越大，随着裂缝导流能力的增大，其对气井产能影响程度呈下降趋势，裂缝非对称率越小，气井产能影响程度下降幅度越大，当裂缝导流能力增加到一定值后，不同裂缝非对称率对气井产能影响程度的差异较小。说明当裂缝导流能力较小时，裂缝非对称率对气井产能影响程度差异较大；当裂缝导流能力较大时，裂缝非对称率对气井产能影响程度差异较小。

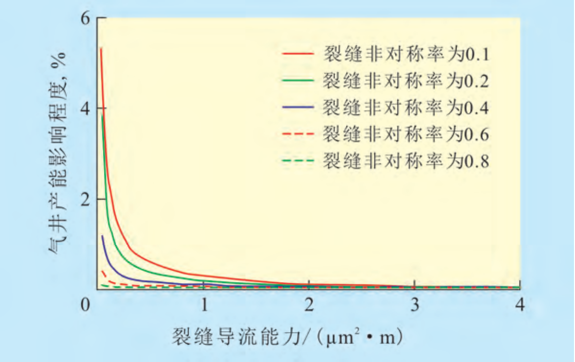

图3 不同裂缝非对称率下裂缝导流能力与气井产能影响程度的关系

2.2 裂缝长度

由不同裂缝长度下裂缝导流能力与气井产能影响程度的关系（图4）可知，不同裂缝长度对气井产能影响程度随着裂缝导流能力增大逐渐减弱；当裂缝导流能力较小时，裂缝长度越大，对气井产能影响程度越大，随着裂缝导流能力的增大，对气井产能影响程度呈下降趋势，裂缝长度越大，气井产能影响程度下降幅度越大，当裂缝导流能力增加到一定值后，不同裂缝长度对气井产能影响程度的差异较小。当裂缝导流能力较小时，不同裂缝长度对气井产能影响程度差异较大，当裂缝导流能力较大时，不同裂缝长度对气井产能影响程度差异较小。

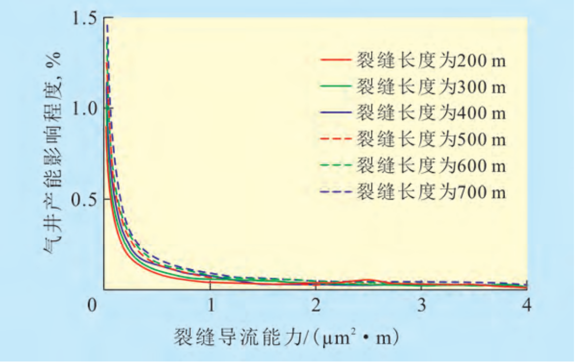

图4 不同裂缝长度下裂缝导流能力与气井产能影响程度的关系

由不同裂缝长度下裂缝非对称率与气井产能影响程度的关系（图5）可以看出，在相同裂缝长度下，气井产能影响程度随裂缝非对称率的增大而减小，即裂缝非对称率越小，产能影响程度越大；在相同裂缝非对称率下，裂缝长度越大，裂缝非对称率对气井产能影响程度越大。说明裂缝长度越大，裂缝非对称率越小，裂缝非对称率对气井产能影响程度越大。

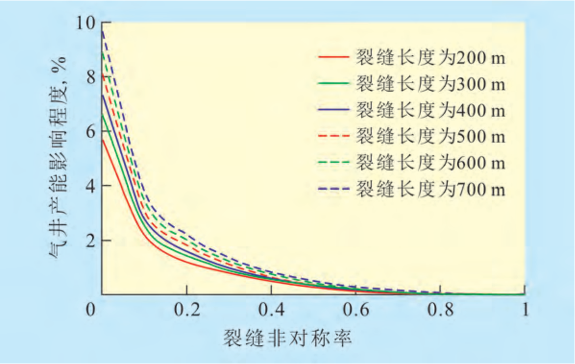

图5 不同裂缝长度下裂缝非对称率与气井产能影响程度的关系

3 结论

利用保角变换方法,基于稳定流理论,推导出气井压裂后产生不对称垂直裂缝条件下的低渗透气藏有限导流产能的预测模型。在相同井底流压下,裂缝非对称率对不对称垂直裂缝井产能影响较小;当裂缝导流能力较小时,不同裂缝长度或裂缝非对称率对气井产能影响程度差异较大,当裂缝导流能力较大时,不同裂缝长度或裂缝非对称率对气井产能影响程度差异较小。裂缝越长,裂缝非对称率越小,对气井产能影响程度越大。

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Xiong Jian, Liu Haishang, Zhao Changhong et al. Study on productivity of asymmetrical vertical fracture well in low-permeability gas reservoirs. *PGRE*, 2013, 20(6): 76-79

Abstract: In view of the asymmetrical vertical fracture in the low permeability reservoir after fracturing development, and based on the steady seepage theory, and by means of the conformal transformation method, a prediction model for the finite-conductivity asymmetrical vertical fracture wells is established in the low-permeability gas reservoirs, and the various factors on the gas well productivity are analyzed. The result shows that, under the same bottom-hole pressure, the fracture asymmetry factor has little effect on the productivity of the gas well with asymmetrical vertical fracture. When the fracture conductivity capacity is small, there is great difference in the productivity of the fracture gas well with respect to fracture length or fracture asymmetry factor. And, when the fracture conductivity capacity is high, there is little difference in productivity with respect to variable fracture length or fracture asymmetry factor in gas well. The longer the fracture length, the less the fracture asymmetrical factor, and the greater influence on the fractured gas well productivity.

Key words: low-permeability gas reservoirs; asymmetrical vertical fracture; fracture conductivity capacity; fracture asymmetry factor; productivity forecast

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Li Aifen, Li Huihui, Lv Jiao et al. Experimental study of foam on gas-liquid relative permeability at different temperature. *PGRE*, 2013, 20(6): 80-82

Abstract: There are many researches about the influence of the foam on gas-liquid relative permeability, but the influence of the temperature on foam relative permeability curve needs to be further studied. The curve reflecting the relationship between foam block pressure and gas-liquid flow rate ratio is measured at different temperature in this paper. So, the impact of the gas-liquid flow ratio and temperature on the block pressure is analyzed. The gas-liquid relative permeability curves both with the and without effects of foam are measured by using steady-state method in this paper. On this base, the flow rules of foam at different temperature are also characterized. The results indicate that the higher the experimental temperature, the better the sealing performance. And, both the foam block pressure and the blocking performance of foam can attain the highest degree in the range of gas-liquid flow ratio between 2 and 4. The foam has no effect on the relationship between the liquid relative permeability and the water saturation. The gas relative permeability, however, has a sharp decline under the action of foam. With the experimental temperature, the critical water saturation became higher with the increase of temperature and the moderate values of the gas relative permeability became lower with the increase of temperature.

Key words: temperature; foam; block pressure of foam; steady-state method; gas-liquid relative permeability; critical water saturation

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Yang Hongbin, Pu Chunsheng, Li Miao et al. Laboratory evaluation and field application on profile control of self-adaptive weak gel. *PGRE*, 2013, 20(6): 83-86

Abstract: In response to the problems of fully developed micro-fractures in low permeability oil fields, severely heterogeneous reservoir and the fact that traditional profile control are less effective, the self-adaptive weak gel is developed. The static performance, sealing characteristics and displacement efficiency are evaluated through lab tests. The results show that the self-adaptive weak gel has good temperature-resistant and salt-resistant properties. When the salinity of formation water is 41 811.5 mg/L, the weak gel system can gelatinize rapidly in 38 hours, and the gel strength is 28 549 mPa·s under the condition of 70 ℃. Its plugging ratio is 84.08% and the recovery ratio reaches 12.1%. The field experiments of the well S in Ganguyi oilfeild indicate that the preferred path of water breakthrough of water injection well is controlled after profile control and flooding, and the injection pressure rises, at the same time, the water content of well group fell to 69.16% from 78.51%, and daily fluid production rate increases by 135.14%, while the daily oil production rate increases by 237.5%. The deep profile control technology of self-adaptive weak gel has good adaptability in fractured low permeability oil fields. It can enlarge the sweep volume of injected water and enhance oil recovery factor greatly, so it can provide reference for other similar reservoirs to obtain good performance on water control and oil increment.

Key words: self-adaptive weak gel; profile control; gelation intensity; plugging; micro fractures; Ganguyi oilfield

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Yuan Lin, Li Xiaoping, Sun Fei et al. Deduction of productivity formula for horizontal well with displacement method between two similar flow. *PGRE*, 2013, 20(6): 87-90

Abstract: As the technology of horizontal well had been widely used in the gas and oil fields, the productivity forecast of horizontal wells will be of great importance. Based on the ellipse constant pressure surfaces near the wellbore, the author divides the seepage prob-