石油与天然气地质
第34卷 第1期 OIL & GAS GEOLOGY 2013年2月

文章编号:0253-9985(2013)01-0124-05

考虑应力敏感性的低渗透油藏油井产能分析

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摘要:低渗透油藏的单井产能主要受储层应力敏感性的影响。油藏流体采出后,地层压力下降,有效应力增加,孔隙度和渗透率均降低,导致油井产能下降。笔者在只考虑基于渗透率降低对低渗透油井产能方程影响的基础上,考虑了孔隙度随应力变化对油井产能的影响,建立了同时考虑渗透率和孔隙度的产能应力敏感性方程,并提出了产能-应力敏感性指数的概念。随着低渗透储层应力敏感性的增强,应力敏感性常数增大,产能-应力敏感性指数同时增大,油井的日产油量迅速降低。新的产能-应力敏感性方程使低渗透油藏油井产能计算结果更加简化和准确。通过实例验证与分析,产能-应力敏感性指数对低渗透油藏单井产能有较强的影响,随着产能应力敏感性指数的增加,油井的无阻流量下降速度降低。与只考虑渗透率降低的油井产能方程相比,新方程更能反映低渗透油藏的实际生产情况,对合理开发低渗透油藏具有一定的指导意义。

关键词:应力敏感性;产能;孔隙度;渗透率;低渗透油藏

中图分类号:TE312 **文献标识码**:A

Analysis on oil well productivity of low-permeability reservoirs with stress-sensitivity being taken into considerations

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Abstract: Stress-sensitivity is one of the main factors that affect single well productivity in low-permeability reservoirs. It is common sense that wells tend to produce less after certain volumes of reservoir fluids were recovered as that would cause drop-down in formation pressure, porosity and permeability and increase of effective stress. The authors modified the previous productivity function of low-permeability oil wells that only considers the influences of permeability decrease by incorporating the influences of stress on porosity, established a new stress-sensitive productivity function with both porosity and permeability being taken into consideration, and proposed the concept of productivity-stress-sensitivity index. Along with the intensifying of stress-sensitivity of low-permeability reservoirs and increase of stress-sensitivity constant, the productivity-stress-sensitivity index also enlarges, and daily oil production quickly shrinks. The new function simplifies the calculation process and improves the accuracy. Practices show that the productivity-stress-sensitivity index exerts a strong influence upon the productivity of wells in low-permeability reservoirs. As the index increases, the decreasing of open flow capacity of oil wells slows down. Compared with the old function, the new one reflects better the actual production of low-permeability reservoirs and therefore could be used to guide their development.

Key words: stress sensitivity, productivity, porosity, permeability, low-permeability reservoir

随着油田勘探开发的深入,低渗透油藏的研究日益受到人们的重视。由于低渗透油藏的低

收稿日期:2012-09-24;**修订日期**:2012-12-26。
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基金项目:国家科技重大专项(2011ZX050102003)。

孔、低渗、非均质性等特征,低渗透油藏的开发中出现了许多不同于中高渗透油藏的特征。

应力敏感是低渗透油藏的显著特征之一,随着油藏开发的进行,流体压力降低,有效应力增加。众多学者[1-16]研究了应力敏感对孔隙度、渗透率的影响,得到大致相同的结论:随着有效应力的增加,孔隙度、渗透率均有不同程度的降低。雷群、王恒贵等学者[17-21]建立了低渗透油藏油井产能的公式,但该公式只考虑了渗透率对产能的影响,没有考虑孔隙度对油井产能的影响。在实际的油藏开发中,不仅应力敏感性常数影响岩石的内应力敏感程度,岩石孔隙度也对岩石的内应力敏感程度产生重要的影响。因此,笔者在前人研究的基础上,建立了同时考虑应力敏感性对孔隙度、渗透率影响的低渗透油井产能方程,使低渗透油藏油井的产能计算结果更加准确。

1　应力敏感现象

所谓应力敏感现象,是指油气藏岩石的渗透率、孔隙度等物性参数随应力条件而变化的性质。通常情况下,油气藏的外应力为一常数,当流体从油气藏岩石的孔隙中采出时,孔隙压力从原始地层压力 p_i 下降到 p,岩石因而被压缩,岩石的相关物性参数也跟着发生变化(图 1)。

2　孔隙度应力敏感状态方程

由于岩石的压缩性,当压力变化时,岩石的固体骨架体积会压缩,同时岩石孔隙体积也发生变化,因而可以把岩石的压缩性看成孔隙度随压力发生变化。岩石压缩性用压缩系数表示[22],即:

$$C_\Phi = \frac{1}{V_\Phi}\frac{\mathrm{d}V_\Phi}{\mathrm{d}p} \tag{1}$$

$$\frac{\mathrm{d}V_\Phi}{V_\Phi} = \frac{\mathrm{d}\Phi}{\Phi} \tag{2}$$

$$C_\Phi = \frac{1}{\Phi}\frac{\mathrm{d}\Phi}{\mathrm{d}p} \tag{3}$$

对(3)式分离变量,并在 $p = p_0$, $\Phi = \Phi_0$ 条件下积分,得孔隙度随压力发生变化的方程:

$$\Phi = \Phi_0 \mathrm{e}^{C_\Phi (p - p_0)} \tag{4}$$

式中:Φ 为压力 p 下岩石的孔隙度,%;Φ_0 为大气压下岩石的孔隙度,%;C_Φ 为岩石压缩系数,MPa^{-1};p_0 为大气压力,MPa。

将(4)式按麦克劳林级数展开,只取其前两项已具有足够的精确性,则考虑应力变化的孔隙度变化方程为:

$$\Phi = \Phi_0 [1 + C_\Phi (p - p_0)] \tag{5}$$

3　渗透率应力敏感状态方程

储集层岩石的渗透率随着应力条件(σ,p)的变化而变化,因此,渗透率可以表示成下面的函数关系[23](图 2):

$$K = f(\sigma, p) \tag{6}$$

计算得到任意地层压力 p 下的储集层渗透率为:

$$K = K_0 \mathrm{e}^{-b\Phi(p_0 - p)} \tag{7}$$

式中:K. 压力为 p 时的岩石渗透率,$10^{-3}\ \mu\mathrm{m}^2$;K_0 为压力为 p_0 时的岩石渗透率,$10^{-3}\ \mu\mathrm{m}^2$;b 为应力敏感性常数。

将(5)式带入(7)式,渗透率、孔隙度和有效应力之间的关系为:

$$K = K_0 \mathrm{e}^{-b\Phi_0[1 + C_\Phi(p - p_0)](p_0 - p)} \tag{8}$$

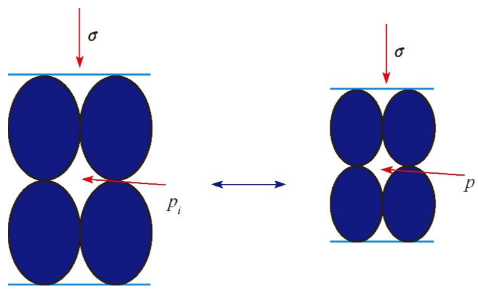

图 1　油藏岩石应力敏感示意图

Fig. 1　Stress-sensitivity of reservoir rocks

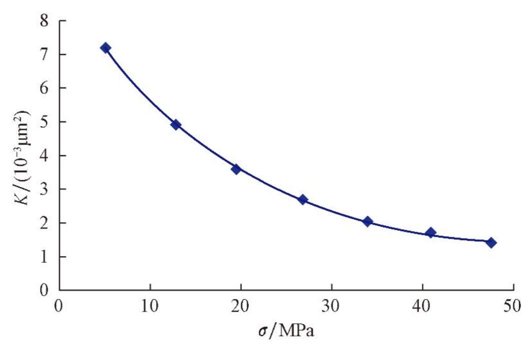

图 2　岩石应力敏感性测试曲线

Fig. 2　Curve of the rock stress-sensitivity test

4 油井产能方程

油井平面径向稳定渗流任一圆环微元体的 Darcy 公式可以写成：

$$q = \frac{2\pi rhK}{\mu}\frac{\mathrm{d}p}{\mathrm{d}r} \tag{9}$$

式中：q 为油井产量，m^3/d；h 为油层厚度，m；μ 为流体的粘度，mPa·s；r 为半径，m。

若考虑应力敏感导致的渗透率变化对油井产能的影响，需把式(8)代入式(9)，得：

$$q = \frac{2\pi rh}{\mu}K_0 e^{-b\Phi_0[1+C_\Phi(p-p_0)](p_0-p)}\frac{\mathrm{d}p}{\mathrm{d}r} \tag{10}$$

对式 (10) 沿径向距离积分：

$$\int_{r_w}^{r_e}\frac{q\mu}{2\pi rh}\mathrm{d}r = \int_{p_{wf}}^{p_e}K_0 e^{-b\Phi_0[1+C_\Phi(p-p_0)](p-p_0)}\mathrm{d}p \tag{11}$$

式中：p_e 为供给压力，MPa；p_{wf} 为井底流压，MPa；r_e 为供给半径，m；r_w 为油井半径，m。

积分后得油井的产量公式：

$$\frac{qu}{2\pi h}\ln\frac{r_e}{r_w} = \frac{\sqrt{\pi}k_0 e^{-\frac{b\Phi_0}{4C_\Phi}}\left[\operatorname{erf}\left(-\frac{b\Phi_0(2C_\Phi p_{wf}+1-2C_\Phi p_0)}{2\sqrt{b\Phi_0 C_\Phi}}\right)-\operatorname{erf}\left(1-\frac{b\Phi_0(2C_\Phi p_e+1-2C_\Phi p_0)}{2\sqrt{b\Phi_0 C_\Phi}}\right)\right]}{2\sqrt{b\Phi_0 C_\Phi}} \tag{12}$$

根据误差函数[24]：

$$\operatorname{erf}(y) = \frac{2}{\sqrt{\pi}}\left(y-\frac{y^3}{1!3}+\frac{y^5}{2!5}-\frac{y^7}{3!7}+\cdots\right) \tag{13}$$

将式(12)中 $\operatorname{erf}\left(-\frac{b\Phi_0(2C_\Phi p_{wf}+1-2C_\Phi p_0)}{2\sqrt{b\Phi_0 C_\Phi}}\right)-\operatorname{erf}\left(-\frac{b\Phi_0(2C_\Phi p_e+1-2C_\Phi p_0)}{2\sqrt{b\Phi_0 C_\Phi}}\right)$ 展开，只取其第一项已具有足够的精确性，则得：

$$\operatorname{erf}\left(-\frac{b\Phi_0(2C_\Phi p_{wf}+1-2C_\Phi p_0)}{2\sqrt{b\Phi_0 C_\Phi}}\right)-\operatorname{erf}\left(-\frac{b\Phi_0(2C_\Phi p_e+1-2C_\Phi p_0)}{2\sqrt{b\Phi_0 C_\Phi}}\right) = \frac{2b\Phi_0 C_\Phi(p_e-p_{wf})}{\sqrt{\pi b\Phi_0 C_\Phi}} \tag{14}$$

将式(14)带入式(12)，得到同时考虑应力敏感效应对孔隙度和渗透率影响的油井产能方程：

$$q = \frac{2\pi K_0 h}{\mu\ln\frac{r_e}{r_w}}(p_e-p_{wf})e^{-\frac{b\Phi_0}{4C_\Phi}} \tag{15}$$

令 $\beta = e^{\frac{b\Phi_0}{4C_\Phi}}$ 为产能-应力敏感指数，则采油指数 $J = \frac{1}{\beta}\frac{2\pi K_0 h}{\mu\ln\frac{r_e}{r_w}}$，油井产能方程可以简写为：

$$q = \frac{1}{\beta}\frac{2\pi K_0 h}{\mu\ln\frac{r_e}{r_w}}(p_e-p_{wf}) = J(p_e-p_{wf}) \tag{16}$$

5 实例分析

以长庆某低渗透油藏为例，研究应力敏感对油井产能的影响，地层流体物性参数如下：$K_0=1\times10^{-3}\ \mu m^2$，$h=9$ m，$\mu=1.41$ mPa·s，$p_e=36$ MPa，$C_\Phi=1.4\times10^{-4}\ MPa^{-1}$，$\Phi_0=5\%$，$r_e=1\ 000$ m，$r_w=0.1$ m。井底流压分别取 0，4，8，12，16，20，24，32 MPa，计算油井产能的物理参数如表 1 所示，在不同的产能-应力敏感指数下，应用公式(16)计算的油井产量随井底流压的变化如图 2 所示。

从图中可以看到：1)低渗透油藏存在强应力敏感性，当产能-应力敏感指数从 1(不存在应力敏感)变为 1.563，井底流压为 0 时，油井的无阻流量从 13.54 m^3/d 降到 8.67 m^3/d，下降速度为 36.02%。2)当产能-应力敏感指数为定值时，井底流压与油井产量成线性关系。随着产能-应力敏感指数的增大，油井产量降低的速度越来越低；

表 1 油井产能参数

Table 1 Oil well productivity parameters

应力敏感常数	产能-应力敏感指数	采油指数/($m^3\cdot d^{-1}\cdot MPa^{-1}$)
0.000	1.000	0.376
0.005	1.563	0.241
0.007	1.868	0.201
0.009	2.234	0.168
0.011	2.670	0.141
0.013	3.192	0.118
0.015	3.816	0.099
0.017	4.562	0.082
0.019	5.454	0.069
0.021	6.521	0.058

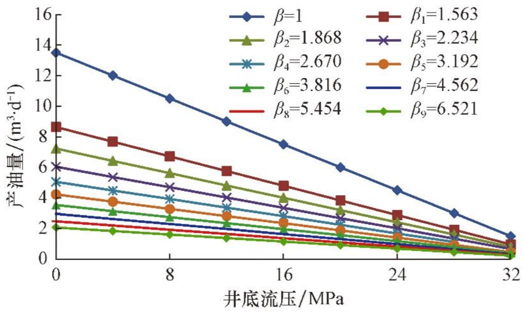

图3　不同应力敏感条件下油井产量曲线

Fig. 3　Oil production curves under different stress-sensitivity conditions

当产能-应力敏感指数从3.192到3.816时,油井的无阻流量下降速度为16.35%。在同一井底流压下,产能-应力敏感指数越大,油井产量越低,说明低渗透油藏单井产能主要受强应力敏感的影响。

只考虑应力敏感对渗透率影响的单井产量计算公式为[17]:

$$q = \frac{2\pi K_0 h}{\mu \ln \frac{r_e}{r_w}}(p_e - p_{wf})e^{-b(p_e - p_{wf})} \qquad (17)$$

将(15)式和(17)式进行对比,可以看出,当应力敏感指数为0(不存在应力敏感)时,两种方法计算的结果相同。以应力敏感指数0.013为例,将新公式与只考虑应力敏感对渗透率影响计算的单井日产油量作比较,两种方法计算的日产油量有较大的差距,只考虑渗透率影响的产能公式过高的估计了油井产能,当井底流压为零时,两者之间的相对误差达49.98%。因此,当低渗透油藏存在强应力敏感时,应同时考虑渗透率和孔隙度对单井日产油量的影响。

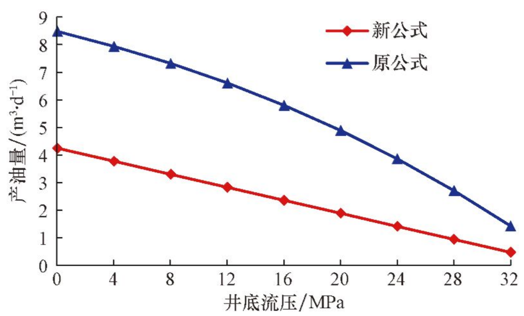

图4　新公式与原公式计算的日产油量对比

Fig. 4　Comparison of daily oil production calculated with the old and the new equations

6　结论

1)建立了同时考虑渗透率和孔隙度影响的低渗透油藏油井产能方程,使低渗透油藏的产能计算结果更加准确;提出了产能-应力敏感指数的概念,更加全面和准确的描述了应力敏感性对油井产能的影响。

2)低渗透油藏存在强的应力敏感性,随着产能-应力敏感指数的增加,油井产量迅速降低,但降低的速度越来越小;当产能-应力敏感指数从1到1.563时,油井的无阻流量下降速度为36.02%,当敏感指数从3.192到3.816时,无阻流量下降速度则为16.35%。

3)只考虑渗透率影响的产能方程高估了油井的产能,油井的无阻流量误差达49.98%。新的产能-应力敏感指数方程能更加准确的描述应力敏感性对低渗透油井产能的影响。

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(编辑 董 立)