双重孔隙压敏介质油藏不稳态产能变化研究*

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摘要　建立由基岩系统和裂缝系统组成，并考虑裂缝渗透率随压降的增加呈指数减小的双重孔隙压敏介质油藏不稳态产能模型，采用隐式差分格式对考虑污染效应的情况进行求解。讨论了无因次渗透率模数和表皮系数、窜流系数、裂缝弹性储容比等对不稳态产能的影响。结果表明，无因次渗透率模数导致不稳态产能明显下降，但其对早期不稳态产能的影响不如表皮系数的影响显著，窜流系数决定着窜流出现的早晚；裂缝弹性储容比则影响着油藏早期不稳态产能的大小和窜流阶段出现的早晚。

关键词　双重孔隙　压敏　不稳态产能变化

前　言

所谓压敏介质[1]，指容易发生部分或者全部不可逆变形的介质，这种变形对介质的物性产生明显影响。

著名学者 Raghavan 和 Miller[2] 针对压敏介质提出了“拟压力”模型，并进行了数值求解；Samaniego[3,4,5] 等人采用数值方法研究压敏介质渗流问题；Pedrosa[6] 引入渗透率变异关系式，用小扰动方法求解压敏介质非线性渗流数学模型，给出了点源的一阶近似解，Kikani 和 Pedrosa[7] 用小扰动方法进一步给出了二阶近似解式；2000年，苏玉亮和栾志安[8] 等人也对变形介质油藏的开发特征进行了研究。但是，对压敏介质油藏的产能变化特征的研究甚少。

双重孔隙压敏介质产能模型

1．有关概念及其假设

为了能够更好的对这类油藏的生产和测试提供理论基础，提出了双重孔隙压敏介质模型的概念，在普通双重介质理想化假设[9] 的基础上，做如下两个额外假设：①地层岩石可压缩，并因此引起渗透率的变化；②油井以定井底压力生产。

为了描述裂缝渗透率随压力变化的规律和程度，定义一个裂缝渗透率变化模数，类似于压缩系数的定义，有

$$\gamma = \frac{1}{K_f}\frac{\partial K_f}{\partial p_f} \tag{1}$$

如果假设裂缝渗透率模数在生产过程中保持不变，则对(1)式进行积分，可以得到

$$K_f / K_{f0} = e^{-\gamma(p_i - p_f)} \tag{2}$$

2．数学模型的建立

根据连续性方程以及达西定律，双重孔隙压敏介质油藏的不稳态产能数学模型如下[10]，即

$$\begin{cases} \dfrac{1}{r_D}\dfrac{\partial}{\partial r_D}\left(r_D e^{-\gamma_D p_{Df}}\dfrac{\partial p_{Df}}{\partial r_D}\right) - \omega_m \dfrac{\partial p_{Dm}}{\partial t_D} = \omega_f \dfrac{\partial p_{Df}}{\partial t_D} \\ -\lambda_{mf}(p_{Dm} - p_{Df}) = \omega_m \dfrac{\partial p_{Dm}}{\partial t_D} \\ p_{Dj}(r_D, t_D)\big|_{t_D=0} = 0 \\ \qquad (j = m, f)\ 1 \leqslant r_D \leqslant +\infty \\ \left[p_{Df} - S e^{-\gamma_D p_{Df}}\dfrac{\partial p_{Df}}{\partial r_D}\right]_{r_D=1} = 1 \\ \lim\limits_{r_D\to\infty} p_{Df}(r_D, t_D) = 0 \end{cases} \tag{3}$$

可以得出压敏介质油藏无因次产量的表达式为

$$q_D = -e^{-r_D p_{Df}}\left.\frac{\partial p_{Df}}{\partial r_D}\right|_{r_D=1} \tag{4}$$

其中无因次参数定义如下：

$$r_D = \frac{r}{r_w},\ t_D = \frac{3.6K_0}{\mu r_w^2 \phi_t C_t}t,\ r_D = (p_i - p_{wf})\gamma$$

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$$p_{Dj}(r_D, t_D) = \frac{p_i - p(r,t)}{p_i - p_{wf}} \quad (j = m, f)$$

$$q_D = \frac{q\mu}{2\pi K_0 h(p_i - p_{wf})}$$

$$\omega_j = \frac{\phi_j C_j}{\phi_t C_t} \quad (j = m, f), \quad \lambda_{mf} = \frac{\alpha_{mf} K_m r_w^2}{k_{f0}}$$

式中：K_{f0}——裂缝初始渗透率，μm^2；

K——渗透率，μm^2；

p——地层瞬时压力（$=p(r,t)$），MPa；

ϕ——孔隙度，小数；

C——压缩系数，MPa^{-1}；

λ_{mf}——基岩和裂缝系统之间的窜流系数；

ω——弹性储容比，无因次；

μ——流体粘度，mPa·s；

r_w——井筒半径，m；

h——油层有效厚度，m；

q——地面流量，m^3/d；

p_i——原始地层压力，MPa；

γ_D——无因次渗透率变化模数；

S——表皮系数，无因次；

下标 m, f, t——基岩、裂缝和总系统。

压敏介质和一般应力不敏感介质的差别表现在数学模型上则是在数学模型(3)的第一个方程中，如果为压敏介质，第一项含有一个由于渗透率变化所引起的指数项，而应力不敏感介质则不存在。

3. 数学模型的求解

数学方程组(3)中的非线性扩散方程为典型的非线性抛物型方程[11]，采用全隐式的差分格式进行求解，结合(4)式，就可以对无因次产量进行求解。

参数敏感性分析

1. 无因次渗透率模数对不稳态产能的影响

由于渗透率模数影响着地层的渗透率，在生产过程中，由于地层压力的降低使得渗透率减小，从而在一定井底压力的情况下，无因次不稳态产能也就相应减小。由于是定井底压力，在生产的一开始就建立了一定的压差，所以使得在早期无因次不稳态产能就有一定的降低（见图1）。

2. 窜流系数对不稳态产能的影响

窜流系数的大小决定着窜流阶段出现的早晚，表现在无因次不稳态产能和时间的双对数曲线上则是平缓段出现的早晚。由于窜流的发生，基岩开始向裂缝窜流供液，这使得仅靠裂缝供液的无因次不稳态产能的减小趋势放缓。在窜流阶段结束之后，油藏进入总系统流的阶段，这时基岩和裂缝同时参与流动，其减小趋势较纯裂缝供液阶段有所放缓（见图2）。

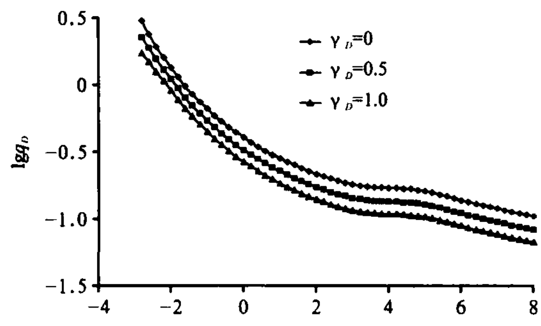

图1 不同无因次渗透率模数的不稳态产能曲线

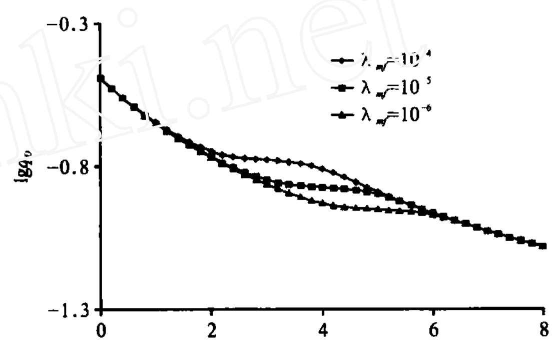

图2 不同窜流系数的无因次不稳态产能曲线

3. 介质弹性储容比对不稳态产能的影响

裂缝弹性储容比的大小表示了裂缝中的弹性储量占系统总弹性储量的比例。由于早期只有裂缝中流体流动，当裂缝的弹性储容比较小时，油井开始生产，其无因次不稳态产能也就会相应较低，减小的速度也较快，达到窜流的时间也就越短，但其窜流段的长度也就越长；否则相反（见图3）。

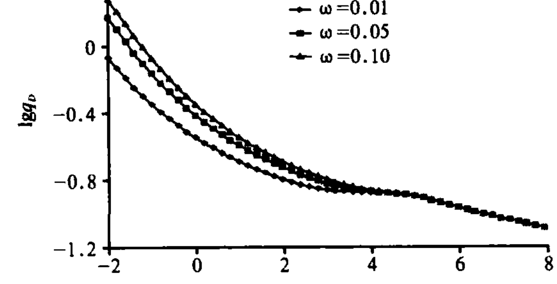

图3 不同裂缝弹性储容比的不稳态产能曲线

4.表皮系数对不稳态产能的影响

表皮系数是由于钻井、洗井等作业过程中的液体对油藏的污染,它对无因次不稳态产能的影响是全程的。如果有表皮系数存在,则会造成相应的附加压力降,也就使得在一定井底压力下的油井不稳态产能大幅度的降低(见图 4)。

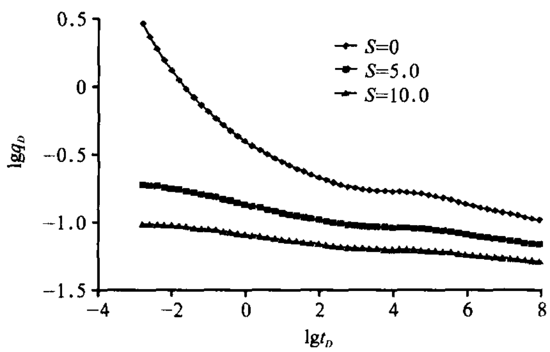

图4 不同表皮系数的不稳态产能曲线

5.表皮系数和无因次渗透率模数对不稳态产能影响的区别

正如前面所分析的那样,表皮系数对无因次不稳态产能影响是全程的,而无因次渗透率模数对不稳态产能的影响虽然也是全程的,但是其在早期和后期影响的幅度是不一样的。这是因为油井在继续生产的过程中,压力持续降低,由于渗透率模数的影响,渗透率也就持续降低,越到后期,渗透率模数的影响越严重(见图 5)。

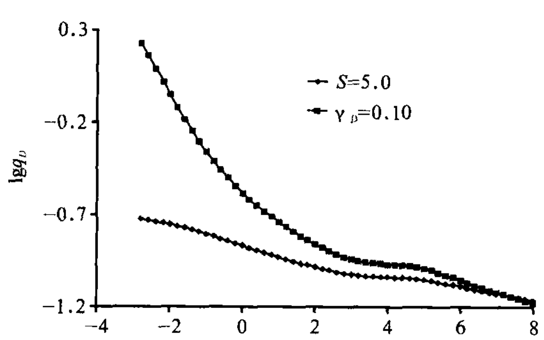

图5 γ_D和S对不稳态产能影响示意曲线

由图 5 可以看出,虽然二者最终的无因次不稳态产能相等,但在早期却有着相当大的差别。

结 论

1.无因次渗透率模数对不稳态产能有着很大影响。无因次渗透率模数增加,不稳态产能下降。

2.介质间的窜流系数影响着窜流阶段出现的早晚。窜流系数越大,窜流出现越早。

3.裂缝的弹性储容比决定着油藏早期不稳态产能的大小,以及介质间窜流阶段出现的时间和窜流阶段持续的时间。裂缝弹性储容比越小,油藏早期不稳态产能越小,窜流阶段出现的时间越早,同时窜流阶段持续的时间就越长。

4.表皮系数对不稳态产能有着很大影响。表皮系数越大,不稳态产能越低;另外,虽然无因次渗透率模数对不稳态产能也有影响,但其结果却不一样。表皮系数影响其全程,且对早期影响较大;而无因次渗透率模数虽然也影响着不稳态产能的全程,但其对早期影响较小,对后期影响较大。

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Abstracts

·Research of Theory & Method·

Study on Production Variation at Transient State in the Double Porosity and Stress-Sensitive Naturally Fractured Reservoir. 2006, 15(5): 1 ~ 3

Wang Zisheng, Yao Jun (University of Petroleum)

The production variation at transient state transient model in the double porosity and stress-sensitive naturally fractured reservoir consisting of matrix and fractures is presented considering permeability of fractures decreases exponentially which taking into account the effects of skin factor is calculated by using the fully-implicit finite-difference form. Effects of permeability modulus and skin factor, inter-porosity flow parameter and fracture storage ratio to output transient of the reservoir are discussed. The results indicate that permeability modulus causes the decrease of the output transient, but the effect is not so strong at early time; the inter-porosity flow parameter determines the time of it and the fracture storage ratio determines the output transient of the early time and the time when inter-porosity flow occurs.

Key words: dual porosity, stress-sensitive, output transient variation

Analysis and Cognition for Unsteady Property of Pressure in Horizontal Well with Bottom Water Boundary. 2006, 15(5): 4 ~ 6

Lv Hong (Engineering Design Research Institute, South-West Branch Company), Guo Qi, Zhang Haiyun (Engineering Tech Research Institute, North-West Branch Company)

According to three dimensions percolation property of horizontal well, for situation of bottom water reservoir, it is also supposed that tip is occluded by infiltrated layer and bottom is a constant pressure boundary, percolation in horizontal well behaves radial flow and constant flowing period at early time and for this, conventional testing analysis can be done. By sample of TKxxDH well and comparison and analysis for static pressure and pressure build-up data, the paper expatiates application of data for unsteady well testing which provides a referenced experience for selecting oil well model to this kind of reservoir and the fruit evaluation.

Key words: unsteady well testing, bottom water boundary, horizontal well

Actuality of Gas Condensate Well Deliverability Prediction. 2006, 15(5): 7 ~ 8, 11

Zhang Na, Duan Yonggang, Chen Wei, Li Shusong (South-West Petroleum Institute), Zhang Limu (Sichuan Petroleum Administrative Bureau)

Based on understanding the gas condensate reservoir characteristics and its seepage flow mechanism, the paper summarizes the harvests towards the gas condensate well deliverability prediction of overseas or inland experts having got so far, and also points out the defects and problems in this domain which shows clearly the development direction for the future.

Key words: gas condensate well, deliverability prediction

A Brief Analysis for Influence of Temperature Change on Transient Testing in Gas Well. 2006, 15(5): 9 ~ 11

Lei Ting, Li Zhiping (China Geo-Science University)

The change of wellbore temperature has obvious influences for gas properties. Using the analytic well bore temperature model presented by Hasan and Kabir, this paper calculates and contrastively analyzes BHP with and without temperature changing respectively and compared the two results. The conclusion is that ignoring the temperature changing in calculating BHP may introduce many errors. So, the temperature change should be considered when accounting BHP in gas well.

Key words: gas well, transient well testing, temperature changing

Application of Dimensionless IPR Curve for Production Potential Forecast in Horizontal Well. 2006, 15(5): 12 ~ 13

Zhu Jiang (Geology Research Institute, Sichuan Petroleum Administrative Bureau), Liu Qiguo (South-West Petroleum University)

A dimensionless inflow performance relationship (IPR) model that is used to predict the deliverability of a hydraulically fractured vertical gas well has been modified to predict the performance of horizontal gas wells. By comparing the IPR curve generated from a conventional modified isochronal analysis and that generated from the new model, the absolute open flow capacity was within 2.1% of each other, and the average error between the two curves was approximately 4%. The dimensionless IPR curve model appears to provide a cost-effective way of predicting horizontal gas well deliverability.

Key words: dimensionless IPR curve, horizontal gas well, prediction of deliverability

Well Testing Analysis Method for Thermal Recovery of Dense oil. 2006, 15(5): 14 ~ 16

Zhao Hong (Well Testing and Oil Extraction Branch Company, Daqing Oilfield Co., Ltd.)

By analyzing and studying on literature materials about well testing analysis method for thermal recovery of dense oil, five methods suggested by Satman based on the model of double district compound reservoir are summarized and typical well testing of pressure fall down is applied which gets a certain cognition.

Key words: dense oil, thermal recovery, well testing interpretation

·Evaluation & Application·

Application of Numerical Well Testing Analysis Method for Testing Data in Exploited Well Net. 2006, 15(5): 17 ~ 18

Shi Guixia (No.5 Oil Extraction Factory, Changqing Oifield Branch Company), Liu Yonghong (Well Testing Company, Huabei Oilfield)

According to feature of production and exploitation in Changqing Jiyuan oilfield, effect of formation and performance of adjacent well on testing data of produced well should be considered comprehensively when exploiting reservoirs fully. By well testing design, it is