天然裂缝性碳酸盐岩封闭油藏产量递减规律研究及应用

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摘要:建立了天然裂缝性碳酸盐岩封闭油藏渗流模型。考虑了封闭油藏定井底压力和变井底压力两种不同的内边界情形,并采用Laplace变换和Duhamel原理对数学模型进行了求解,得到了天然裂缝性碳酸盐岩封闭油藏的递减曲线,在曲线上产量出现两个明显的递减阶段和两个相对平缓的递减阶段,讨论了窜流系数和裂缝弹性储容比对天然裂缝性油藏递减曲线的影响。实例表明,实际产量资料与理论递减曲线的拟合可确定地层参数,预测产量变化。

关键词:天然裂缝性油藏;产量递减规律;碳酸盐岩;渗流模型
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引言

天然裂缝性油藏在我国油气资源中占有十分重要的地位,由于裂缝性油藏的复杂性,对该类油藏的产量进行预测难度较大。本文运用油气渗流力学理论,建立了能够描述天然裂缝性油藏产量变化的渗流数学模型,从理论上分析、阐述了天然裂缝性油藏的产量变化特点和规律,为制定天然裂缝性油藏的合理生产制度提供理论指导。

1 渗流物理模型

天然裂缝性碳酸盐岩封闭油藏是由基岩孔隙系统和裂缝系统组成的连续介质[1]。相对于裂缝系统而言基岩系统的导流能力很小,渗流物理模型中只考虑裂缝系统向井筒供液,基岩系统的作用只是向裂缝系统窜流[2]。为了建立物理模型须作如下假设:①地层流体和地层岩石为微可压缩,流体为单相流动,压缩系数为常数;②流体在基岩系统和裂缝系统中的渗流满足达西渗流方程;③地层中仅一口井,油井投产前地层中压力均匀分布;④忽略重力和毛管力的影响;⑤忽略基岩内部的流体流动,基岩作为供液源[3,4]。

2 渗流数学模型及其解

2.1 渗流数学模型

裂缝系统的渗流方程为

$$\frac{\partial^2 p_{fD}}{\partial {r_D}^2} + \frac{1}{r_D} \cdot \frac{\partial p_{fD}}{\partial r_D} = (1-\omega)\frac{\partial p_{mD}}{\partial t_D} + \omega \frac{\partial p_{fD}}{\partial t_D} \quad (1)$$

基岩系统向裂缝系统的窜流方程为

$$(1-\omega)\frac{\partial p_{mD}}{\partial t_D} = \lambda(p_{fD} - p_{mD}) \quad (2)$$

初始条件为

$$p_{fD}\big|_{t_D=0} = p_{mD}\big|_{t_D=0} = 0 \quad (3)$$

定井底压力下内边界条件为

$$p_{fD} - s\left(\frac{\partial p_{fD}}{\partial t_D}\right)_{r_D=1} = 1 \quad (4)$$

变井底压力下内边界条件为

$$p_{fD} - s\left(\frac{\partial p_{fD}}{\partial t_D}\right)_{r_D=1} = p_{wD}(t_D) \quad (5)$$

封闭油藏的无因次外边界条件为

$$\left.\frac{\partial p_{fD}}{\partial r_D}\right|_{r_D=r_{eD}} = 0 \quad (6)$$

无因次流量为[5]

$$q_D(t_D) = -\left(\frac{\partial p_{fD}}{\partial r_D}\right)_{r_D=1} \quad (7)$$

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式中:p 为压力,MPa;t 为时间,s;s 为表皮系数;r 为泄油半径,m;q 为产量,m^3/d;f 为裂缝系统;m 为基岩系统;w 为井底;e 为油藏外边界;q_D为无因次产量;p_{jD}为无因次压力(j = m,f);t_D为无因次时间;ω 为裂缝系统弹性储容比;λ 为窜流系数。

2.2 定井底压力条件下的产量公式

对于定井底压力数学模型,采用 Laplace 变换进行求解,得到定井底压力条件下 Laplace 空间无因次流量为

$$\bar{q}_D(z) = \frac{M[K_1(M)I_1(r_{eD}M) - I_1(M)K_1(r_{eD}M)]}{sK_1(r_{eD}M)[I_0(M) - zMI_1(M)] + sI_1(r_{eD}M)[K_0(M) + zMK_1(M)]} \tag{8}$$

$$M = \sqrt{zf(z)} \tag{9}$$

式中:z 为拉普拉斯算子;$K_0(x)$ 为零阶第二类虚宗量 Bessel 函数;$K_1(x)$ 为阶第二类虚宗量 Bessel 函数;$I_0(x)$ 为零阶第一类虚宗量 Bessel 函数;$I_1(x)$ 为阶第一类虚宗量 Bessel 函数。

2.3 变井底压力条件下的产量公式

对于变井底压力数学模型,也采用 Laplace 变换进行求解,得到变井底压力条件下无因次流量为

$$\bar{q}_D(z) = \frac{\bar{P}_w(z)M[K_1(M)I_1(r_{eD}M) - I_1(M)K_1(r_{eD}M)]}{K_1(r_{eD}M)[I_0(M) - zMI_1(M)] + I_1(r_{eD}M)[K_0(M) + zMK_1(M)]} \tag{10}$$

将式(8)和(10)进行数值 Laplace 反演可得到真实空间中的无因次产量 q_D 随无因次时间 t_D 的变化。

3 产量变化特征

对公式(8)或(10)采用数值 Laplace 反演计算可得到天然裂缝性油藏的产量。

3.1 产量特征

均质油藏的产量有一个相对平缓的递减阶段和迅速递减的阶段(压力波到达封闭边界后)。而天然裂缝性油藏整个生产过程中产量出现两个相对平缓稳定阶段和两个递减阶段(图 1)。第一个平缓阶段主要反映了裂缝系统的流动,持续时间较短;第一个下降阶段主要反映了基岩往裂缝系统的窜流;第二个平缓阶段表明基岩往裂缝流动和裂缝往井筒的流动达到平衡,此时相当于一个均质系统,持续时间远比第一个平缓阶段长;第二个产量递减阶段主要是受封闭外边界的影响,产量迅速下降。

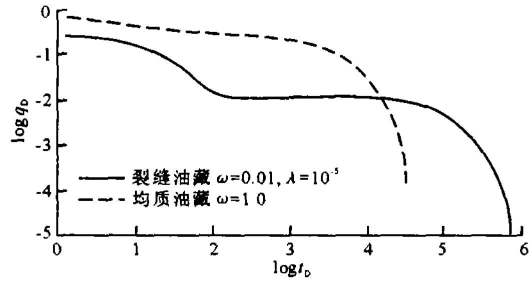

图 1 均质油藏与天然裂缝油藏的产量递减曲线

3.2 影响产量递减曲线的参数

3.2.1 窜流因子

裂缝系统的产量递减非常快。窜流因子越大,第二个相对平缓的递减阶段产量越高;窜流因子较小时,第二个递减阶段的产量很小,几乎为零(图 2)。

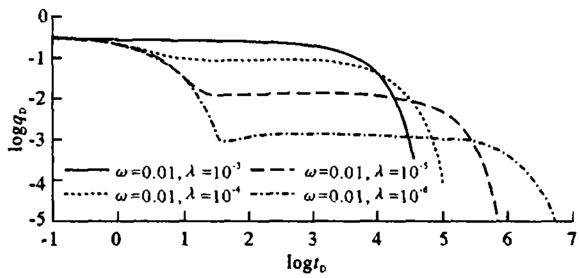

图 2 封闭定压下窜流因子对产量的影响

3.2.2 裂缝弹性储容比

裂缝弹性储容比越大,裂缝系统的弹性能量越大;裂缝系统流体流动时间越长,第一个平缓阶段持续时间越长(图 3)。

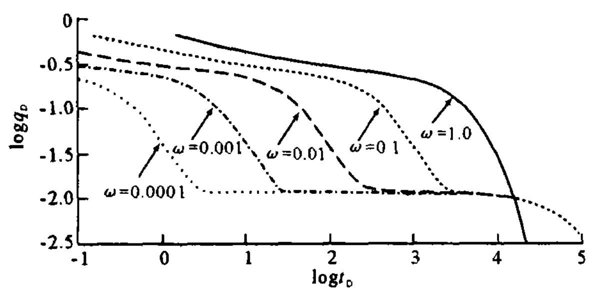

图 3 裂缝弹性储容比对天然裂缝性油藏产量递减曲线的影响

3.2.3 变井底压力

天然裂缝性封闭油藏在变井底压力下的双对数生产曲线与定井底压力条件下的递减曲线一样,都有两个拐点,第一个拐点体现了基岩系统向裂缝系统发生拟稳态窜流的开始,第二个拐点体现了窜流过程的结束,两个系统的压力达到了平衡,可视为一个均质系统的情况(图 4)。对比天然裂缝性封闭油

藏定井底压力和变井底压力的双对数递减曲线(图5)。曲线的前部分(即第一拐点前)变井底压力和定井底压力的曲线几乎重合,这是因为基岩和裂缝通过窜流达到压力平衡的时间期较短,压力降不明显。当窜流结束两个系统的压力平衡后,变井底压力条件下的产量下降的速度大于定井底压力条件下的速度,递减加快。

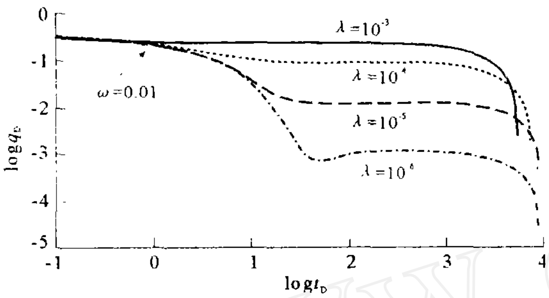

图 4　封闭油藏变井底压下的双对数生产曲线

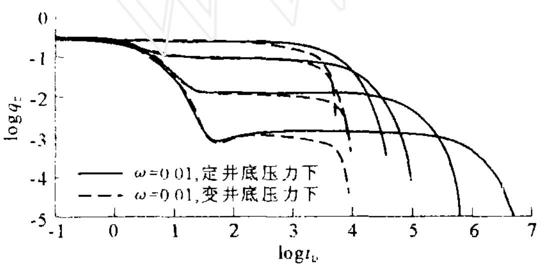

图 5　封闭油藏不同内边界下的双对数对比曲线

4　矿场应用

塔河油田奥陶系油藏是以裂缝、溶洞发育为主的碳酸盐岩油藏,可分为裂缝发育型和溶洞发育型。从裂缝型油藏某井的实际生产数据与天然裂缝性油藏的理论递减曲线的拟合图(图 6)可以看出,该井的实际生产数据与天然裂缝性油藏的理论递减曲线的特征拟合较好,通过拟合得到主要地层参数:裂缝弹性储容比为 2.8×10^{-2};裂缝系统的渗透率 $761\times10^{-3}\mu m^2$;污染系数为 0.5;窜流系数为 3.2×10^{-5};封闭边界半径为 193.0m。

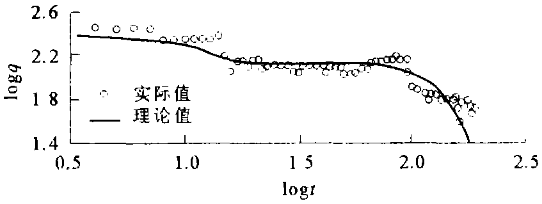

图 6　某油井实际生产数据与理论计算数据拟合图

5　结论

天然裂缝性油藏的产量双对数曲线上有两个相对平缓的递减阶段和两个迅速递减阶段;裂缝系统的产量递减较快;窜流因子越大,第二个相对平缓的递减阶段产量越高;裂缝弹性储容比越大,裂缝系统流体流动时间越长。

通过实际生产资料与理论计算产量递减曲线的拟合,可以确定地层也可以预测今后的产量。

参考文献:

1 Prat G D. Well test analysis for naturally fractured reservoir: [Ph. D. Thesis]. Stanford: Stanford University, 1980

2 Warren J E, Root P J. The behavior of naturally fractured reservoirs. SPE 426

3 姚军,戴卫华,王子胜等. 变井筒储存的三重介质油藏试井解释方法研究. 石油大学学报(自然科学版),2004,28(2):46～51

4 Olarewaju J S, Schlumberger Dawell, Lee W J. Rate behavior of dual－porosity reservoir. SPE 21703

5 Everdingen Van, Hurst W. The application of the Laplace transformation to flow problems in reservoirs. Trans, AIME, 1949, 186(12):305～324

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Cui Wenfu. Classification of intercalation and the longitudinal remaining oil distribution pattern in reverse rhythm thick reservoir-taking 8 ~ 15 sand bodies of Es_2 in Shengtuo oilfield as examples. *PGRE*, 2005, 12(1): 52 ~ 55

Characteristics of intercalation distribution in reverse rhythm thick reservoir of delta front were studied systematically in 8 ~ 15 sand bodies of Es_2 in Shengtuo oilfield. The intercalation is divided into 54 kinds of combination. And then four kinds of shield formed by oil and water migration for different combinations were analyzed. By applying different field data, seven distribution patterns for longitudinal remaining oil of this kind of reservoirs at the extra high water-cut stage were studied, and then corresponding measures for tapping the potential were worked out, which is of great value in the adjustment and further development of Shengtuo oilfield.

Key words: delta front, thick reservoir, intercalation, remaining oil, pattern

Cui Wenfu, Shengli Oil Production Plant, Shengli oilfield Ltd. Co., Dongying City, Shandong Province, 257051, China

Yao Jun, Hou Liqun, Li Aifen. Research and application on production decline rule of closed carbonate reservoir with natural fractures. *PGRE*, 2005, 12(1): 56 ~ 58

A percolation model for closed carbonate reservoir with natural fractures was built. Considering both constant and variable bottomhole pressure as the inner boundary conditions and solving its corresponding mathematical model using Laplace transform and Duhamel principle gave decline curve of the production rate in the oil reservoir, on which both two rapid declining phases and two relative gentle ones appeared. The influence of interporosity flow coefficient and elastic storage-volume ratio on the decline curve for the naturally fractured reservoir was discussed. Field example demonstrates that by matching actual production data with theoretical decline curve formation parameters can be determined and future production can be predicted.

Key words: naturally fractured reservoir, production decline rule, carbonate rock, percolation model

Yao Jun, Petroleum Engineering Institute, University of Petroleum, Dongying City, Shandong Province, 257061, China

Sun Jianping, Ran Qiquan, Shi Huandian. Waterflooding characteristic and effect evaluation of the fractured volcanic heavy oil reservoir of block Zao35. *PGRE*, 2005, 12(1): 59 ~ 62

According to the characteristics of fracture distribution and fluid in the fractured volcanic oil reservoir of block Zao35, dynamic data after water flooding were analyzed in detail using reservoir engineering method. After waterflood development in this oil reservoir, the trend of sudden drop in formation pressure was controlled and began to rise slowly, but the decline rate of the oil production was still very high. The injected water channeled rapidly along the natural fracture of this reservoir, and most of the oil production wells were flooded severely. The water cut of this reservoir went up integrally and rapidly, and only after 15 months of water-injection it entered high-water-cut period. Invalid cycle of the injected water made water-restrained rate, waterflooding index and volumetric sweep efficiency were very low. Water injection of $1 \times 10^4 m^3$ can only produce $0.22 \times 10^4 t$ equivalent oil. At present recovery percent of reserves is 4.06%, and the terminal recovery efficiency of water-flooding is less than 6%. Remaining recoverable reserve of the water-flooding reservoir was low, but the actual remaining recoverable reserve was high, so the potential of the oil reservoir can not be tapped efficiently. Other production way should be adopted to improve the usage degree of the remaining resources in this oil reservoir.

Key words: fracture, volcanic rock, heavy oil, waterflooding, effect evaluation, block Zao35

Sun Jianping, The Southwest Petroleum Institute, Chengdu City, Sichuan Province, 610500, China

Yin Wenjun, Chen Yongsheng, Wang Hua et al. Building of the interpretation model of the large channels and remaining oil saturation by hydraulic survey. *PGRE*, 2005, 12(1): 63 ~ 65

The hydraulic survey technology is a well test one for surveying reservoir conditions between water injection wells and oil production wells. It can not only provide information of reasonable productivity, formation parameters, formation pressure and so on, but also apply in planar remaining oil survey in oil-bearing formations and the large channel recognition in development phase of extra high water cut. The interpretation model built by hydraulic survey of connected well-pair permeabili-