存在邻井影响条件下的油井数值试井分析

刘曰武*　陈慧新　张大为　　**周　蓉**　　**刘　妍**
(中国科学院力学研究工程科学部)　(中国科学院力学研究所)　(大庆油田物探公司研究所)

摘要　根据油田开发特征,建立了圆形定压地层中考虑存在邻井影响条件下的油井不稳定试井的数值试井模型,提出存在邻井影响的测试资料分析方法,对邻井的性质和产注量对试井理论曲线的影响进行了分析讨论。该方法应用于油田实际井例对开发试井理论具有积极的指导意义。

主题词　试井　渗流　数值分析

前　　言

不稳定试井的发展已有几十年的历史[1～10],所使用的不稳定试井理论和分析方法都是基于勘探阶段的物理模型基础,假设油藏为无限大地层或圆形地层或矩形地层,油层为水平板状地层,地层中只有一口以定产量生产的油井,国内外在这一方面已经开展了一系列研究工作,主要论点集中在单井不稳定试井理论和应用上,即通常所说的勘探试井理论。分析其原因主要是单井不稳定试井理论在简单的几何边界条件下可以获得解析解或半解析解,便于分析讨论。但是,当油田处于开发阶段以后,地层中的井不再是一口,而是多口井。对于中高渗油田往往存在邻井对测试资料的影响问题。而用通常的试井理论解释分析这些资料时,通常将这些资料解释为边界影响,从而给生产带来许多错误的引导。因此,只能用数值试井理论进行分析讨论。20 世纪 90 年代以来,人们开始使用数值试井求解方法,所使用的计算手段主要是差分方法、边界元方法和 Green 元方法等[11～16]。文献[17]用有限元方法讨论了井位于圆形定压油藏中任意位置的数值试井理论。但是以上所有理论仍然都集中在单井试井理论上。

本文给出了圆形定压地层中考虑存在邻井影响条件下的油井不稳定试井的数值试井模型,提出了存在邻井影响时测试资料的分析方法,对邻井的性质和产注量对试井理论曲线的影响进行了分析讨论,并对油田实际井例进行了分析。

物理模型和数学模型的描述

1. 物理模型

油藏为水平板状、均质各向同性、边界定压的圆形地层。地层中有两口井,其中一口井在圆形油藏中的中心,井贯穿地层并以一定产量生产。另一口井在圆形油藏中的任意位置,井贯穿地层并以一定产量生产(或注水)。地层中流体为弱可压缩、定常粘度的牛顿流体;流体在地层中的流动为层流状态,遵从达西定律。整个测试过程是一个等温过程,忽略重力作用,不考虑其它物理化学变化的影响。

2. 数学模型

控制方程:

$$\frac{\partial^2 p_D}{\partial r_D^2} + \frac{1}{r_D}\frac{\partial p_D}{\partial r_D} = \frac{\partial p_D}{\partial t_D} \tag{1}$$

初始条件:

$$p_D(t_D = 0) = 0 \tag{2}$$

定压外边界条件:

$$p_D\Big|_{r_D = R_{eD}} = 0 \tag{3}$$

相邻井的边界条件:

$$\frac{1}{r_D}\frac{\partial p_D}{\partial r_D}\Big|_{\Gamma} = \text{cons} \tag{4}$$

内边界条件:

$$\frac{1}{r_D}\frac{\partial p_D}{\partial r_D}\Big|_{r_D = 1} = -1 + C_D\frac{\partial p_{wD}}{\partial t_D} \tag{5}$$

(若为生产井,则 cons < 0;若为注水井,则 cons

---

*　刘曰武,男,副研究员,博士后,目前从事渗流力学和油气藏工程方面的研究工作。地址:北京市海淀区中关村 15 号中国科学院力学所,邮政编码:100080。

> 0)

其中　$p_D = \frac{kh(p_i - p)}{1.1842 \times 10^{-3} q\mu B}$; $t_D = \frac{3.6kt}{\phi\mu C_t r_w^2}$

$T_D = \frac{t_D}{C_D}$; $r_{we} = r_w e^{-S}$; $C_D = \frac{1.592C}{\phi h C_t r_w}$

式中:p_i ——地层原始压力,MPa; q ——生产率;
ϕ ——油藏孔隙度; B ——体积系数;
k ——油藏渗透率,μm^2; r_w ——油井半径,m;
h ——地层有效厚度,m; S ——表皮系数;
C ——井筒存储系数,m^3/MPa;
C_t ——总压缩系数,MPa^{-1};
μ ——地层中流体的粘性,mPa·s。

有限元网格划分

根据文献[10]～[12]所提供的方法,对所研究的油藏绘制成的网格如图 1 所示,近井区域的网格图如图 2 所示。

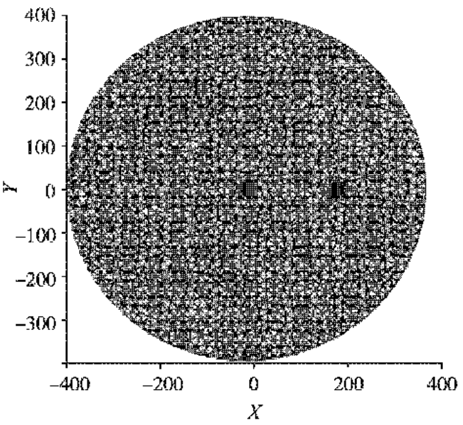

图1　所研究油藏三角形网格

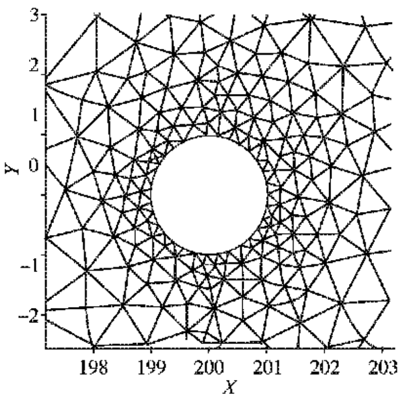

图2　近井区域网格

有限元方程构造和计算

首先构造计算区域内每个网格单元的有限元方程,即

$$\iint_A \phi_i^e \left(\frac{\partial^2 p_D^e}{\partial x^2} + \frac{\partial^2 p_D^e}{\partial y^2} - \frac{1}{C_D e^{2S}} \frac{\partial p_D^e}{\partial T_D} \right) dA = 0 \quad i = 1,2,3 \tag{6}$$

式中:ϕ_i^e ——单元插值函数;
p_D^e ——计算单元每个结点上的压力。

然后,集成整体矩阵,最后,求得整体矩阵的解,从而得到每个结点上的压力值。计算流程框图如图 3 所示。

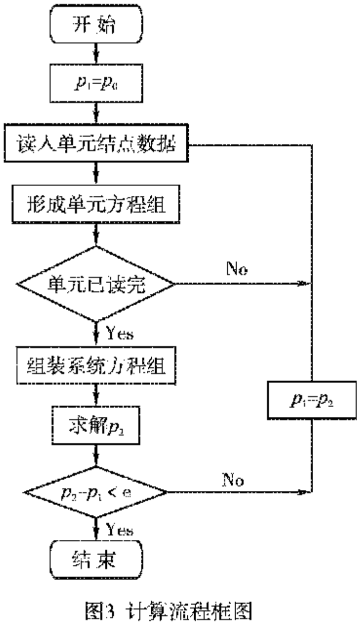

图3　计算流程框图

邻井影响数值试井模型分析讨论

1. 测试井为生产井,邻井为注水井情况

①压力和压力导数双对数理论曲线图:在取不同的 $C_D e^{2S}$ 参数值时,所计算的井底压力随时间变化的理论曲线如图 4 所示,图中曲线 1,2,3,4,5,6 分别是 $C_D e^{2S}$ 为 10^0,10^1,10^2,10^3,10^4,10^5 时的压力导数曲线。由图 4 可知,在早期段压力曲线和压力导数曲线合并到一条斜率为 1 的直线,这一段反映的是纯井筒储存效应。由于邻井的影响使压力导数曲线的晚期出现偏转。

②压力传播过程图:从压力传播过程图可以看

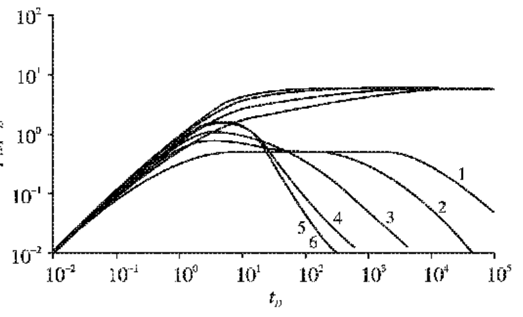

图4 不同$C_D e^{2S}$时井底压力随时间变化曲线图

出(见图 5),在一口井生产而另一口井以相同流量注入的情况下,两井中间位置会形成一条定压直线边界。

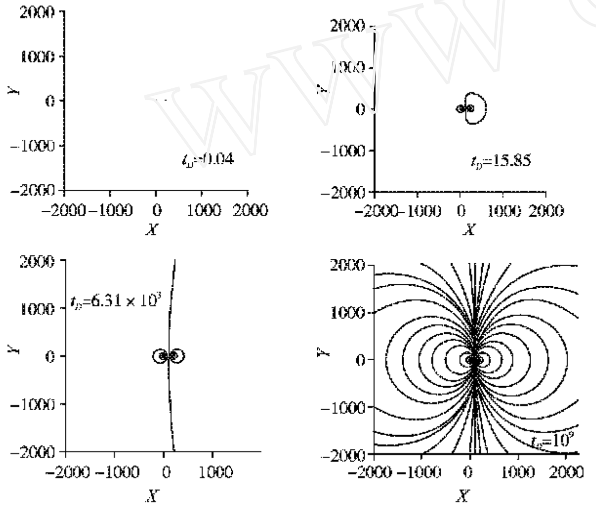

图5 压力发展过程图

③井间压力分布曲线:通过计算可以得到不同时间井间的压力分布曲线如图 6 所示。

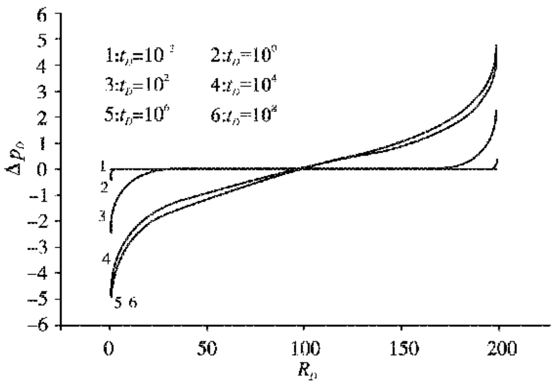

图6 不同t_D时刻的压力p_D径向分布图

2. 两口井均为生产井,且流量相同情况下的压力传播过程图

①压力和压力导数双对数理论曲线图:在取不同的 $C_D e^{2S}$ 参数值时,所计算的井底压力随时间变化的理论曲线如图 7 所示。

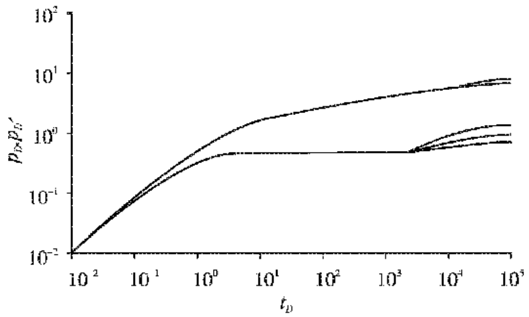

图7 井底压力随时间变化的理论曲线

②压力传播过程图:从压力传播过程图可以看出(见图 8),若两口井以等产量生产,则在这两口井中间位置会形成一条不渗透直线边界。

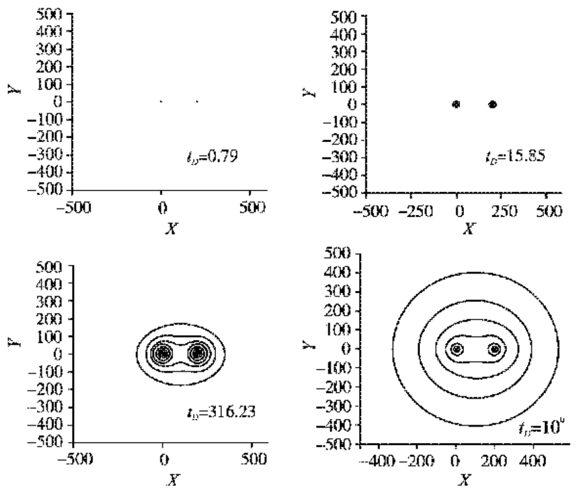

图8 压力发展过程图

实例分析

测试资料基本数据:地层有效厚度 9.500 m;孔隙度 18 %;井筒半径 0.100 m;关井前生产时间 2400.000 h;关井前产量 4.000 m^3/d;流体体积系数 1.001;流体粘度 1.1600 mPa·s;综合压缩系数 1.023 $\times 10^{-3} MPa^{-1}$。注水井的距离为 180 m,注水井注入量为 43 m^3/d。

对油井实测数据采用圆形定压边界油藏中有注水井影响不稳定试井模型进行拟合得出:井筒储集系数为 0.0004 m^3/MPa;表皮系数为 2.5176;平均地层压力为 11.3371 MPa;定压外边界半径为62.0 m。测试数据分析段的双对数拟合图如图 9 所示。

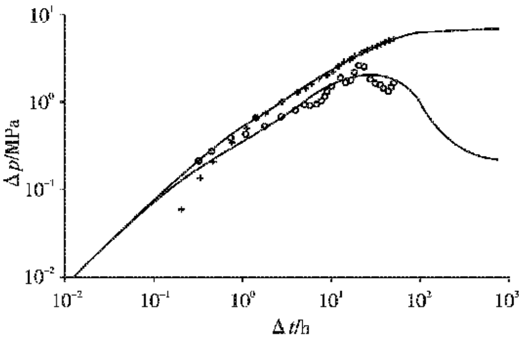

图9 解释段双对数拟合图

结 论

建立了圆形定压地层中考虑存在邻井影响条件下油井不稳定试井数值试井模型,得到了邻井具有不同性质情况下的不稳定压力扩散过程,绘制了它们的井底压力理论曲线。提出了存在邻井影响的测试资料的分析方法,对邻井的性质和产注量对试井理论曲线的影响进行了分析讨论。从计算结果可以看出,如果两口井以等产量生产,则在这两口井中间位置会形成一条不渗透直线边界,如果一口井生产而另一口井以相同流量流入,则在两井中间位置会形成一条定压直线边界。此结果对开发试井理论具有积极的指导意义。

参 考 文 献

1. Matthews, C. S., Rusell, D. R.: Pressure Buildup and Flow Test in Wells Soc. Pet. Eng. of AIME, New York, 1967, Dallas.
2. Earlougher, R. C. Jr.: Advances in Well Test Analysis, Monograph Series SPE, 1977.
3. Raghavan, R.: Well Test Analysis, Prentice-Hall, Inc., New Jersey, 1993:126-164.
4. 孔祥言:高等渗流力学,中国科学技术大学出版社(合肥),1999。
5. C.V. Theis: The Relation Between the Lowering of the Piezom-Tric Surface and the Rate and Duration of Discharge of a Well Using Groundwater Storage, Tans. Aug., 1935:519 - 524.
6. Van Everdingen, A. F. and Hurst, W.: The Application of the Laplace Transformation to Flow Problem in Reservoirs, Trans., AIME(1949) Vol. 186:305 - 324.
7. Horner D. R.: Pressure Build-up in Wells, Proc. Third World Pet. Cong, The Hague Sec. II, 1951, 503 - 523.
8. Ramey, H. J., Jr.: Short-Time Well Test Data Interpretation in the Presence of Skin Effect and Wellbore Storage, JPT, Jan. 1970:97.
9. Gringarten, A. C., Bourdet, D., Landel, P. A. and Kniazeff, V.: A Comparison between Different Wellbore Storage and Skin Type Curves for Early-Time Transient Analysis, SPE 8205, 1979.
10. Bourdet, D., Whittle, T. M., Douglas, A. A. and Pirard, Y. M.: A New Set of Type Curves Simplifies Well Test Analysis, World Oil, May 1983: 95 - 106.
11. Puchyr, P. J.: A Numerical Well Test Model, SPE 21815, Presented at the Rocky Mountain Regional Meeting and Low-Permeability Resevoirs Symposium, Denver, Colorado, April 15 - 17, 1991.
12. Warren, G. M.: Numerical Solutions for Pressure Transient Analysis, SPE 26177, Presented at the Gas Technology Symposium, Calgary, Alberta, Canada, June 28 - 30, 1993.
13. Blance, G.: Contribution of the Pressure Movments to the Interpretation of Numerical Simulation of Well Test ECM 5, Presented at the 5th Earoup Conference on the Mathematics of oil Recovery, Leoben, Austria, 3 - 6 Sept 1996.
14. Pach, F., Analytical and Numerical Simulation Well Test Model, ECM 5, Presented at the 5th Earoup Conference on the Mathematics of Oil Recovery, Leoben, Austria, 3-6 Sept 1996.
15. Stephen, K. M.: Simulation of Transient Well-Test Signature for Geologically Realistic Fauts in Sandstone Reservoirs, SPEJ March 1998, or SPE 38442.
16. Rosalind A. Archer and Roland N. Horne: The Green Element Method for Numerical Test Analysis, SPE 62916.
17. 周蓉,刘曰武,周富信:均质圆形定压油藏不稳定渗流的数值解,油气井测试,2001(6)10。

本文收稿日期:2002 - 06 - 18 编辑:穆立婷

WELL TESTING (YOUQIJING CESHI)

Vol. 11 No. 5 (Serial No. 73) 2002

Abstracts

·Research of Theory & Method·

Analysis of Pressure Distribution for a Well in Dual-Porosity Formations. 2002 (5) 11 : 1～3

Li Shunchu, Huang Bingguang, Li Xiaoping (South-West Petroleum Institute)

An alterative-rate solutions to the problem of dimensionless formation pressure and bottom-hole pressure in Laplace domain are studied with conditions of three type outer boundary and two type inner boundary in a dual-porosity formation. A universal formula has been obtained by deeply analyses of structure and connection of the solution. The relation between formation pressure and bottom-hole pressure are discovered. A brief introduction of application is also presented.

Subject headings: dual-porosity, pressure distribution, alterative rate, solution in Laplace domain, universal formula

Numerical Well-Test Analysis for Oil Wells in Condition of Adjacent Wells Influences. 2002 (5) 11 : 4～7

Liu Yuewu, Chen Huixin, Zhang Dawei, Zhou Rong (Institute of Mechanic, Chinese Academy Sciences), Liu Yan (Research Institute of Exploration, Daqing Oilfield)

Based on characteristics of a oilfield development, a numerical well-test analysis model including influences of adjacent wells is brought forward in a constant-pressure circular bounded formation. By the model, not only a method to analyze well-test data is presented, but also influence of type and rate of adjacent wells is discussed. Application of the method in oilfield may bring positive and directive significance.

Subject headings: well testing, percolation, numerical analysis

Two or Three Insights into Oil-Gas-Water Three-Phase Well Test. 2002 (5) 11 : 8～11

Zhu Chengrong, Bi Wenping, Huang Ju (The Second Petroleum Production Factory, Jiangsu Oilfield)

Multi-phase flow exists common in oilfield. Some characteristics of well-test curves may be covered up by the approximate analysis based on single-phase flow method. The oil-gas-water three-phase well test can better be studied by a numerical well test model. Mechanism of curve shape changes in different conditions are analyzed by the model. Several opinions about multiphase well test are presented in the paper.

Subject headings: well testing, multiphase flow, gas, saturation, viscosity, permeability

A Study on the Well Test Model in Compartmentalized Reservoirs. 2002 (5) 11 : 12～15

Xu Yan (Liaohe Oilfield Company)

Porous flow models including interface skin and typical outer boundaries are presented in a compartmentalized reservoir. A direct and systemic method of Integral transformation is presented to solve the non-homogeneous problem of transient 3D porous flow. The method can be used to study porous flow and well test problems in the reservoir with low permeability.

Subject headings: oil reservoir, well testing, model, integral transform, percolation

A New Method to Determine IPR Curves of Non-Flowing Wells by DST Data. 2002 (5) 11 : 16～17

Wang Weiying, Zhang Gongshe (Jianghan Petroleum Institute), Zhang Xueqin (Well Testing Company, Huabei Oilfield), Li Jinzhen (No. 2 Oil Production Factory, Jiangsu Oilfield)

Base on theory derivation, a method is presented to determine IPR curves of non-flowing wells by DST data. It is claimed that relationship of pressure buildup difference versus time is accorded with a straight line. The slope of the line can be used to obtain a ultimate index of liquid production. Liquid rate of both in maximum situation and in different flow pressures can be acquired by the index. It is validated by filed application in which the relative error is less than 2 %.

Subject headings: oil production test, plug flow, pressure analysis, production control

A Method Study on the Pollution Correction of Water Injection Profile. 2002 (5) 11 : 18～21