考虑煤层气稳定解吸的数值试井方法

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摘要　建立了考虑煤层气解吸作用的煤层气稳定解吸均质试井模型,在控制方程中引入稳定源来描述煤层气解吸作用,利用有限元方法求得其数值解。通过分析解吸系数的影响,明确了煤层气解吸作用能缓解地层中压力下降、减缓压力波的传播。当解吸作用达到一定强度时,煤层气解吸量已经达到生产量,压力停止传播,这种情形类似于遇到了定压边界。另外,还考虑了临界解吸压力对试井理论曲线的影响,临界解吸压力和初始地层压力相差的越小,煤层气解吸出现的时间越早,对测试曲线影响也越大。

关键词　煤层气　渗流　解吸　数值试井　有限元

0　引　言

煤层气试井是获取煤层气储层参数的重要手段,也是对煤层中的渗流机理进行直接验证的有效方法。在煤层气开发前以及生产过程中都需要了解煤层气储层的特性,在不同阶段获取的储层渗透率、井筒储集常数和表皮系数等有关参数是及时了解储层情况和井况的定量评价数据,从而为煤层气井的勘探开发和生产潜能评价提供科学的依据。

煤层气开采与常规天然气开采的主要区别是煤层气在煤层中的赋存状态不同[1],煤层气的开采需要排水降压,当压力低于临界解吸压力之后,煤层气才从煤基质上解吸出来,并参加煤层中的流体渗流。而常规天然气则是主要以游离态存在于地层中,被直接开采出来。因此,煤层气试井与常规天然气试井的根本区别在于,煤层气试井模型的描述中必须有解吸附规律的描述[2]。

对于煤层气开采的不同阶段,煤层气试井对象和分析方法也有所不同[3]。在煤层气初始打开时,由于一般的原始地层压力高于煤层气的临界解吸压力,且常常不存在游离的煤层气,通常是利用常规油气井测试方法进行测试,普遍采用的是注入压降测试。在对煤层气井排水降压后,煤层气开始解吸,此时为气水两相流阶段。当煤层割理中水抽完后,煤层中基本为单相气体,Anbarci 等[4]、Sung 等[5]对单相煤层气渗流试井进行过研究,其采用的试井模型是基于双重介质的单相流试井模型。刘曰武等[6]研究了多井开采下煤层气不定常渗流问题,建立了在多井条件下考虑井筒储存和表皮效应的煤层气不定常渗流模型,所使用的解析规律只是常规的朗氏等温吸附规律,对渗流场的压力规律未进行深入研究。卢德唐等[7]、庄惠农等[8]指出,虽然煤岩具有双重孔隙的结构,但试井时并不表现油气层中的双孔介质流动特征,某些现场测试资料虽被牵强地解释为双重介质,但就目前见到的这些资料,经分析核实后发现,实际是特定的测试方法所形成的变井筒储存影响。

由于煤层“双重”介质结构的特殊性,在实际试井测试过程中,煤层通常表现为均匀介质的特征。这种现象主要是煤层基质的渗透率远远小于煤层中裂缝的渗透率所造成的。

本文以均匀单重介质模型为基础,考虑煤层气解吸作用的影响,建立考虑井筒储存效应和表皮效应的煤层气试井模型,并推导出其有限元方程。通过数值计算得到方程的解,分析了煤层气稳定解吸系数对试井理论曲线的影响和地层压力传播的影响,并讨论了解吸系数取值的范围,以及临界解吸压

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力对试井理论曲线的影响。

1　物理模型和数学模型

1.1　物理模型描述

煤层为均匀各向同性介质，煤层中的流体为弱可压缩、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。煤层中存在解吸附现象，当煤层压力大于临界解吸压力时，煤层气不解吸；只有当煤层压力小于临界解吸压力时，煤层气才开始解吸，而且解吸是瞬间完成的。由于假定解吸发生的过程与时间无关，因此该模型为稳定解吸模型。由于测试时间相对较短，忽略重力和温度变化对流动的影响，且不考虑其他物理化学的影响。

1.2　数学模型描述

针对煤层气解吸特性，在常规的压力扩散方程中添加一恒定的源项 α_{1D}（$\alpha_{1D} < 0$ 代表煤层气解吸；$\alpha_{1D} > 0$ 代表煤层气吸附），由于煤层气开采过程中主要采用压力降落试井方法，故模型中的 α_{1D} 小于或等于 0。α_{1D} 的大小与解吸的强度及该点的压力值有关。当压力值高于煤层气的临界解吸压力，则煤层不解吸，解吸系数等于 0；当压力值低于临界解析压力，解吸系数小于 0。

流动的控制方程为

$$\frac{\partial^2 p_D}{\partial x_D^2} + \frac{\partial^2 p_D}{\partial y_D^2} + \alpha_{1D} = \frac{1}{C_D e^{2S}} \frac{\partial p_D}{\partial T_D} \tag{1}$$

初始条件：

$$p_D = 0 \tag{2}$$

边界条件：

内边界条件：

$$\left(\frac{\partial p_D}{\partial x_D} \cos\theta + \frac{\partial p_D}{\partial y_D} \sin\theta \right) \Bigg|_{r_D = 1} = -1 + \frac{\mathrm{d} p_{Dw}}{\mathrm{d} T_D} \tag{3}$$

外边界条件：

无限大边界：

$$p_D \big|_{x, y \to \infty} = 0 \tag{4}$$

定压边界：

$$p_D \big|_{\Gamma_{out}} = 0 \tag{5}$$

封闭边界：

$$\frac{\partial p_D}{\partial n} \Bigg|_{\Gamma_{out}} = 0 \tag{6}$$

1.3　有限元方程

利用伽辽金加权余量法，令其权函数为差值函数，即

$$N_i = a_i + b_i x + c_i y \qquad i = 1, 2, 3$$

则有

$$\iint_A N_i^e \left(\frac{\partial^2 p_D}{\partial x_D^2} + \frac{\partial^2 p_D}{\partial y_D^2} + \alpha_{1D} - \frac{1}{C_D e^{2S}} \frac{\partial p_D}{\partial T_D} \right) \mathrm{d}A = 0 \tag{7}$$

其弱表示形式为

$$\iint_A \left[\frac{\partial N_i^e}{\partial x_D} \frac{\partial p_D}{\partial x_D} + \frac{\partial N_i^e}{\partial y_D} \frac{\partial p_D}{\partial y_D} - N_i^e \alpha_{1D} + \frac{N_i^e}{C_D e^{2S}} \frac{\partial p_D}{\partial T_D} \right] \mathrm{d}A = \int_\Gamma N_i^e \frac{\partial p_{Dw}}{\partial n} \mathrm{d}l \tag{8}$$

离散后得到有限元方程为

$$\begin{aligned} & \left(b_1^2 + c_1^2 + \frac{1}{C_D e^{2S}} \frac{1}{6\Delta T_D} \right) p_1^{e, n+1} + \left(b_1 b_2 + c_1 c_2 + \frac{1}{C_D e^{2S}} \frac{1}{12\Delta T_D} \right) p_2^{e, n+1} + \left(b_1 b_3 + c_1 c_3 + \frac{1}{C_D e^{2S}} \frac{1}{12\Delta T_D} \right) p_3^{e, n+1} \\ = & \frac{1}{C_D e^{2S}} \frac{1}{6\Delta T_D} p_1^{e, n} + \frac{1}{C_D e^{2S}} \frac{1}{12\Delta T_D} p_2^{e, n} + \frac{1}{C_D e^{2S}} \frac{1}{12\Delta T_D} p_3^{e, n} + \frac{\alpha_{1D}}{3} + \left(1 - \frac{p_1^{e, n+1} - p_1^{e, n}}{\Delta T_D} \right) \frac{L}{2A} \end{aligned} \tag{9}$$

$$\begin{aligned} & \left(b_1 b_2 + c_1 c_2 + \frac{1}{C_D e^{2S}} \frac{1}{12\Delta T_D} \right) p_1^{e, n+1} + \left(b_2^2 + c_2^2 + \frac{1}{C_D e^{2S}} \frac{1}{6\Delta T_D} \right) p_2^{e, n+1} + \left(b_2 b_3 + c_2 c_3 + \frac{1}{C_D e^{2S}} \frac{1}{12\Delta T_D} \right) p_3^{e, n+1} \\ = & \frac{1}{C_D e^{2S}} \frac{1}{12\Delta T_D} p_1^{e, n} + \frac{1}{C_D e^{2S}} \frac{1}{6\Delta T_D} p_2^{e, n} + \frac{1}{C_D e^{2S}} \frac{1}{12\Delta T_D} p_3^{e, n} + \frac{\alpha_{1D}}{3} + \left(1 - \frac{p_2^{e, n+1} - p_2^{e, n}}{\Delta T_D} \right) \frac{L}{2A} \end{aligned} \tag{10}$$

$$\begin{aligned} & \left(b_1 b_3 + c_1 c_3 + \frac{1}{C_D e^{2S}} \frac{1}{12\Delta T_D} \right) p_1^{e, n+1} + \left(b_3 b_2 + c_3 c_2 + \frac{1}{C_D e^{2S}} \frac{1}{12\Delta T_D} \right) p_2^{e, n+1} + \left(b_3^2 + c_3^2 + \frac{1}{C_D e^{2S}} \frac{1}{6\Delta T_D} \right) p_3^{e, n+1} \\ = & \frac{1}{C_D e^{2S}} \frac{1}{12\Delta T_D} p_1^{e, n} + \frac{1}{C_D e^{2S}} \frac{1}{12\Delta T_D} p_2^{e, n} + \frac{1}{C_D e^{2S}} \frac{1}{6\Delta T_D} p_3^{e, n} + \frac{\alpha_{1D}}{3} + \left(1 - \frac{p_3^{e, n+1} - p_3^{e, n}}{\Delta T_D} \right) \frac{L}{2A} \end{aligned} \tag{11}$$

其中

$$A = \frac{1}{2}\begin{vmatrix} 1 & 1 & 1 \\ x_1 & x_2 & x_3 \\ y_1 & y_2 & y_3 \end{vmatrix}$$

$$b_1 = \frac{1}{2A}(y_2 - y_3)$$

$$b_2 = \frac{1}{2A}(y_3 - y_1)$$

$$b_3 = \frac{1}{2A}(y_1 - y_2)$$

$$c_1 = \frac{1}{2A}(x_3 - x_2)$$

$$c_2 = \frac{1}{2A}(x_1 - x_3)$$

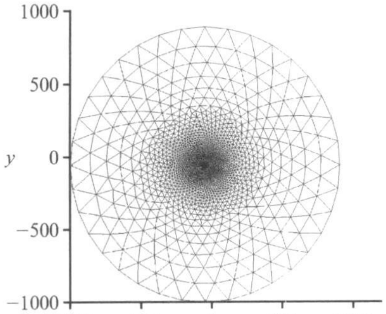
$$c_3 = \frac{1}{2A}(x_2 - x_1)$$

式中: A —— 面积。

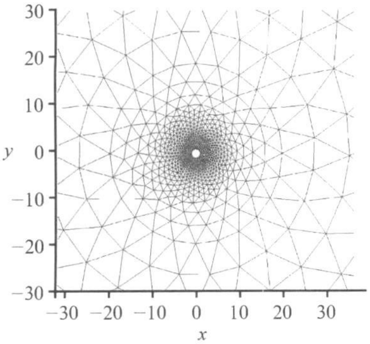
(9) 式～ (11) 式中的最后一项只有当三角形的 2 个结点落在边界上时才存在, 由单元方程组组装系统方程组。求解系统方程组, 即可得到任意网格点 (x, y) 上 $n+1$ 时刻的压力值 $p(x, y)$。

1.4　有限元网格离散

为了进行有限元计算, 需对计算区域进行离散, 采用非结构三角形网格, 外边界为圆形边界(见图 1) 。



a. 圆形煤层气地层



b. 近井区域的网格图

图1　煤层气地层的非结构网格图

2　计算结果及分析

根据所建立的数学模型和推导出的有限元方程, 利用所划分的有限元网格计算了不同解吸系数、不同边界性质(全封闭、全定压) 情况下的煤气层中生产井井底压力和压力导数的双对数理论曲线。

2.1　解吸作用对试井理论曲线影响的分析

为了得到煤层气解吸现象给试井理论曲线所带来的影响, 分别取稳定解吸系数为 0 和 -1×10^{-6}, 无量纲临界解吸压力取 0(即假定初始压力已经达到临界解吸压力) , 其它参数 $C_De^{2S} = 10$, 圆形地层半径 $R = 1000$, 计算得到的试井理论曲线见图 2, 其中曲线 1 代表没有解吸现象的情况; 曲线 2 代表具有解吸现象的情况。

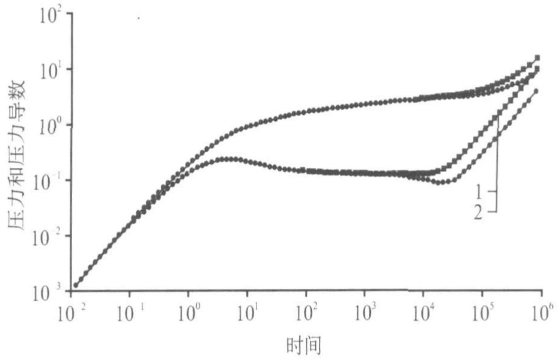


图2　具有解吸现象的试井理论曲线

从图中可以看到, 在井筒储集阶段, 考虑解吸与不考虑解吸的试井理论曲线的压力和压力导数曲线都是斜率为 1 的直线, 说明在不稳定流动的早期, 流体的流动是由井筒储存效应所控制的。在径向流阶段的早期, 压力导数曲线为水平 0.5 线, 而后期曲线开始下掉, 原因是煤层气的解吸缓解了压力下降; 晚期阶段, 在封闭边界的影响下, 两曲线都是斜率为 1 的直线, 说明地层中流体的流动已经达到了拟稳定流动状态。

2.2　稳定解吸系数的影响分析

取组合系数 $C_De^{2S} = 1$, 圆形地层半径 $R = 1000$, 稳定解吸系数分别为 -1×10^{-6}、-1.5×10^{-6} 和 -2×10^{-6}, 计算得到的试井理论曲线如图 3 所示。

从图 3 可以看出: ①在试井理论曲线的早期和中期, 解吸系数的影响不大, 与常规天然气试井的理论曲线是基本一致的; ②在试井理论曲线的晚期, 解吸系数越大, 试井理论曲线的压力曲线越平缓, 压

力导数曲线下掉的幅度越大,原因是解吸系数越大(代表解吸强度越大),煤层气解吸的量越大,从而缓解储层压力下降的幅度也就越大。

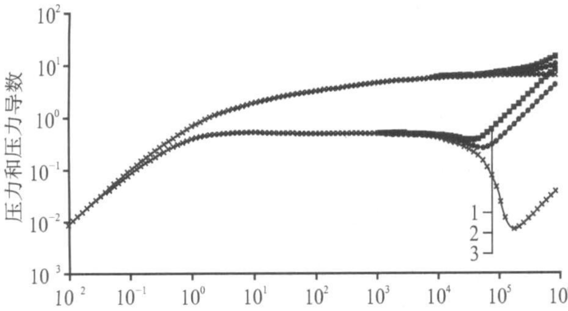


图3 稳定解吸系数对试井理论曲线的影响图

另外,可以通过计算得到不同煤层气解吸系数条件下的压力剖面(见图4)。除解吸系数不同之外,其它条件均相同的条件下,曲线1代表没有解吸作用的压力剖面图;曲线2代表解吸系数为-1×10^{-6}的情形;曲线3代表解吸系数为-2×10^{-6}的情形。从图4的压力剖面图可以看出,煤层气井稳定生产煤层气解吸作用不仅缓解了井筒压力的下降,也减缓了储层中压力波的传播,且解吸系数越大,压力传播的越慢。

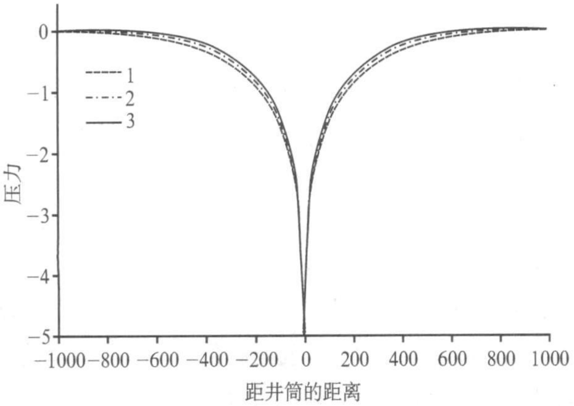


图4 稳定解吸系数对地层压力传播的影响图

2.3 解吸系数范围的影响分析

解吸系数是有一定的范围限制的,当煤层气解吸的量能够达到生产的量,则压力不再下降,流动达到一个稳定的状态,压力波不再传播出去,在试井理论曲线上类似于遇到定压边界,此时的解吸系数达到临界值(见图5)。曲线1、2的组合系数$C_D e^{2S}$=1, 10,圆形地层半径R=1000,达到稳定状态的临界解吸系数$\alpha_{1D}=-2.004\times10^{-6}$,达到稳定状态下的压力值不变,压力导数曲线下掉。

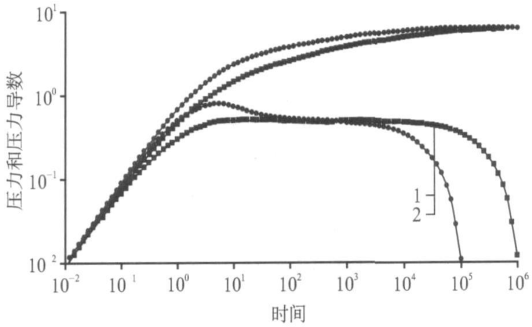


图5 解吸达到稳定状态的情形

2.4 边界性质的影响分析

边界性质对特征线的影响如图6所示。图中曲线1表示封闭边界计算的结果;曲线2表示定压边界的结果。遇到封闭边界曲线上翘,为斜率等于1的直线,流动达到拟稳定状态;而当遇到定压边界时,压力导数曲线下掉,压力达到稳定值,流动状态达到稳定状态。

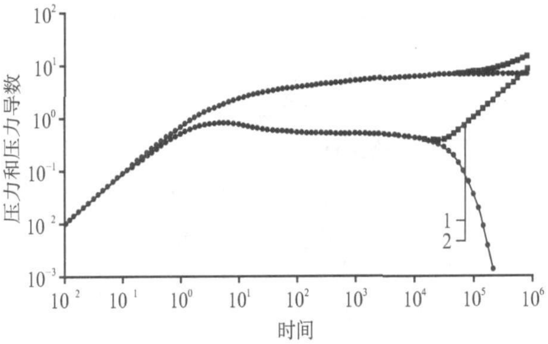


图6 边界性质的影响图

2.5 临界解吸压力的影响分析

以上计算结果都是在无量纲临界解吸压力为0的情况下所得到的。当初始地层压力不等于煤层气的临界解吸压力时,计算的试井理论曲线如图7所示,曲线1~4分别代表无量纲临界解析压力为0、0.5、1.0和1.5。当初始地层压力不等于临界解吸压力时,压力导数曲线会出现拐点,并且两压力值差得越大,拐点出现越晚,解吸作用的影响也就越小。

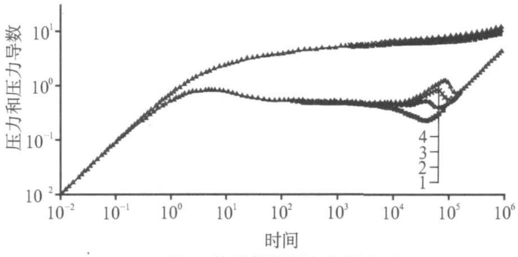


图7 临界解吸压力的影响图

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存在一条“封闭”的线性边界，表明沿该流线流动流体较难流到另一口井。对于不同性质的两井，有一条垂直于两井间连线的压力等值线，该压力等值线就像“定压供源”一样使注入的流体顺利输送到生产井，类似于煤层中存在一条“定压”的线性边界，表明垂直通过该等压线的流体易于流到生产井中。

(4) 分析了邻井流量(产/注量)对压力场的影响，对于两生产井，在等产量条件下垂直于两井的连线流线变弯，并向产量小的生产井弯曲，表明“死油区”向产量小的生产井方向移动，同时也表明有更多的流体流向产量较大的生产井。对于一口注入井和一口生产井的情况，如果注入井的注入量大于生产井的产量，在等注入量条件下垂直于两井的连线压力等值线变弯，并向生产井弯曲，表明煤层中注入压力较大。

(5) 分析了外边界性质邻井对压力场的影响，无论生产井还是注入井，煤层中的压力等值线都正交于外边界线上。对于生产井，说明外边界是封闭的不能提供流体供源；对于注入井，说明外边界是封闭的不能向外传输流体。

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3 结论

本文建立了考虑解吸作用的煤层气数值试井模型，从计算结果的分析及对比可知，煤层气解吸作用影响试井理论曲线的中后期，能缓解地层中压力下降，减缓压力波的传播，且当解吸作用达到一定强度，煤层气解吸量达到生产量时，压力停止传播，这类似于定压边界。临界解吸压力对试井理论曲线的影响也比较明显，临界解吸压力和初始地层的压力相差越小，煤层气解吸出现的时间越早，影响也越大。

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the problem why CBM is cleaner, efficient and safe energy resource. First, CBM is a new energy showed by it's development history and unconventional properties. Second, CBM is cleaner than other energy resources considering it's combustion products. Third, CBM is more efficient due to it's calorific value and utilization ratio. In addition, CBM is safe in atmospheric environment and coal mine environment. In this paper, C/H ratio is considered to be a key factor to energy resources mainly comprised of carbon element and hydrogen element in determining the quality of the energy. That is to say, the smaller the C/H ratio is, the better(cleaner, more efficient and safer) the energy is. Finally, according to the advantages of CBM, it plays an important role in energy supply and environment protection, which shows the importance of development and utilization of CBM.

Key words: coalbed methane, clean energy, efficient energy, safe energy, environment pollution

Study on AGA8-92DC Method of Gas Deviation Factor Calculation. 2010, 19(6): 29~36

Su Zhongliang, Liu Yuewu (Institute of Mechanics, Chinese Academy of Sciences), Zhang Junqing (International Division, CNPC)

The deviation factor, as one of the most important physical property parameters of natural gas, plays an important role in the exploration, production, transportation, processing and use of natural gas. In this paper, the existing methods of calculating the gas deviation factors are summarized, and a special research of a widely used method named AGA8-92DC (AGA8) is conducted. Although AGA8 has been an international standards on calculating gas deviation factors since 1992, few studies have been conducted up to now. So the scope of application or the accuracy of AGA8 is not well known. Using the self-compiled C++ program for AGA8, we obtain the deviation factors of the gases with different components under different temperatures and pressures. By comparing the computed deviation factors with the Standing-Katz chart data or experimental data , the scope of application of AGA8 is determined. This study will lay a solid foundation for the application and extension of AGA8 method.

Key words: natural gas, deviation factor (compressibility factor), critical properties, EOS

Review on CBM Desorption/Adsorption Mechanism. 2010, 19(6): 37~44

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By analyzing factors that restricting the development of CBM and energy demand at home and abroad, the paper pointed out that researching CBM desorption and adsorption mechanism is significant. Through analyzing domestic and international history and current status of CBM desorption and adsorption mechanism, CBM desorption and adsorption mechanism was grouped into two classes: monolayer adsorption and multi-molecular layer adsorption. CBM desorption and adsorption mechanism model was divided into five categories: Langmuir isothermal and the extended model, BET multi-molecular layer adsorption model, adsorption potential theoretical model, adsorption solution model and experimental data analysis model. Factors that affecting CBM desorption and adsorption which included coal bed property, pore structure, components of CBM, pressure conditions, temperature conditions and so on were analyzed in detail. The research showed future direction of desorption and adsorption mechanism, especially the way of methane and water combining and separation with carbon molecules in coal bed, was to study mainly the dynamic process of CBM desorption and adsorption states in the condition of complex factors at current.

Key words: coalbed methane (CBM), absorption/desorptio, mechanisum, model

Research on Unstructured Grid Generation for CBM Numerical Well Testing. 2010, 19(6): 45~48

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This paper analyzes the unstructured grid generation methods in numerical well testing. The "winged edge" data structure is designed by using the good characteristics of Delaunay triangulation. The constrained Delaunay triangulation algorithm with good mesh quality is achieved. Examples show that the resulting grid with boundary constraint consistency and better quality, which can meet the requirements of CBM computing numerical well testing.

Key words: CBM well tesing, unstructured grid, Delauany triangulation, constrained, Voronoi diagram

Numerical Well Testing Method for Well by Considering CBM Desorption. 2010, 19(6): 49~52, 70

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The distinguish character between CBM well test and normal gas well test is the desorption phenomena in coalbed. This paper developed a new well test model for CBM well by considering the desorption effect in homogeneous coalbed. The stable source method is introduced to describe the desorption effect in the governing equation. And the numerical solution is obtained by finite element method. By analyzing the desorption coefficient, it shows that the desoption effect made the pressure drop slowly and the pressure wave propagate slowly also. When the desorption coefficient reached a certain value, the desorption rate will be equal to the production rate and the pressure wave will stop propagate. It is similar to that there exists a constant pressure boundary in the coalbed. In addition, by considering the effect of critical desorption pressure, it shows that the smaller difference between the critical desorption pressure and the initial pressure, the earlier emerging of the desorption effect and the greater impact on well test type test curve.

Key words: CBM, seepage, desorption, numerical well testing, finite element

Numerical Well Test Model for CBM Infinite Conductivity Vertical Fracture Well. 2010, 19(6): 53~56

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Considering the effects of CBM desorption and absorption in coalbed, a new infinite conductivity vertical fracture well test model is developed in this paper, the finite element equation was derived and numerical solution was obtained. The type curve in double logarithmic form and pres-