洞穴完井煤层中渗流场的数值研究

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摘要 提出了煤层气井洞穴完井的物理模型,将完井洞穴看成一个在煤层气井井底附近渗透率远大于外区煤层的高渗区域,并假定该区域中的流体流动仍然符合 Darcy 流动。在此基础上建立了煤层气井洞穴完井的渗流数学模型,通过有限元求解方法得到了洞穴完井煤层气井在圆形煤层和任意四边形煤层中的渗流场分布。为了与裸眼完井煤层气井的渗流场进行对比,模拟了圆形存在一口洞穴完井煤层气井和一口裸眼完井煤层气井及一口洞穴完井煤层气井和两口裸眼完井井的渗流场,明显看出了洞穴完井煤层气井渗流场与常规裸眼完井井的差异。该研究成果对更好地了解洞穴完井煤层气井的流体流动规律及压力分布状态有积极的意义。

关键词 煤层气 洞穴完井 模型 渗流场 有限元

0 引 言

煤层气是一种高效清洁的新型非常规天然气新能源[1,2],然而煤层气的排采受到许多因素的制约。中国的煤层气藏大多数都是低渗透煤层气藏,其煤层气排采技术一般采用水力压裂改造煤层或水平井完井排采技术。这两种技术各有其优缺点,水力压裂技术对于常规油气藏较为成熟,但在煤层气井压裂过程中容易压穿煤层造成水窜;水平井技术是先进的常规油气藏完井技术,但在煤层气藏水平井完井过程中,由于煤质疏松容易造成水平井眼垮塌,给水平井完井施工和后续施工维护带来诸多不便。而洞穴完井是目前世界上提出的一种新的完井技术,已逐步在世界范围内推广应用。

洞穴完井是由 Mavor[3] 在 1992 年首先提出的一种完井方法,它包括一系列的注入/排出过程。本质上,洞穴完井是在裸眼完井的基础上发展起来的一种独特的煤层气井完井方式。一般有自然裸眼洞穴完井、动力或人工裸眼洞穴完井两种方式。自然裸眼洞穴完井是在较高生产压差的作用下,利用井眼不稳定性,在井壁煤岩发生破坏后允许煤块塌落到井筒中,进而形成物理洞穴。动力或人工裸眼洞穴完井是人工施加压力从地面注气,使井壁煤层发生破坏,再清除井底的煤粉,进而形成物理洞穴。美国在圣胡安盆地实施了这项技术,从现场试验结果来看,裸眼洞穴完井的产量都较高,且大大高于压裂完井的产量。分析认为,获得高产的主要原因有两个方面,一是煤层气井的泄流面积增大了,二是由于井底压力场的改变使周围的应力场发生了相应变化,使裂缝的沟通得到改善,从而增加了井底附近区域煤层的渗透率,进而使煤层气的生产产量增加。1998 年,我国田中岚等人[4] 对该项技术进行了介绍。2002 年,J. Q. Shi 等人[5] 对洞穴完井技术中的关键影响因素进行了较为全面的分析,给出了洞穴完井后煤层中的孔隙压力分布状况。

针对这种完井技术的煤层气渗流场作了较详细的研究工作,首先抽象出了煤层气井洞穴完井的物理模型,即在煤层气井井底附近区域存在一个远大于煤层的高渗区域,并假定该区域中的流体流动仍然符合 Darcy 流动。在物理模型描述的基础上,建立了煤层气井洞穴完井井的数学模型。通过有限元求解方法得到了洞穴完井井在圆形煤层和任意四边形煤层中的渗流场分布。为了与裸眼完井煤层气井的渗流场进行对比,模拟了圆形存在 1 口洞穴完井井和 1 口裸眼完井井及 1 口洞穴完井井和 2 口裸眼

[基金项目] 本研究得到国家重大专项"大型气田及煤层气开发"专项支持,课题编号 2009ZX05038001。

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完井井的渗流场,从而明显看出了洞穴完井井渗流场与常规裸眼完井井的差异。本文的研究成果可以更好的了解洞穴完井井的流体流动规律及压力分布状态变化有积极的意义。

1 基本渗流物理模型

物理模型描述:

(1) 煤层为均匀各向同性介质,煤层成水平板状展布。

(2) 煤层中的流体为弱可压缩、定常粘度的牛顿流体,流体在煤层中的流动为层流状态,遵从达西定律。

(3) 煤层气井定产量产液,气水混合均匀。

(4) 由于是洞穴完井,在煤层气井井底附近区域存在一个远大于煤层的高渗区域,并假定该区域中的流体流动仍然符合 Darcy 流动。

(5) 由于测试时间相对来说较短,故在整个测试过程中可以认为煤层气稳定解吸。

(6) 忽略重力和温度变化对流动的影响,且不考虑其它物理化学的影响。

2 不定常渗流数学模型

根据所描述的洞穴完井的物理模型,可以得到洞穴完井煤层气井的不定常渗流数学模型。

洞穴内的扩散方程为:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p_1}{\partial r}\right)+q_1=\frac{\varphi_1\mu_1 C_{t1}}{3.6K_1}\frac{\partial p_1}{\partial t}\qquad 0<r<r_a \tag{1}$$

洞穴外的扩散方程为:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p_2}{\partial r}\right)+q_1=\frac{\varphi_2\mu_2 C_{t2}}{3.6K_2}\frac{\partial p_2}{\partial t}\qquad r_a<r<r_e \tag{2}$$

初始条件:

$$p_1\big|_{t=0}=p_i \tag{3}$$

$$p_2\big|_{t=0}=p_i \tag{4}$$

内边界条件:

$$r\frac{\partial p_1}{\partial r}\bigg|_{r=r_w}=\frac{1.842\times10^{-3}quB}{Kh}-C\frac{\mathrm{d}p_w}{\mathrm{d}t} \tag{5}$$

外边界条件:

无限大边界: $p_2\big|_{r\to\infty}=p_i$ (6)

定压边界: $p_2\big|_{r=r_e}=p_i$ (7)

封闭边界: $r=\frac{\partial p_2}{\partial r}\bigg|_{r=r_e}=0$ (8)

连接边界条件:

压力连续边界条件:

$$p_1(r_a,t)=p_2(r_a,t) \tag{9}$$

流量连续边界条件:

$$r\frac{\partial p_1}{\partial r}\bigg|_{r=r_a}=Mr\frac{\partial p_2}{\partial r}\bigg|_{r=r_a} \tag{10}$$

式中: B —— 体积系数, m^3/m^3;

C —— 井筒存储系数, m^3/MPa;

C_t —— 总压缩系数, m^3/MPa;

h —— 煤层有效厚度, m;

K —— 煤层渗透率, $10^{-3}\mu m^2$;

p —— 煤层压力, MPa;

p_i —— 煤层原始压力, MPa;

q —— 井的产液量, m^3/d;

q_1 —— 煤层气的解吸量, m^3/d;

r —— 距井点的距离, m;

r_w —— 煤层气井半径, m;

r_a —— 洞穴完井区的半径, m;

r_e —— 煤层外边界半径, m;

φ —— 煤层孔隙度;

μ —— 煤层中流体的粘性, mPa·s;

M —— 流度比。

将上述方程无量纲化,洞穴内的流动控制方程:

$$\frac{1}{r_D}\frac{\partial}{\partial r_D}\left(r_D\frac{\partial p_{1D}}{\partial r_D}\right)+\alpha_D=\frac{\partial p_{1D}}{\partial t_D}\qquad 1\leqslant r_D\leqslant r_{aD} \tag{11}$$

$$\frac{1}{r_D}\frac{\partial}{\partial r_D}\left(r_D\frac{\partial p_{2D}}{\partial r_D}\right)+\alpha_D=M\frac{\partial p_{2D}}{\partial t_D}\qquad r_{aD}\leqslant r_D\leqslant r_{eD} \tag{12}$$

初始条件:

$$p_{1D}(r_D,0)=0 \tag{13}$$

$$p_{2D}(r_D,0)=0 \tag{14}$$

内边界条件:

$$r_D\frac{\partial p_{1D}}{\partial r_D}\bigg|_{r_D=1}=-1+C_D\frac{\mathrm{d}p_{wD}}{\partial t_D} \tag{15}$$

外边界条件:

无限大边界: $p_{2D}\big|_{r_D\to\infty}=0$ (16)

定压边界: $p_{2D}\big|_{r_D=r_{aD}}=0$ (17)

封闭边界: $r_D \left.\frac{\partial p_{2D}}{\partial r_D}\right|_{r_D = r_{eD}} = 0$ (18)

连接边界条件:

压力连续边界条件:

$$p_{1D}(r_{aD}, t_D) = p_{2D}(r_{aD}, t_D) \quad (19)$$

流量连续边界条件:

$$\left.\frac{\partial p_{1D}}{\partial r_D}\right|_{r_D = r_{aD}} = M \left.\frac{\partial p_{2D}}{\partial r_D}\right|_{r_D = r_{aD}} \quad (20)$$

无量纲量的定义如下:

$$p_{jD} = \frac{2\pi K_2 h(p_i - p_j)}{q \mu_2 B} \qquad j = 1, 2$$

$$t_D = \frac{3.6Kt}{\phi\mu C_t r_w^2} \qquad C_D = \frac{0.1592C}{\phi h C_t r_w^2}$$

$$r_D = \frac{r}{r_w} \qquad a = \frac{r_1}{r_w}$$

$$r_{eD} = \frac{r_e}{r_w} \qquad M = \frac{K_2/\mu_2}{K_1/\mu_1}$$

$$\alpha_D = \frac{K_1 h q_1}{1.842 \times 10^{-3} Q \mu B}。$$

式中: p_{jD} —— 无量纲压力;

t_D —— 无量纲时间;

a —— 界面的无量纲半径;

r_{aD} —— 洞穴完井区的无量纲半径;

α_D —— 解吸系数。

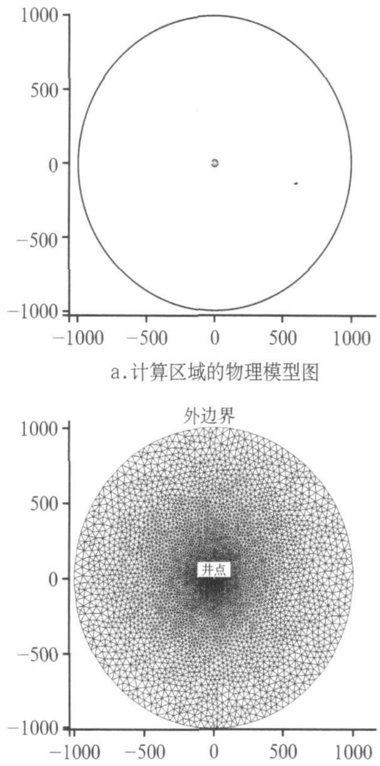
3　单一洞穴完井煤层气井渗流场

3.1　圆形煤层中洞穴完井煤层气单井的渗流场

为了模拟煤层气单井的渗流场, 首先选定一圆形煤层, 其中煤层气井位于煤层的中心, 由于假设煤层是均匀水平板状的, 可以忽略重力的影响, 计算区域的物理模型, 如图 1a 所示。用 2D 模型来模拟实际的 3D 问题, 计算区域及网格划分图如图 1b 所示。所研究的问题可以抽象为图 1a 所示的图形, 煤层的范围为无量纲半径 1000 的圆, 完井的洞穴为无量纲半径 10 的圆。有限元计算的非结构化网格如图 1b 所示。

通过有限元计算可以得到计算区域渗流场, 计算区域渗流场图如图 2 所示, 其中带网格的压力场云图如图 2a 所示, 由流线和压力等值线构成的渗流场图如图 2b 所示。

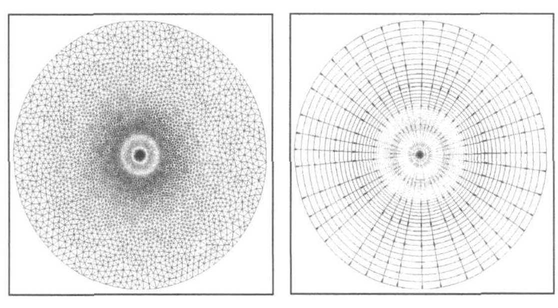
从图 2 可以看出, 近井区域存在一个压力低值区域, 说明近井区域流动阻力较小。从图 2b 可以看出, 整个流动区域内的流体流动为径向流, 流线方向指向煤层气井。压力波在均质煤层中的传播是径向的、向外扩展的, 将煤层气井设在圆形煤层的中心是便于看到煤层中的压力以同心圆的方式向外扩展的。由于洞穴完井后, 近井附近的煤层渗透率较大, 压力波传播速度会有较快的发展。



a.计算区域的物理模型图

b.计算区域的网格图

图1　计算区域及网格划分图

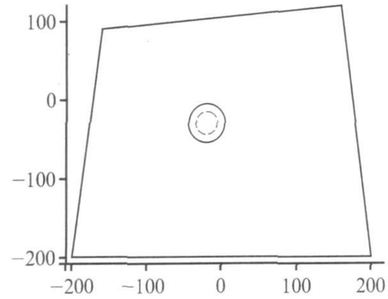


a.网格的压力场云图　　b.计算区域的渗流场图

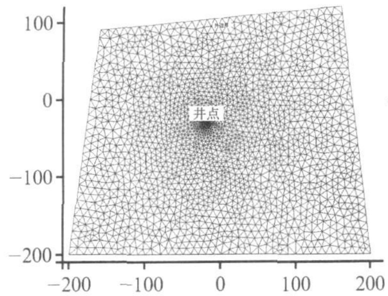
图2　计算区域的渗流场图

3.2　任意四边形煤层中洞穴完井煤层气单井的渗流场

为了说明模型边界特征, 对线性组合边界煤层中煤层气单井的渗流进行了模拟计算。选定面积区域较小的一个任意四边形煤层。计算区域的物理模型及计算区域的物理数据如图 3a 所示; 计算区域及网格划分图如图 3b 所示。



a. 计算区域的物理模型图



b. 计算区域的网格图

图3 计算区域及网格划分图

通过有限元计算可以得到计算区域渗流场图如图 4 所示。

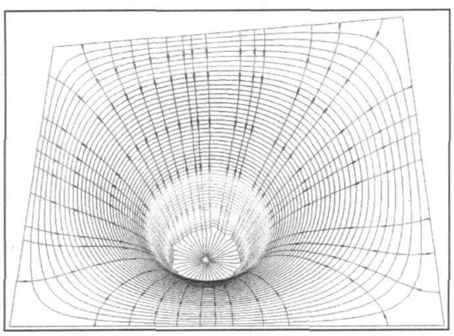


图4 计算区域的拟3D渗流场图

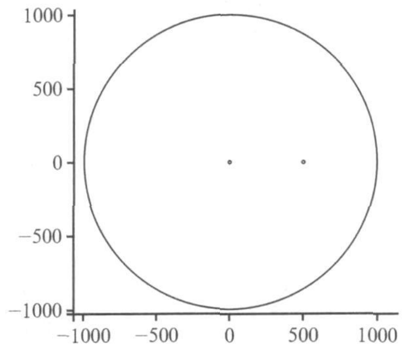
从图 4 可以看出, 由于计算区域较小, 洞穴完井的近井高渗区域的渗流场压力梯度较小, 远井区域压力梯度较大。

4 洞穴完井煤层气井与常规裸眼完井渗流场对比

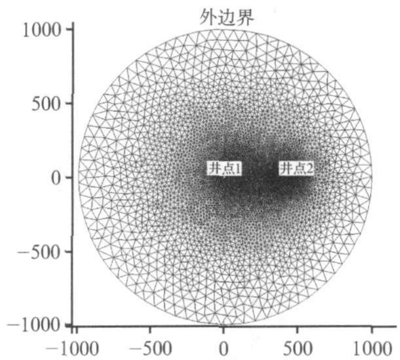
在洞穴内形成的一个高渗区域的大小是由洞穴完井工程的规模所决定的。洞穴完井煤层气井与常规完井煤层气井渗流场的差异是由洞穴完井后洞穴的性质所决定的, 即由洞穴区域的渗透率及洞穴尺寸所决定的。以下给出了不同井数条件下的计算模拟对比。

4.1 圆形煤层中洞穴完井煤层气井与 1 口裸眼完井煤层气井的渗流场的模拟

选定一个圆形煤层区域, 边界性质为封闭边界, 圆形煤层区域内有两口煤层气井, 其中 1 口井为洞穴完井煤层气井; 而另 1 口煤层气井是常规裸眼完井煤层气井。计算区域的物理模型及计算区域的物理数据如图 5a 所示; 计算区域及网格划分图如图 5b 所示。



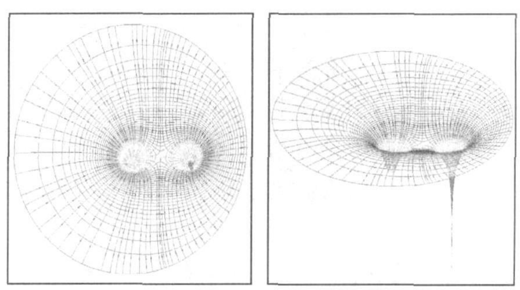
a. 计算区域的物理模型图



b. 计算区域的网格图

图5 计算区域及网格划分图

通过有限元计算可以得到计算区域渗流场, 计算区域渗流场图如图 6 所示, 其中由流线和压力等值线构成的 2D 渗流场图如图 6a 所示, 由流线和压力等值线构成的 3D 渗流场图如图 6b 所示。



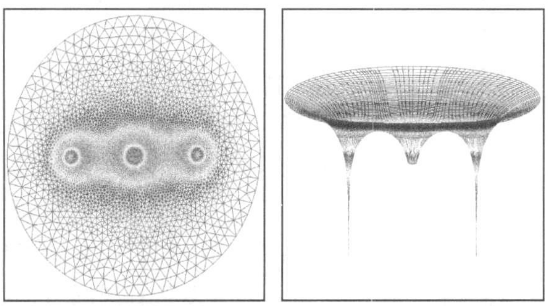
a. 两井对比情况下2D渗流场图 b. 两井对比情况下3D渗流场图

图6 计算区域的渗流场图

从图 6 可以看出, 洞穴完井煤层气井的渗流场与常规裸眼完井煤层气井的渗流场存在明显差异, 洞穴完井煤层气井的近井区域压力梯度较小, 而常规裸眼完井煤层气井的近井区域压力梯度较大, 远井区域的压力梯度的差异较小。

4.2　圆形煤层中洞穴完井煤层气井与 2 口裸眼完井煤层气井的渗流场的模拟

选定一个圆形煤层区域, 边界性质为封闭边界, 圆形煤层区域内有 3 口煤层气井, 其中 1 口井为洞穴完井煤层气井; 而另 2 口煤层气井是常规裸眼完井煤层气井。通过有限元计算可以得到计算区域渗流场, 计算区域渗流场图如图 7 所示, 其中由流线和压力等值线构成的 2D 渗流场图如图 7a 所示, 由流线和压力等值线构成的 3D 渗流场图如图 7b 所示。



A.3井对比情况下
带网格的压力场云图　　b.3井对比情况下3D渗流场图

图7　计算区域的渗流场图

从图 7 可以看出, 洞穴完井煤层气井的渗流场与常规裸眼完井煤层气井的渗流场存在明显差异, 洞穴完井煤层气井的近井区域压力梯度较小, 而常规裸眼完井煤层气井的近井区域不存在压力梯度低值区域, 且常规裸眼完井煤层气井的近井区域压力梯度较大, 远井区域的压力梯度的差异较小。

5　结　论

(1) 首次提出了煤层气井洞穴完井的物理模型, 即将完井洞穴看成是一个在煤层气井井底附近渗透率远大于外区煤层的高渗区域, 并假定该区域中的流体流动仍然符合 Darcy 流动。

(2) 在物理模型描述的基础上, 建立了煤层气井洞穴完井的渗流数学模型。

(3) 通过有限元求解方法, 得到了洞穴完井煤层气井在圆形煤层和任意四边形煤层中的渗流场分布, 可以明确看到近井区域渗流场与远井区域渗流场的差异。

(4) 通过模拟了圆形存在 1 口洞穴完井煤层气井和 1 口裸眼完井煤层气井及 1 口洞穴完井煤层气井和 2 口裸眼完井井的渗流场, 从与裸眼完井煤层气井的渗流场的对比, 明显看出洞穴完井煤层气井渗流场与常规裸眼完井井的差异。

致　谢

本项目得到国家重大专项"大型油气田及煤层气开发"专项的支持, 课题编号 2009ZX05038001, 感谢中石油煤层气有限责任公司允许本论文的发表。

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本文收稿日期: 2010– 11– 08　编辑: 方志慧

sure distribution field in coalbed are all showed in detail. The well test type curves showed that there are parallel straight section lines in pressure and pressure derivative curve with slope equal to 0.5, which confirmed the existence of linear flow in coalbed. From the pressure distribution field map, we found that the elliptic flow around fractures, but the radial flow far away from fractures. The effect of CBM desorption to theoretical curves showed pressure and pressure derivative curves drew down in middle and later periods of curves. And the reason was CBM desorption delayed the pressure decrease. By analyzing the fracture asymmetry about the wellbore, the results show that there is less impact of fracture asymmetry on the well test type curve for the different calculation cases, since the fractures are infinite conductivity vertical fracture. wellbore asymmetry had well test theory curves.

Key words: CBM, numerical well testing, desorption, infinite conductivity, fractures well, type curve

The Exploration of Finite Volume Method in CBM Numerical Well Testing. 2010, 19(6): 57~63

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By comparing the advantages and disadvantages among the normally used numerical methods in modern numerical well testing technology, it shows that the finite volume method is the best one for solving the governing equation of CBM. So we choose finite volume method to solve CBM numerical well testing model. 1-D radial flow and 2-D flow model are developed for the well in circular CBM region with steady desorption. The corresponding discrete equation forms of the finite volume method are derived for both 1-D and 2-D cases. The influence of desorption coefficient, the boundary distance, boundary properties, the combination coefficient etc on test well test type curves are discussed in detail in this work. The results show that the type curves clearly reflected the pressure changes of CBM wells in the different conditions, and finite volume method is very suitable for solving CBM well test problem. Finite volume method provides a new numerical calculation method for solving CBM well test model. It leads a productive progress on developing CBM numerical well test.

Key words: CBM, finite volume method, numerical well test, steady desorption

Research on Pressure Field in Circle Bounded Coalbed With Two Wells. 2010, 19(6): 64~70

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The nature of CBM production is draining water to drop pressure and produce methane. So it is important to know the pressure dropping effect for producing methane. By considering CBM desorption effect, mathematical model for unsteady seepage flow is developed in circle bounded coalbed with two wells. The numerical solutions are obtained by using the finite element method. The desorption effects on the well test type curve are analyzed in detail. The results show that CBM desorption decrease the pressure wave transmitting velocity in the coal bed. The effect of the neighbor well property on type curve is also analyzed for describing the development of pressure field. Four kind of description methods are intrduced and evaluated in this paper. The effects of well property, flow rate of the neighbor well and property of the outer boundary on the pressure field are analyzed for the pressure field changing under different conditions.

Key words: coalbed methane, pressure field, well test, desorption

Numerical Study on Seepage Field in Coalbed With Cavity Well. 2010, 19(6): 71~75

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Physical model of fluid flow in coalbed with CBM cavity well is described in this paper at the first time. Near the wellbore there exists a high permeability region whose permeability is far greater than that of the coalbed far from the CBM well. The fluid flow in this region also obeys Darcy's flow. Based on the description of physical model, mathematic model for fluid flow in coalbed wih CBM cavity well is developed in this paper. Seepage field in coalbed with CBM cavity well is obtained under circular and arbitrary quadrilateral outer boundary by using finite element method. In order to compare seepage field in coalbed with CBM cavity wells with that of open hole completion well, seepage is simulated about one cave completion, one open hole completion and one cave completion, two open hole completions. So the difference of seepage between cave completion and open hole completion is visible. The results of this research is significant important to comprehend fluid flow mechanics and pressure distribution in coalbed with CBM cavity wells.

Key words: CBM, model, seepage, seepage field, finite element

Software Design and Development of CBM Well Test. 2010, 19(6): 76~81

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The significance of design and development of CBM well test analysis software is introduced and the characteristics of oil and gas well test analysis software normally used at home or abroad are summarized in this paper. With the development of CBM well test technique and the requirements of CBM well test analysis, software technical requirement and development are introduced, framework and all function modules of the software are designed, all based on the special nature of CBM such as desorption, deformation, low permeability, etc. CBM well test analysis software is designed and developed based on software engineering thought. The software includes data preparation module, well test analysis module, well test design module and report generation and output module. The software has friendly UI, rich models, powerful function and friendly framework.

Key words: software, CBM, well test, design and development