煤层气数值模拟的地质模型与数学模型

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摘 要 煤层气数值模拟是以计算机为支持条件, 模拟煤层气产出的全过程。基本步骤是: 首先根据煤储层的地质特征, 建立合理的地质模型; 并据煤层气产出机理, 建立能描述煤层气运动过程基本物理现象和边界条件、初始条件的数学模型, 再离散化成数值模型; 然后编制成计算机程序, 建立计算机模型。文中介绍的煤层气数值模拟方法能全面、系统地综合分析各种影响因素, 客观反映流体在储层中的流动特性, 并具有开发成本低、可重复进行的特点。

主题词 煤层 孔隙结构 渗透率 地质模型 数学模型

煤层气数值模拟的物理机理与地质模型

(1) 煤的孔隙结构与含气性

煤为双孔隙结构, 分为基岩(质)孔隙和割理孔隙。基岩孔隙(或称基质孔隙)又称微孔隙, 孔径很小, 一般为 0.5~ 1 nm, 水被认为是不能到达的。煤的微孔隙极其发育, 煤层气储集的主要机理是吸附在微孔隙的表面, 因此煤层气的绝大部分储集在微孔隙中, 在压力作用下呈吸附状态。割理孔隙是煤化作用的结果(内生裂隙), 局部也由构造力所引起(外生裂隙)。割理间距比较均一, 从几毫米到几厘米, 在煤中出现两种类型的割理, 面割理和端割理。割理孔隙的孔径从几纳米到几十纳米, 它是气水流动的主要通道。在初始状态, 一般认为由 100% 的水充填。煤的割理孔隙度随着煤层孔隙压力的降低而变小。

煤对水的总有效孔隙度一般小于 2%, 但对气的有效孔隙度可高达 10%, 其原因是微孔隙对水的不可到达性。

$$\Phi_a = \Phi_0 e^{C_p(P - P_0)} \qquad (1)$$

式中: Φ_a 为割理孔隙度; Φ_0 为初始孔隙度; P 为地层压力; P_0 为初始地层压力; C_p 为地层孔隙压缩系数。

煤层气以吸附、游离、溶解 3 种状态赋存于煤层中。煤层气的绝大部分呈吸附状态保存于煤的基岩(质)微孔的内表面上。煤层气在煤储层中的赋存状态, 随着排采过程中的地层压力的改变而发生变化。

(2) 煤的吸附机理

吸附是一种物理现象, 吸附能力与温度、压力有关。当温度一定时, 随压力的升高吸附量增大; 当压力达到一定程度时, 煤的吸附能力达到饱和。吸附是百分之百的可逆过程。当压力降低时, 气体将解吸出来。实验室可测定煤的等温吸附线。

煤的吸附作用有三类数学模型: 亨氏等温吸咐模型(Henry)、付氏等温吸附模型(Freudlich)、兰氏等温吸附模型(Langmuir)。

对柳林杨家坪煤层气实验区 6 口井的 28 个煤岩样品作等温吸附实验, 结论是: 93% 符合兰氏模型, 7% 符合付氏模型, 无一符合亨氏模型。

压力降低到使吸附在煤层微孔隙表面上的气体开始解吸的压力称之为解吸压力。当解吸压力等于原始地层压力时, 这种煤层为饱和煤层; 当解吸压力小于原始地层压力时, 这种煤层为欠饱和煤层。欠饱和煤层往往在漫长的地质年代中由于地质运动造成吸附气的散失而又未得到补充。解吸压力可由含气量数据和等温吸附数据计算求得。

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(3) 煤层气的扩散机理

在煤层微孔隙系统中, 由于渗透性很差, 对气的单相渗透率可以忽略, 扩散是气体迁移的主要方式, 它遵守 Fick 定律。

$$\frac{m_g}{A} = - MD_i \nabla C_i \tag{2}$$

式中: m_g 表示扩散量; A 表示面积; M 表示气体分子量; D_i 表示扩散系数; C_i 表示气体浓度。

实验室测定的扩散系数在 $9.3\times10^{-7}\sim 9.3\times10^{-11}$ ft^2/d 之间($1\ ft^2= 92.903\,0\times10^{-3}m^2$) 。

所有的双重孔隙模型, 都把储层理想化为间距均一的几何基岩(质) 块体, 这些几何块体有: 板状、圆柱状和球体。处理煤层气的扩散有二种模型: ①非稳态吸附模型。它基于 Fick 第二定律, 用偏微分方程描述几何块体的扩散过程, 几何块体内的浓度从中心到边缘是变化的, 一般假定几何块体中心的浓度变化率为零, 几何块体边缘浓度是受地层压力控制的吸附浓度, 随着开采过程中地层压力的变化, 几何块体的浓度也发生变化。 ②拟稳态吸附模型。它基于 Fick 第一定律, 认为煤层气在扩散过程中的每一个时间段都有一个平均浓度。这个平均浓度是上一个时间段平均浓度、解吸时间、时间段值及边缘吸附浓度的函数, 根据平均浓度随时间的变化计算气体扩散量。

煤层气的扩散受几何块体边缘浓度的控制, 而该浓度与割理系统中游离气的压力处于平衡状态。对于常规油气藏的双孔隙模型而言, 则假定压力在原生孔隙和次生孔隙网络的分界面是连续的。这是煤层气模型与常规油气藏模型的一个明显区别。

(4) 煤的渗透性

煤中气水的输导主要受割理孔隙度和各种裂隙控制, 煤层为低渗地层, 渗透率通常小于 1 mD* 。煤层渗透性的一个重要特点是各向异性, 延伸较长的面割理方向具有较高的渗透性, 常比端割理方向的渗透性高几倍甚至一个数量级。煤层渗透率也取决于地层孔隙压力, 随地层孔隙压力的降低引起割理封闭, 从而使渗透率减小。

渗透率随地层孔隙压力的变化由下式表示:

$$K = K_0[e^{C_p(P-P_0)}]^n \tag{3}$$

式中: K 表示渗透率; K_0 表示初始渗透率; n 表示常数, 一般取 3。

煤层气开采使饱含水的煤层处于气、水两相流状态, 气水流动受到相对渗透率的影响。由于煤层较之于常规砂岩层, 有较高的束缚水饱和度, 水的饱和度总是保持在较高的水平。在该饱和度范围内随着压力降低, 水的相对渗透率急剧下降, 而气的相对渗透率则处于较低的水平。

(5) 煤层气的流动机理

煤层气由解吸、扩散进入割理孔隙系统, 产生气、水两相流动。

1) 气相流动

割理孔隙中的游离气服从真实气体方程, 流动有二种机理, 在压力驱动下的达西流动和滑动。达西流动遵循达西定律, 气体流动的质量流速 m_g 为:

$$m_g = V_g \rho_g \tag{4}$$

$$V_g = \frac{q_g}{A} = -\alpha\lambda_g \nabla P_g \tag{5}$$

$$\lambda_g = \frac{KK_{rg}}{\mu_g} \tag{6}$$

$$\rho_g = \frac{MP_g}{ZRT} \tag{7}$$

式中: V_g 为气的体积流速; ρ_g 为气体密度; q_g 为体积流量; A 为面积; α 为单位转换常数; λ_g 为气的流动系数; P_g 为气相压力; K_{rg}为气相相对渗透率; μ_g 为气相粘度; Z 为气体偏差系数; R 为气体常数; T 为温度。

气体滑动是对达西流动的补充, 考虑到煤储层一般埋藏较浅, 因而地层压力较低, 同时煤储层的渗透率一般也较低。滑动采用了 Fick 扩散方程(类似前述方程) 。

气体滑动的质量流速 m_g 为:

$$m_g = - MD_a \nabla C_a \tag{8}$$

$$C_a = \frac{S_g P_g}{ZRT} \tag{9}$$

式中: D_a 为气体滑动因子; C_a 为气体浓度; S_g 为含气饱和度。

2) 水相流动

割理孔隙系统中水相的流动遵循压力驱动下的

* 但美国一些煤层的渗透率是较高的, 有的可达到 10 mD 以上, 1 mD= $10^{-3}\mu m^2$。

达西定律。

水的质量流速 m_w 为:

$$m_w = -\frac{\alpha K K_{rw}}{\mu_w B_w}\nabla P_w \tag{10}$$

式中: K_{rw}为水相相对渗透率; μ_w 为水的粘度; B_w 为水的体积系数; P_w 为水相压力。

(6) 煤层气的产出

煤层气的产出可由井点所在网格计算, 利用径向不可压缩流体流动方程计算气、水产量, 同油藏中所用计算公式是相同的, 如下所示:

$$Q_{gsc} = \frac{2\pi\alpha h K \lambda_g}{\ln\frac{r_e}{r_w} + S}(P_g - P_{wf}) \tag{11}$$

$$Q_{wsc} = \frac{2\pi\alpha h K \lambda_w}{\ln\frac{r_e}{r_w} + S}(P_w - P_{wf}) \tag{12}$$

式中: Q_{gsc}为产气量; Q_{wsc}为产水量; h 为煤层厚度; r_e 为有效半径; r_w 为井筒半径; λ_g 为气相流动系数; λ_w 为水相流动系数; S 为井筒表皮系数; P_g 为网格气相压力; P_w 为网格水相压力; P_{wf}为井底流动压力。

煤层气数值模拟的数学模型

1. 煤层气数值模拟的数学模型

流体运动的基本微分方程 ——连续性方程是:

$$\frac{\partial p}{\partial t} + \mathrm{div}(\rho\vec{v}) = f \tag{13}$$

由该方程可得割理(裂缝) 中气相流动和水相流动的渗流方程以及微孔中煤层气浓度分布的扩散方程。事实上, 将煤层视为水平层状孔隙—裂缝双重非均匀介质, 由煤层气在介质中渗流的 Darcy 定律可得裂缝中的气相(以下标 g 表示) 渗流方程, 亦即:

$$-\mathrm{div}(\rho_g\vec{v}_g) + m_{ai} = \frac{\partial}{\partial t}(\Phi_a\rho_g S_{ag}) \tag{14}$$

式中: ρ_g 为气体密度; $\vec{v}_g$ 为气体的体积流速; m_{ai}为单位时间内单位体积微孔向割理解吸气体的质量; Φ_a 为割理孔隙度; S_{ag}为气饱和度。

气体的体积流速由 Darcy 流速和滑动流速两项合成, 再由真实气体定律得割理中的气相渗流方程:

$$\nabla\left(\frac{\alpha\lambda_g}{B_g}\nabla P_{ag} + D_a\nabla\frac{S_{ag}}{B_g}\right) + q_{ai} = \frac{\partial}{\partial t}\left(\Phi_a\frac{S_{ag}}{B_g}\right) \tag{15}$$

其中:

$$\frac{1}{B_g} = \frac{T_{sc}P_{ag}}{P_{sc}TZ} \qquad \lambda_g = \frac{KK_{rg}}{\mu_g} \tag{16}$$

其中: q_{ai}为为单位体积微孔向割理解吸气体的体积速率; T_{sc}为标准温度; P_{sc}为标准压力。

同理, 可得割理中的水相(以下标 w 表示) 渗流方程。

$$\nabla\left(\frac{\alpha\lambda_w}{B_w}\nabla P_{aw}\right) = \frac{\partial}{\partial t}\left(\Phi_a\frac{S_{aw}}{B_w}\right) \tag{17}$$

在拟稳态情况下, 可认定煤层气的解吸速度与基质内表面气体浓度同基质中气体平均浓度的差呈正比, 于是

$$\frac{dV_i}{dt} = D_i F_s[V_E(P_{ag}) - V_i] \tag{18}$$

$$q_{ai} = -F_G\frac{dV_i}{dt} \tag{19}$$

式中: V_i 为基质单元内气体的平均浓度; V_E 为基质内表面气体浓度; F_s 为基质单元形状因子; F_G 为几何相关因子。

方程(15)、(17) 为包含未知函数 P_{ag}、S_{ag}、P_{aw}、S_{aw}的二阶非线性偏微分方程组, 此外尚有物态方程:

$$S_{ag} + S_{aw} = 1 \tag{20}$$

$$P_{cgw}(S_{ag}) = P_{ag} - P_{aw} \tag{21}$$

式中: S_{agw}为气饱和度, S_{aw}为水饱和度; $P_{cgw}(S_{ag})$ 称毛管压力函数, 为已知函数; P_{ag}和 P_{aw}分别为气相、水相压力。

方程(18) 通过方程(19) 与前述方程组藕合。

2. 拟三维暨二维煤层气数学模型

如果含气煤层夹于上、下渗透性砂岩层之间, 开采过程中源于砂岩层的水渗透, 对中间含气煤层的气压分布显然会产生影响。本模型以拟三维形式考虑这些影响。

模型假定: ①三层地层, 中间为含气煤层, 上、下为渗透性含水地层; ②煤层为非均匀微孔隙—割理双重介质, 气、水两相二维流动, 割理中为 Daray 渗流, 微孔中为拟稳态气相吸附扩散; ③群井; ④开采过程中仅考虑上、下砂岩层中水的垂向流动, 因而砂岩层对煤层有水的渗透。

(1) 数学模型

若考虑重力势的影响, 由方程(15) 可得割理(裂缝) 中气相渗流方程。

$$\frac{\partial}{\partial x}\left\{\frac{\alpha\lambda_{xg}}{B_g}\frac{\partial}{\partial x}\left[P_{ag}+(-1)^m\rho_g gh\right]+D_a\frac{\partial}{\partial x}\left(\frac{S_{ag}}{B_g}\right)\right\}+\frac{\partial}{\partial y}\left\{\frac{\alpha\lambda_{yg}}{B_g}\frac{\partial}{\partial y}\left[P_{ag}+(-1)^m\rho_g gh\right]+D_a\frac{\partial}{\partial y}\left(\frac{S_{ag}}{B_g}\right)\right\}+q_{ai}-q_g=\frac{\partial}{\partial t}\left(\frac{\Phi_a S_{ag}}{B_g}\right) \quad (22)$$

为考虑重力势的影响, $m=1$ 时 Z 坐标向上; $m=2$ 时 Z 坐标向下。

q_g 为气体源强度。在群井情况下, 根据生产井的不同状态(定井底流压、定产气量、定产水量等)来确定。

割理中水相渗流方程为:

$$\frac{\partial}{\partial x}\left\{\frac{\alpha\lambda_{xw}}{B_w}\frac{\partial}{\partial x}\left[P_{aw}+(-1)^m\rho_w gh\right]\right\}+\frac{\partial}{\partial y}\left\{\frac{\alpha\lambda_{yw}}{B_w}\frac{\partial}{\partial y}\left[P_{aw}+(-1)^m\rho_w gh\right]\right\}+q_{up-water}+q_{down-water}-q_w=\frac{\partial}{\partial t}\left(\frac{\Phi_a S_{aw}}{B_w}\right) \quad (23)$$

其中: $q_{up-water}$、$q_{down-water}$分别表示上、下注水强度。

相饱和度关系为: $S_{ag}+S_{aw}=1$　(24)

毛细管压力函数为: $P_{ag}-P_{aw}=P_{cgw}(S_{ag})$　(25)

微孔拟稳态气相方程及气体解吸量为:

$$\frac{dV_i}{dt}=D_iF_s[V_E(P_{ag})-V_i] \quad (26)$$

$$q_{ai}=-F_G\frac{dV_i}{dt} \quad (27)$$

上、下渗水层流入煤层的水流强度 $q_{up-water}$、$q_{down-water}$由相应层内水的渗流方程:

$$\frac{\partial}{\partial z}\left(\frac{\alpha K_z}{\mu_w B_w}\frac{\partial}{\partial z}P_w\right)=\frac{\partial}{\partial t}\left(\frac{\Phi_w}{B_w}\right) \quad (28)$$

求出 P_w 后得上渗水层水流强度:

$$q_{up-water}=\frac{\alpha K_z}{\mu_w B_w}\frac{\partial P_w}{\partial z}\Big|_{z=0}\cdot\frac{1}{h} \quad (29)$$

下渗水层水流强度:

$$q_{down-water}=\frac{\alpha K_z}{\mu_w B_w}\frac{\partial P_w}{\partial z}\Big|_{z=h_{down}}\cdot\frac{1}{h} \quad (30)$$

各方程的初始条件和边界条件是:

$$P_{ag}(x,y,0)=P^0_{ag}(x,y)$$

$$S_{ag}(x,y,0)=S^0_{ag}(x,y)$$

外边界条件

$$\frac{\partial P_{ag}}{\partial n}\Big|_{re}=0 \qquad \frac{\partial S_{ag}}{\partial n}\Big|_{re}=0$$

由于版面的原因, 有关数值模型与算法的内容在此从略。

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中原油田一项煤层气钻探技术获国家专利

中原油田钻井四公司自行研制的中原 9508－1 绳索式取心工具, 近日获得国家专利局颁发的实用新型取心工具专利证书。

中原油田钻井四公司从 1997 年 5 月开始研制这种工具, 于同年 10 月在山西省屯留县 TL－002 井煤层气清水取心中应用并获得成功。试验从 626.88～633.60 m 井段先后 6 次取心, 平均收获率达 57.26%, 创出了国内粉煤井取心的最新纪录。

这种工具的特点是能在短时间内取心成功, 减少岩心的浸泡时间, 有效防止煤层气的逸散, 并能及时、准确地提供煤层分析的有关参数。

(陈敏　供稿)

Xiuyi (Huainan College of Industry). *NATUR. GAS IND.* v. 18, no. 4, pp. 21~24, 7/25/98. (ISSN-0976; **In Chinese**)

ABSTRACT: While studying the data on the coalbed methane resource evaluation for partial coal-bearing areas in China, the authors found that there were larger difference in treating several basic problems as the analysis of coalbed methane data, the calculation of methane resource extent and the drawing of methane content graph, so it was necessary to carry out a monographic study to make the evaluation standard be identical and the evaluation results really become a decision basis of resource development. A discussion on the problems mentioned above is carried out in the resoearch on the coalbed methane resources in the west of Huainan coal field and following knowledge is obtained: ①when the data on coalbed methane are analyzed, it is necessary to carry out the constitution of efficient methane data on the basis of the original testing results of gas-coal samples collected by various methods in geological exploration for coal resources; ②two fundamental parameters, coal reserve and coalbed methane content, should be objectively determined and elected, to make the calcuated coalbed methane resource extent be conformable with the actual situation; ③an indirect expression form of content vs depth relationship should be adopted for making up the coalbed methane content graph and the ground state of the methane content utilized is a combustible radicle.

SUBJECT HEADINGS: Coal-formed gas, Resources assessment, Content determining, Resources calculation.

Liu Jianhua: *(senior engineer)*, born in 1957, graduated from Shandong Mining Institute in 1982 and published several articles, such as "A Comparison between Coalbed Methane Contents Sampled and Tested by Gas-collected Method and Desorption Method Respectively", etc. He is now engaged in the geological analysis for coal mine design. Add: No. 355, North Fuyang Road, Hefei, Anhui (230041), China Tel: (0551) 5527225.

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ESTIMATION METHOD OF COALBED GAS RESERVES

Wang Xingjin and Wang Wei (North China Petroleum Bureau of China National Star Petroleum Corporation). *NATUR. GAS IND.* v. 18, no. 4, pp. 24~27, 7/25/98. (ISSN 1000-0976; **In Chinese**)

ABSTRACT: Owing to the distinctive geological characteristics of coalbed gas, it is determined that the estimation method of its reserves is different from that of conventional gas ones. The procedure of setting up the estimation method of coalbed gas reserves is introduced, i.e. in combining the material balance method with volumetric method, it is automatically finished by computer through the iteration of two groups of equations. As distinct from the conventional gas, a comprehensive contribution of the absorption gas and free gas should be fully considered in the estimation of coalbed gas reserves and the three mechanisms of desorption, diffusion and percolation flow should be included in the material balance equations at the same time. Both the resources and reserves in one coalbed gas field in Shanxi Province are estimated by use of the method. The estimation accuracy of the method is high for these tracts with high degree of prospecting and reliable data and their economic recoverable reserves may be also estimated; on the contrary, the accuracy of estimated resources is low and the reserves cann′t be estimated.

SUBJECT HEADINGS: Coal-formed gas, Reserve calculation, Material balance method; Volumetric method, Calculation method, Resource extent.

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GEOLOGICAL AND MATHEMATICAL MODELS OF NUMERICAL SIMULATION OF COALBED GAS

Yue Xiaoyan, Tan Shijun and Wu Dongping (North China Petroleum Bureau of China National Star Petroleum Corporation). *NATUR. GAS IND.* v. 18, no. 4, pp. 28~31, 7/25/98. (ISSN 1000-0976;

In Chinese)

ABSTRACT: The numerical simulation of coalbed gas is to simulate the overall process of yielding coalbed gas by taking computer as the supporting conditions. The basic steps are: firstly to set up a reasonable geological model according to the geological characteristics of coal reservoir; then to set up a mathematical model, which can describe the basic physical phenomena of coalbed gas movement and the boundary and initial conditions, in light of the mechanism of yielding coalbed gas, and to transform the mathematical model into the numerical model by the methods of discrete mathematics; and then to set up a computer model through programming. By use of the coalbed gas numerical model method introduced in the paper, various influence factors can be overall, systematicallly and comprehensively analyzed and the flow property of the fluids in reservoir can be objectively reflected. In addition, the method is of the properties of low development cost and to be repeatedly utilized.

SUBJECT HEADINGS: Coal bed, Pore structure, Permeability, Geologic model, Mathematical model.

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A RESEARCH ON THE INTERPOLATION OF CORE ANALYSIS DATA

Liu Zhengfeng and Xia Hongquan (Southwest Petroleum Institute). *NATUR. GAS IND.* v. 18, no. 4, pp. 32～34, 7/25/98. (ISSN 1000-0976; **In Chinese)**

ABSTRACT: In the process of core analysis, the coring intervals are not quite equal to each other, which makes the non-isometric core analysis data to be formed. The log data, however, are isometrically acquired in general. In order to make the core data and log data well-matched, it is necessary to interpolate the core analysis data, which may cause the analysis data isometric. Then, a filtering is carried out for the core data after having been interpolated according to various logs, so as to cause the resolutions of both the core analysis data and the log data to be matched. By use of the handled data, the model set up is accurate or the data analysis carried out is creditable. The Kriging interpolation and fractal interpolation are nonlinear mathematical interpolation methods, which can better reflect the inherent distribution law of the data in comparison with the common ones. A deep-going research on the interpolation of core data is carried out by use of the theories of the Kriging interpolation and fractal interpolation respectively in this paper. Relevant models are set up in light of the theories of the two interpopla-tion methods. Through contrasting and analyzing the examples according to the two interpolation theories, the merits and demerits of the two nonlinear interpolation methods are found, which lays a foundation for further study.

SUBJECT HEADINGS: Statistical analysis, Fractal, Log data, Core, Porosity.

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OVERALL DEVELOPMENT PROJECT AND DEVELOPMENT PERFORMANCE CHARACTERISTICS OF YA-13-1 GAS FIELD

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ABSTRACT: The Ya-13-1 gas field is the first offshore giant gas field in China cooperatively developed by Western South China Sea Company, CNOOC and ARCO, USA. The gas reservoir in the field is a low-porosity medium-permeability～medium-porosity high-permeability reservoir bed with high-temperature and high-pressure, being divided into north and south regions by Fault-Y3. The gas-water contacts in the two regions are different from each other and most of the reservoir boundary is limited by the fault, only a few of it is connected with the edge water. In regard of reservoir drive type, the elastic gas drive occupies the leading position and the weak water drive the secondary one. Carbon dioxide content is about 10% in the gas component. When formation pressure dropped down to 28.0 MPa in testing, condensate might be formed, The major contents of the overall development project of the field are expounded, including fundamental development principle, development