论文

有机质孔隙对页岩气流动能力影响研究

姚军^{1*}, 宋文辉¹, 李阳², 孙海¹, 杨永飞¹, 张磊¹

1. 中国石油大学(华东)石油工程学院, 青岛 266580;

2. 中国石化油田勘探开发事业部, 北京 100029

*联系人, E-mail: RCOGFR_UPC@126.com

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摘要 页岩中存在有机质孔隙和无机质孔隙, 目前页岩气表观渗透率模型忽略了孔隙类型、孔隙半径分布对气体流动能力的影响. 本文基于页岩二维剖光扫描电镜图像数值重建页岩三维数字岩心, 并提取孔隙相中轴拓扑结构. 根据地质上对有机质孔隙空间分布、有机质孔隙和无机质孔隙半径分布的认识, 在对应孔隙喉道位置, 充填满足对应孔隙半径分布以及空间分布关系的有机质孔隙和无机质孔隙, 建立3种不同有机质孔隙分布模式的页岩孔隙网络模型: 有机质孔隙条带状分布、有机质孔隙连片分布、有机质孔隙分散在无机质孔隙中. 有机质孔隙中气体流动考虑吸附解吸、表面扩散、黏性流、努森扩散, 无机质孔隙中气体流动考虑黏性流、努森扩散, 气体性质计算考虑真实气体效应以及在微纳米孔道中相态变化. 结果表明, 当有机质孔隙半径分布小于无机质孔隙半径分布, 有机质孔隙成条带状分布模型气体流动能力最强, 有机质孔隙连片分布模型气体流动能力最弱. 当有机质孔隙半径分布大于无机质孔隙半径分布, 有机质孔隙成条带状分布模型气体流动能力最强, 有机质孔隙分散在无机质孔隙模型气体流动能力最弱. 本文的研究对认识页岩气流动能力具有显著意义.

关键词 页岩气, 运移机制, 孔隙网络模型, 有机质孔隙, 无机质孔隙**PACS:** 47.56.+r, 51.10.+y, 91.60.Np

页岩微纳米孔道中气体流动能力是目前非常规领域研究热点^[1]. 吸附气和自由气共存于页岩孔隙中. 气体在页岩中的质量传输有以下3种机制^[2-4]: 黏性流、Knudsen扩散、表面扩散. 如图1所示, 同种气体分子与分子之间碰撞产生黏性流; 分子与壁面碰撞产生Knudsen扩散; 吸附在孔隙壁面的气体分子沿孔隙表面蠕动产生表面扩散. 由于连续性假设在微纳米孔道

中不适用, 一般采用气体分子运动自由程与孔隙半径的比值Knudsen数判定页岩中的气体运移模式^[5](图2), 不同Knudsen数对应气体运移机制不同. Beskok等人^[6]和Civan等人^[7-9]建立了基于Knudsen数的气体表观渗透率模型, Javadpour课题组^[5,10-12]和Wu等人^[13-15]建立了基于多重气体运移机制叠加的气体表观渗透率模型. 但目前基于单管分析的页岩气表观渗透率模型忽

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图1 (网络版彩图) 气体传输机制

Figure 1 (Color online) Gas transport mechanisms in porous media.

图2 基于Knudsen数多孔介质流动形态和控制方程的分类
Figure 2 Classification of the gas flow regimes and governing equations based on Knudsen number.

略了页岩地层的非均质性, 并且没有考虑有机质孔隙与无机质孔隙在气体传输、空间分布、孔隙半径分布上的差异. 此外, 目前研究页岩气体流动并没有考虑气体在微纳米孔道中的相态变化.

Fishman等人^[16,17]通过分析有机质孔隙和无机质孔隙结构, 认为有机质孔隙和无机质孔隙半径通常在100 nm以内. Mastalerz等人^[18]研究认为有机质孔隙半径范围在5–70 nm. 虽然常规认识认为有机质孔隙半径小于无机质孔隙半径, 但也存在有机质孔隙半径大于无机质孔隙半径的情况^[19]. Loucks等人^[20]认为有机质孔隙平均半径为100 nm, 并给出了3种有机质分布模式(图3). 图3中A模式有机质孔隙成条带状分布, 无机质孔隙介于有机质孔隙之间, B模式有机质孔隙连片分布, 交错分布于无机质孔隙中, C模式有机质孔隙零散分布在无机质孔隙中.

目前普遍认为无机质孔隙如黏土孔隙具有大量吸附气是建立在固-气界面吸附理论基础上, 其对页岩气藏不适应^[21]. 由于黏土矿物具有极强的亲水性, 实际储层黏土孔隙表面吸附水膜, 并且孔隙中存在一定毛细水及可动水^[22–26]. 在黏土孔隙表面存在水膜情况下, 大多数甲烷分子表现为聚集在孔隙中心, 或者吸附在水膜上, 而并非吸附在黏土表面^[27,28], 这就在很大程度上降低了黏土对甲烷的吸附能力. 相比于有机质对甲烷的强吸附能力, 无机质孔隙吸附能力可以忽略^[21].

图3 有机质分布模式^[20]

Figure 3 Organic matter distribution pattern [20].

Wang等人^[29]通过氮气和二氧化碳页岩吸附实验发现气体主要吸附在有机质微孔隙中, Heller等人^[30]的吸附实验结果发现活性炭最大甲烷吸附能力(5×10^3 scf/ton)远大于伊利石最大甲烷吸附能力(100 scf/ton)和高岭石最大甲烷吸附能力(20 scf/ton). 在模拟页岩气流动和气藏储量计算中一般忽略无机质孔隙中的吸附气^[31,32].

本文首先建立了有机质孔隙无机质孔隙气体传导率方程, 然后对两种不同类型孔隙单管流动能力进行了分析. 有机质孔隙中气体流动考虑吸附解吸、表面扩散、黏性流、努森扩散, 无机质孔隙中气体流动考虑黏性流、努森扩散. 气体性质计算考虑真实气体效应以及气体在微纳米孔道产生的相态变化. 由此基于图3中的有机质分布模式, 采用马尔科夫链-蒙特卡罗(Markov chain Monte Carlo, MCMC)方法基于页岩二维剖光扫描电镜图像重建页岩三维数字岩心, 并提取孔隙相中轴拓扑结构, 在对应孔隙喉道, 充填满足对应孔隙半径分布以及空间分布关系的有机质孔隙和无机质孔隙, 建立了3种页岩孔隙网络模型: 有机质孔隙成条带状分布的A模式页岩孔隙网络模型、有机质孔隙连片分布的B模式页岩孔隙网络模型、有机质孔隙分散在无机质孔隙中的C模式页岩孔隙网络模型. 基于3种页岩孔隙网络模型, 讨论了不同有机质孔隙半径分布下气体流动能力的差异.

1 气体传导率方程

1.1 吸附解吸对流动半径的影响

页岩中吸附气量可采用Langmuir等温吸附表示, 吸附气在孔隙壁面的覆盖度可表示为

$$\theta = \frac{p_o / Z}{p_L + p_o / Z}. \quad (1)$$

考虑吸附解吸后有机质孔隙中自由气流动半径可表示为

$$r_{\text{eff_or}} = r - d_m \theta. \quad (2)$$

1.2 真实气体效应和相态变化对气体性质的影响

采用Islam等人^[33]提出的修正格式的范德华方程描述微纳米孔道气体临界压力临界温度变化

$$T_c = \frac{8}{27bR} \left[a - 2\sigma^3 \varepsilon N^2 \frac{d_m}{r_{\text{eff}}} \left(2.6275 - 0.6743 \frac{d_m}{r_{\text{eff}}} \right) \right], \quad (3)$$

$$P_c = \frac{8}{27b^2} \left[a - 2\sigma^3 \varepsilon N^2 \frac{d_m}{r_{\text{eff}}} \left(2.6275 - 0.6743 \frac{d_m}{r_{\text{eff}}} \right) \right], \quad (4)$$

其中, 有效半径 r_{eff} 在无机质孔隙中为孔隙半径 r , 有机质孔隙中为自由气流动半径 $r_{\text{eff_or}}$.

气体压缩因子 Z 采用如下公式进行计算^[34-36]:

$$P_{\text{pr}} = \frac{P_o}{P_c}, \quad (5)$$

$$T_{\text{pr}} = \frac{T}{T_c}, \quad (6)$$

$$Z = (0.702e^{-2.5T_{\text{pr}}}P_{\text{pr}}^2 - 5.524e^{-2.5T_{\text{pr}}}P_{\text{pr}} + 0.044T_{\text{pr}}^2 - 0.164T_{\text{pr}} + 1.15). \quad (7)$$

黏度计算采用Lee等人^[37]提出的方法. 该方法已被其他学者应用到气体黏度计算中^[38,39]. Lee等人方法的压力适用范围0.69–55 MPa, 温度适用范围311–444.2 K. 本文中选用气藏压力为40 MPa, 地层温度为400 K, 因此符合适用条件.

$$\mu = (1 \times 10^{-4})K \exp(X\rho^Y), \quad (8)$$

$$\rho = 1.4935 \times 10^{-3} \frac{p_o M}{ZT}, \quad (9)$$

$$K = \frac{(9.379 + 0.01607M)T^{1.5}}{(209.2 + 19.26M + T)}, \quad (10)$$

$$X = 3.448 + \frac{986.4}{T} + 0.01009M, \quad (11)$$

$$Y = 2.447 - 0.2224X. \quad (12)$$

1.3 自由气传导率方程

真实气体平均分子自由程可表示为^[40]

$$\lambda = \sqrt{\frac{\pi ZRT}{2M_w}} \frac{\mu}{p_o}. \quad (13)$$

Knudsen数在有机质孔隙和无机质孔隙中可分别表示为

$$K_n = \frac{\lambda}{r_{\text{eff_or}}}, \quad (14)$$

$$K_n = \frac{\lambda}{r}. \quad (15)$$

Beskok等人^[6]建立了基于Knudsen数的单管气体流量公式, 如下式所示:

$$q_h = f(K_n) \frac{\pi R_h^4}{8\mu} \frac{\Delta P}{L_h}, \quad (16)$$

其中, $f(K_n)$ 可表示为

$$f(K_n) = (1 + \alpha K_n) \left(1 + \frac{4K_n}{1 - \beta K_n} \right). \quad (17)$$

无因次气体稀薄系数 α 可表示为

$$\alpha = \frac{128}{15\pi^2} \tan^{-1}[4.0K_n^{0.4}]. \quad (18)$$

虽然滑移系数 β 值为-1, 最初仅被使用于滑脱流动阶段, Beskok与分子模拟数据对比显示滑移系数 β 值为-1可适用于全部Knudsen数流动阶段^[41]. 根据式(16)自由气传导率可表示为

$$g_{\text{free}} = \frac{\pi r_{\text{eff}}^4 f(K_n)}{8\mu L}. \quad (19)$$

1.4 吸附气传导率方程

吸附气通过表面扩散方式进行流动. 单位面积气体分子摩尔流量可表示为^[42,43]

$$J_a = D_s \frac{dC_a}{dx}, \quad (20)$$

吸附气浓度 C_a 通过Langmuir等温吸附计算^[30]:

$$C_a = C_{\text{amax}} \theta. \quad (21)$$

对于有机质孔隙, 不同页岩岩石干酪根类型不同, 气体吸附能力不同^[44,45]. 在本模型中, 孔隙材质对气体

流动的影响是通过在模型中通过最大吸附浓度作为模型参数进行输入来考虑. 有机质表面最大吸附浓度 $C_{a\max}$ 如下式所示^[46]:

$$C_{a\max} = \frac{V_L \rho_{sc, gas} \rho_{grain}}{\varepsilon_{ks} M}. \quad (22)$$

根据式(20)–(22), 吸附层气体分子摩尔流量如下式所示:

$$J_A = D_s C_{a\max} \frac{d\theta}{dp} \pi (r^2 - r_{eff_or}^2) \frac{dp}{dx}. \quad (23)$$

根据式(23), 吸附气体流量可表示为

$$V_A = \frac{M}{\rho} D_s C_{a\max} \frac{d\theta}{dp} \pi (r^2 - r_{eff_or}^2) \frac{dp}{dx}. \quad (24)$$

考虑气体覆盖度的影响, 表面扩散系数 D_s 采用如下公式进行计算^[43,47,48]:

$$D_s = \frac{(1-\theta) + \frac{\kappa}{2}\theta(2-\theta) + \{H(1-\kappa)\}(1-\kappa)\frac{\kappa}{2}\theta^2}{\left(1-\theta + \frac{\kappa}{2}\theta\right)^2}, \quad (25)$$

$$D_{s0} = 8.29 \times 10^{-7} T^{0.5} \exp\left(-\frac{\Delta H^{0.8}}{RT}\right), \quad (26)$$

$$H(1-\kappa) = \begin{cases} 0, & \kappa \geq 1, \\ 1, & 0 \leq \kappa \leq 1, \end{cases} \quad (27)$$

$$\kappa = \frac{\kappa_b}{\kappa_m}. \quad (28)$$

当 $\kappa_m > \kappa_b$, 不论运动前方的位置是否已被分子占据, 都将发生表面扩散; 当 $\kappa_b > \kappa_m$, 气体分子被堵塞, 表面扩散停止.

根据式(24)吸附气传导率方程可表示为

$$g_{surface} = \frac{1}{l} \frac{M}{\rho} D_s C_{a\max} \frac{d\theta}{dp} \pi (r^2 - r_{eff_or}^2). \quad (29)$$

1.5 有机质孔隙与无机质孔隙气体传导率方程

有机质孔隙中气体以吸附气和自由气两种形式流动, 根据式(19)和(29), 有机质孔隙气体传导率方程可表示为

$$g_{or} = \frac{\pi r_{eff_or}^4}{8\mu L} \left(1 + \frac{128}{15\pi^2} \tan^{-1}[4.0K_n^{0.4}]K_n\right) \left(1 + \frac{4K_n}{1+K_n}\right) + \frac{1}{l} \frac{M}{\rho} D_s C_{a\max} \frac{d\theta}{dp} \pi (r^2 - r_{eff_or}^2). \quad (30)$$

无机质孔隙中考虑自由气流动, 根据式(19)无机质孔隙气体传导率方程可表示为

$$g_{in} = \frac{\pi r^4}{8\mu L} \left(1 + \frac{128}{15\pi^2} \tan^{-1}[4.0K_n^{0.4}]K_n\right) \times \left(1 + \frac{4K_n}{1+K_n}\right). \quad (31)$$

2 有机质孔隙与无机质孔隙单管流动能力分析

选取孔隙半径 5, 20, 40 nm 单管在两端定压差情况下进行气体流量计算, 由于气体传导率与压力有关, 采用非线性迭代求解, 模型参数见表1^[43,46].

从图4中可看出, 在 $r=5$ nm 时有机质孔隙单管气体流动能力要高于无机质孔隙单管流动能力, 这是由于 $r=5$ nm 时有机质孔隙中吸附气表面扩散作用较强, 从而提高了有机质孔隙气体流动能力. 当 $r=20, 40$ nm 时 (图5和6) 吸附气表面扩散能力减弱, 但吸附层仍占据孔隙表面一定厚度, 使自由气流动截面相比无机质孔隙中自由气流动截面减少, 从而使有机质孔隙气体流

表1 单管流动能力分析模型参数

Table 1 Single tube gas flow ability analysis model parameter

模型参数	数值
单管长度 L (nm)	100
孔隙压力 p_o (MPa)	40
地层温度 T (K)	400
孔隙半径 r (nm)	5, 20, 40
压力梯度 P_g (MPa/m)	0.05, 0.1, 0.15, 0.2, 0.25
Langmuir 压力 P_L (MPa)	13.789514 ^[46]
最大吸附浓度 $C_{a\max}$ (mol/m ³)	328.7 ^[46]
有机质占总岩石骨架体 积比例 ε_{ks}	0.01 ^[46]
岩石密度 ρ_{grain} (kg/m ³)	2.66×10^3
覆盖度“0”时的等量吸附 热 ΔH (J mol ⁻¹)	16000 ^[43]
气体壁面扩散阻塞系数 κ ^[43]	0.5

图4 (网络版彩图) $r=5$ nm时两种孔隙类型单管气体流量
Figure 4 (Color online) Gas flux in two different types of tube when $r=5$ nm.

图6 (网络版彩图) $r=40$ nm时有机质单管和无机质单管气体流量
Figure 6 (Color online) Gas flux in two different types of tube when $r=40$ nm.

图5 (网络版彩图) $r=20$ nm时有机质单管和无机质单管气体流量
Figure 5 (Color online) Gas flux in two different types of tube when $r=20$ nm.

动能力小于无机质孔隙中气体流动能力. 单管流动能力分析得到了有机质孔隙与无机质孔隙气体传输能力的不同, 在第3节将单管流动规律应用到孔隙网络模型中.

3 页岩气孔隙网络模型

3.1 考虑有机质孔隙分布因素的页岩孔隙网络模型

图7所示某页岩剖光扫描电镜图像, 分辨率为12 nm, 经过图像二值化处理采用MCMC方法数值重建三维页岩数字岩心^[49,50]. 重建后页岩数字岩心大小为 $400 \times 400 \times 400$ (图8), 采用居中轴线法提取孔隙几

图7 页岩二维剖光扫描电镜图像. (a) 二值化前; (b) 二值化后
Figure 7 Two dimensional polished shale SEM image. (a) Unsegmented image; (b) segmented image.

何拓扑^[51,52], 提取后孔隙几何拓扑(图9)中孔隙个数为49407, 喉道个数为79450, 孤立孔隙个数为32. 有机质孔隙基本标记单元为单个喉道和与之相连的两个孔隙(图10). 在孔隙几何拓扑中标记孔隙类型, 建立3种

图8 (网络版彩图) MCMC重建得到的三维页岩数字岩心
Figure 8 (Color online) Reconstructed three dimensional shale digital core based on MCMC algorithm.

图9 (网络版彩图) 三维页岩数字岩心孔隙相中轴拓扑结构(红色表示孔隙位置, 白色表示喉道位置)
Figure 9 (Color online) Medial axis in the pore space of three dimensional shale digital core (red color represents pore location, white color represents throat location).

图10 有机质孔隙基本标记单元(单个喉道和与之相连的两个孔隙)
Figure 10 Basic labeling unit for organic pores (single throat with two connected pores).

页岩孔隙网络模型(图11–13). 3种页岩孔隙网络模型中红色表示有机质孔隙, 蓝色表示无机质孔隙.

3种页岩孔隙网络模型中, 有机质孔隙数量占据总孔隙数量均为10%. 图11为A模式页岩孔隙网络模型, 在孔隙网络上部和下部呈条带状分布, 中部为无机质孔隙. 图12为B模式页岩孔隙网络模型, 有机质孔隙在孔隙网络中连片分布, 有机质孔隙一部分位于孔隙网络上部和底部, 并在孔隙网络中间位置从上至下贯穿分布. 图13为C模式页岩孔隙网络模型, 有机质孔隙在孔隙网络中分散分布.

3.2 有机质孔隙和无机质孔隙的半径分布

页岩中有机质孔隙、无机质孔隙半径分布通常呈现以10为底的对数正态分布^[53–55], 表示形式如下:

$$N(r, ave, \sigma) = e^{\left[-\frac{(\log_{10} r - ave)^2}{2\sigma^2} \right]}. \quad (32)$$

图11 (网络版彩图) A模式页岩孔隙网络模型
Figure 11 (Color online) Pattern A shale pore network model.

图12 (网络版彩图) B模式页岩孔隙网络模型
Figure 12 (Color online) Pattern B shale pore network model.

图 13 (网络版彩图) C模式页岩孔隙网络模型
Figure 13 (Color online) Pattern C shale pore network model.

根据国内某盆地页岩区块孔喉分析数据, 无机质孔隙半径分布以及两组来自不同地层的有机质孔隙半径分布参数见表2. 有机质孔隙和无机质孔隙半径分布见图14. 从图14中可以看出, 有机质孔隙半径分布 a 小于无机质孔隙半径分布, 有机质孔隙半径分布 b 大于无机质孔隙半径分布. 在3种页岩孔隙网络模型中, 无机质孔隙半径大小按照无机质孔隙半径分布设置, 有机质孔隙半径大小分别按照 ab 两种不同有机质孔隙半径分布设置, 产生6组不同孔隙分布模式、不同孔径分布的页岩孔隙网络模型. 根据式(13)–(15)计算得到的Knudsen数在有机质孔隙以及无机质孔隙中随孔隙半径变化见图15. 由于吸附层的存在, 有机质孔隙Knudsen数稍大于无机质孔隙Knudsen数. 孔隙半径在10 nm以下时自由气流动主要处于滑移流动和过渡流动区域, 10 nm以上时自由气流动高压时主要处于连续流动区域, 低压时主要处于滑移流动区域.

3.3 页岩气孔隙网络流动模拟

对于每个孔隙气体流入流出量相等可表示为

$$\sum_{j=1}^{N_i} Q_{ij} = 0, \quad (33)$$

$$Q_{ij} = g_{ij}(p_i - p_j). \quad (34)$$

根据图10, 相连孔隙间传导率可表示为^[56]

$$\frac{L_i + L_t + L_j}{g_{i,j}} = \frac{L_i}{g_i} + \frac{L_t}{g_t} + \frac{L_j}{g_j}. \quad (35)$$

对孔隙网络整体非线性迭代求解得到定压差条件

表 2 有机质无机质孔隙半径分布模型参数

Table 2 Organic pore and inorganic pore size distribution model parameters

孔隙类型	均值 μ	标准差 σ
有机质孔隙半径分布 a	0.7	0.12
有机质孔隙半径分布 b	1.7	0.12
无机质孔隙半径分布	1.2	0.14

图 14 (网络版彩图)有机质无机质孔隙半径分布
Figure 14 (Color online) Organic pores and inorganic pores size distributions.

图 15 (网络版彩图) Knudsen数随孔隙半径以及孔隙压力的变化

Figure 15 (Color online) Knudsen number change versus pore radius and pore pressure.

下通过孔隙网络模型的气体流量 Q_t , 初始参数见表1. 图16为压力梯度0.1 MPa/m两端压差0.48 Pa情况下, 6组不同孔隙分布模式、不同孔径分布的页岩孔隙网络模型压力分布计算结果, 为减少可视化内存需要, 喉道半径不予显示.

图 16 (网络版彩图) 6组不同孔隙分布模式不同孔径分布的页岩孔隙网络模型压力分布计算结果. (a) A模式-有机质孔径分布a; (b) A模式-有机质孔径分布b; (c) B模式-有机质孔径分布a; (d) B模式-有机质孔径分布b; (e) C模式-有机质孔径分布a; (f) C模式-有机质孔径分布b

Figure 16 (Color online) Shale pore network pressure distribution calculation results under different pore size distribution and different organic pore distribution pattern. (a) Pattern A-organic pore size distribution a; (b) Pattern A-organic pore size distribution b; (c) Pattern B-organic pore size distribution a; (d) Pattern B-organic pore size distribution b; (e) Pattern C-organic pore size distribution a; (f) Pattern C-organic pore size distribution b.

图17为有机质孔隙半径分布小于无机质孔隙半径分布时, 3种页岩孔隙网络模型气体流量随压力梯度的变化情况. 有机质孔隙成条带状分布的A模式页岩孔隙网络模型气体流动能力最强, 有机质孔隙分散在无机质孔隙中的C模式页岩孔隙网络模型气体流动能力次之, 有机质孔隙连片分布的B模式页岩孔隙网络模型气体流动能力最弱. 这是由于有机质孔隙连片分布时, 在孔隙网络模型中央形成相对于无机质孔隙传导率低的屏障, 导致气体流动能力降低, 如图16(c)所示, 气体通过有机质孔隙需要克服更大的流动阻力, 因此在有机质孔隙上压力降较大. 有机质孔隙成条带状分布时, 气体主要在中部无机质孔隙流动, 形成高流动能力的通道, 因此相比其他两种孔隙网络模型, 气体流动能力最强.

图18为有机质孔隙半径分布大于无机质孔隙半径

图 17 (网络版彩图) 有机质孔径分布a下3种页岩孔隙网络模型气体流量随压力梯度变化

Figure 17 (Color online) Gas flux versus pressure gradient in three different types of shale pore network under the organic pore size distribution a.

图 18 有机质孔径分布b下3种页岩孔隙网络模型气体流量随压力梯度变化

Figure 18 Gas flux versus pressure gradient in three different types of shale pore network under the organic pore size distribution b.

分布时, 3种页岩孔隙网络模型气体流量随压力梯度的变化情况. 有机质孔隙成条带状分布的A模式页岩孔隙网络模型气体流动能力最强, 有机质孔隙连片分布的B模式页岩孔隙网络模型气体流动能力次之, 有机质孔隙分散在无机质孔隙中的C模式页岩孔隙网络模型气体流动能力最弱. 这是由于C模式页岩孔隙网络模型气体流动能力主要由孔径较小的无机质孔隙控制, 孔隙半径分布较大的有机质孔隙分散在无机质孔隙中, 因此C模式页岩孔隙网络模型气体流动能力变化幅度较小. A模式页岩孔隙网络模型顶部和底部形成高渗条带, 气体流动能力有很大提高. B模式页岩孔隙网络模型形成Z型高渗条带, 因此气体流动能力

也有提高,但由于相对于A模式,高渗区域曲折分布,因此气体流量小于A模式下的气体流量.

4 结论

根据地质上对有机质孔隙分布、有机质孔隙无机质孔隙半径分布的认识,建立了3种页岩孔隙网络模型:有机质孔隙成条带状分布的A模式页岩孔隙网络模型、有机质孔隙连片分布的B模式页岩孔隙网络模型、有机质孔隙分散在无机质孔隙中的C模式页岩孔隙网络模型.有机质孔隙中气体流动考虑了吸附解吸、表面扩散、黏性流、努森扩散,无机质孔隙中气体流动考虑了黏性流、努森扩散,气体性质计算考虑了真实气体效应以及气体在微纳米孔道产生的相态变化.

当有机质孔隙半径分布小于无机质孔隙半径分布时,有机质孔隙成条带状分布的A模式页岩孔隙网

络模型气体流动能力最强,有机质孔隙分散在无机质孔隙中的C模式页岩孔隙网络模型气体流动能力次之,有机质孔隙连片分布的B模式页岩孔隙网络模型气体流动能力最弱.

当有机质孔隙半径分布大于无机质孔隙半径分布时,有机质孔隙成条带状分布的A模式页岩孔隙网络模型气体流动能力最强,有机质孔隙连片分布的B模式页岩孔隙网络模型气体流动能力次之,有机质孔隙分散在无机质孔隙中的C模式页岩孔隙网络模型气体流动能力最弱.

本文建立的页岩孔隙网络模型考虑了页岩地层中有有机质孔隙无机质孔隙的地质分布模式,并且考虑了有机质孔隙与无机质孔隙在气体传输、孔径分布上的差异.相比于传统页岩气单管表观渗透率模型,本文提出的页岩孔隙网络模型更能准确地预测页岩气流动能力.

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Study on the influence of organic pores on shale gas flow ability

YAO Jun^{1*}, SONG WenHui¹, LI Yang², SUN Hai¹, YANG YongFei¹ & ZHANG Lei¹

¹ School of Petroleum Engineering, China University of Petroleum (East), Qingdao 266580, China;

² Department of Oilfield Exploration & Development, China Petro-Chemical Corporation, Beijing 100029, China

In shale gas reservoirs, gas is stored in organic pores and inorganic pores with nm-scale pore size. Conventional single tube apparent permeability model is based on homogeneity assumption and neglects the influences of organic pores spatial distribution pattern, pore size distribution on gas flow ability. In this study, three dimensional shale digital core is reconstructed by Markov Chain Monte Carlo (MCMC) algorithm and medial axis in the pore space is extracted. According to geological study on the organic pores distribution pattern and pore size distribution, different sizes of organic pores and inorganic pores are assigned to corresponding spatial location of pores and throats. Three different types of shale pore network are built: shale pore network model with dense continuous layers of organic pores; shale pore network model with sparse continuous layers of organic pores; shale pore network model with discontinuous organic pores. Gas transport mechanisms of adsorption and desorption, surface diffusion, viscous flow, Knudsen diffusion are considered in organic pores. Gas transport mechanisms of viscous flow, Knudsen diffusion are considered in inorganic pores. Gas property calculation takes the influences of real gas effects and phase behavior change into account. Analysis results indicate that when the organic pores size distribution is smaller than inorganic pores size distribution, the permeability of shale pore network model with dense continuous layers of organic pores is larger than that of the other two types of shale pore network model. The permeability of shale pore network model with sparse continuous layers of organic pores is smallest. When the organic pores size distribution is bigger than inorganic pores size distribution, the permeability of shale pore network model with dense continuous layers of organic pores is also larger than that of the other two types of shale pore network model. The permeability of shale pore network model with discontinuous organic pores is smallest. Our study results are significant for understanding gas flow ability in shale gas reservoirs.

shale gas, transport mechanisms, pore network model, organic pores, inorganic pores

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