页岩气藏多重介质流体跨尺度传质表征方法研究

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摘要 页岩气藏多尺度孔隙介质发育、非均质性强, 不同尺度介质流体运移机制复杂, 明确多重介质流体跨尺度传质表征方法的适用范围对开展页岩气藏数值模拟研究具有重要意义. 本文基于体积压裂改造页岩气藏储层多尺度介质分布特征及多尺度介质气体运移特性, 以储层不同区域微小单元体为研究对象, 分别建立离散介质、拟稳态窜流双重介质、瞬态窜流双重介质表征单元体模型, 对比分析不同储层条件和裂缝参数时离散介质模型与不同窜流模式双重介质表征单元体模型内流体产量变化规律, 得到页岩气藏多重介质流体跨尺度传质表征方法适用范围. 研究表明: 生产早期不同窜流模式对窜流量影响较大, 多重介质渗透率相差越大, 生产早期不同窜流模式得到的窜流量相差越大, 窜流量差异持续时间越长; 采用瞬态窜流或拟稳态窜流双重介质模型可以较为准确地描述干酪根有机质-无机基岩之间流体跨尺度传质规律; 无机基岩-次生缝网流体跨尺度运移规律需要采用离散介质模型进行描述. 离散缝网耦合干酪根-无机基岩双重介质模型可以比较精确描述体积改造页岩气藏流体运移规律, 该模型对开展页岩气藏数值模拟研究具有重要的理论意义.

关键词 页岩气藏, 离散介质, 多重介质, 跨尺度传质

1 引言

页岩气藏干酪根有机质和无机基岩发育微纳米级孔隙, 储层天然裂缝闭合, 渗透率极低^[1,2], 需要实施体积压裂等措施改造才能获得经济产量^[3-6]. 体积压裂页岩气藏储层多尺度孔隙介质发育^[1,2,7-10](干酪根有机质孔隙、无机基岩孔隙及次生裂缝网络)、非均质性强,

不同尺度介质之间流体跨尺度传质机制复杂^[11-16]. 与常规气藏相比, 页岩气主要以吸附相和游离相的方式储集在有机质中^[11,17,18], 运移机制复杂(滑移效应、努森扩散、表面扩散、吸附解吸等)^[11-14], 开发过程中受压力变化较明显^[19]. 国内外对页岩气藏微纳米尺度介质中气体多种介质运移机理描述进行了大量研究, 采用数学表征等方法开展了页岩气藏吸附气表面扩散机

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理^[20-22]、自由气滑移流与努森扩散^[23,24]、高压下真实气体效应^[19,21]、页岩气藏应力敏感特性^[25,26]、页岩气藏微裂缝气体传输机理^[27,28]以及相同尺度下多种气体运移机制耦合^[9,15,29]等方面的研究。而针对页岩气藏多尺度介质中不同尺度之间流体交换机制研究较少,需要对页岩气藏多重介质流体跨尺度传质规律进行专门研究。

目前油气藏数值模拟器中主要采用多重连续性介质模型和离散裂缝模型对多尺度介质流体运移进行耦合表征。多重连续性介质模型是多尺度介质耦合表征的常用方法^[30-33]。Warren和Root^[34]基于Barenblatt等人^[35]提出的双重连续性模型,将拟稳态窜流双重孔隙度模型应用到天然裂缝油藏单相流模拟;Kazemi^[36], de Swaan^[37]及Najurieta^[38]对拟稳态窜流双重孔隙度模型进行进一步发展,建立了瞬态窜流双重孔隙度模型;Blaskovich等人^[39], Hill和Thomas^[40]及Dean和Lo^[41]考虑双重介质模型中基质内部流体运移,建立了双重渗透率模型。前人将上述双重介质模型与数值模拟结合,开发了基于多重连续性介质的常规油气藏数值模拟器^[30-33]。页岩气藏干酪根有机质与无机基岩发育孔隙尺度差别大,但是由于滑移效应、努森扩散以及表面扩散等因素影响,其渗透率比达西渗透率高3个数量级左右^[11,12,42,43],需要采用双渗介质模型^[43]。考虑页岩气藏发育干酪根有机质、无机基岩以及压裂改造产生的次生裂缝网络等多尺度介质,学者们^[15,44-46]引入多重连续性模型描述页岩气藏多尺度介质耦合运移机制,多重介质之间流体跨尺度传质多采用拟稳态窜流表征^[17,47,48],其合理性需要进一步研究讨论。离散裂缝模型(DFM)是在裂缝分布规律定量认识的基础上,采用非结构化网格等手段表征次生裂缝几何形状和位置,通过有限元等数值方法求解基质-裂缝耦合渗流规律^[49-52]。DFM广泛应用于非均质性强的油气藏数值模拟器中^[53-58],与多重介质模型相比可以更准确描述复杂裂缝系统引起的流体跨尺度运移特征,该方法需要定义大量网格以准确表征裂缝形态,计算效率低。学者们^[59-61]基于DFM模型开发了嵌入式离散裂缝模型(EDFM),使得离散介质模型可以简单地应用于油气藏模拟器,并且获得了更高的计算效率。离散介质模型可以准确表征流体在基质-裂缝之间的跨尺度传质规律,相比于多重介质模型,其计算效率低、裂缝分布描述困难,一般应用于多重介质模型无法表征的强非均质

性储层。

采用多重介质模型描述多尺度介质流体耦合流动特征,关键在于如何表征多尺度介质流体跨尺度传质规律。非常规油气藏数值模拟中主要采用以下3种方法进行表征^[43]:(1) 边界条件法,该方法通过在每一步迭代计算中为裂缝和基质团块添加适当的边界条件而准确获得基质-裂缝之间流体传质规律^[42,62,63]。边界条件法主要适用于裂缝分布在近井地带小范围内的情况,很难直接应用于油藏尺度模拟。(2) Warren-Root拟稳态窜流方法,该方法假设基质-裂缝之间流体传质为拟稳态流动,其窜流量可通过基质团块形状因子和基质-裂缝压差进行定量表征^[34,63]。Warren-Root拟稳态窜流方法广泛应用于常规油藏基质-次生裂缝/天然裂缝流体跨尺度传质表征,而非常规油气藏中基质-裂缝渗透率相差较大,流体从无机基质向缝网窜流达到稳态需要时间较长^[43,64-67],采用拟稳态窜流法不能准备描述生产早期流体运移特征。(3) 瞬态窜流法,针对非稳态窜流法存在需要很长时间达到稳态的问题,学者们在解析/半解析模型中通过将基质和裂缝转换成典型形状定量表征基质-裂缝之间瞬态窜流^[37,68],然而该方法很难应用于数值模拟器中。Zimmerman等人^[64]采用代数逼近的方法,利用压力对基质团块形状因子进行修正,得到了可以在数值模拟器中方便应用并可以准确描述瞬态窜流运移形态的窜流量方程^[66]。由于拟稳态窜流相对较简单,目前页岩气藏数值模拟中大多采用拟稳态窜流模型进行多尺度介质耦合流动表征^[17,47,48],但拟稳态窜流模型在干酪根有机质-无机基岩-次生缝网等多尺度介质中适应性需要进一步讨论。

页岩气藏不同介质内气体赋存形式及介质属性特征多样,干酪根有机质孔隙(纳米级)、无机基岩孔隙(微纳米级)及次生缝网(微毫米级)尺度差异大,体积压裂改造后储层不同区域非均质性相差大,目前对页岩气藏多尺度介质流体跨尺度传质表征方法适用性尚没有统一的认识。本文基于体积压裂改造页岩气藏储层多尺度介质分布特征、多尺度介质气体运移特性,以储层不同区域微小单元体为研究对象,分别建立离散介质、拟稳态窜流双重介质、瞬态窜流双重介质表征单元体模型。采用有限元方法对模型进行求解,在此基础上对比分析了双重介质瞬态窜流和拟稳态窜流计算得到的窜流量变化规律,同时分别采用离散介质、瞬态窜流双重介质及拟稳态窜流双重介质表征单元体模

型对比分析干酪根有机质-无机基岩和无机基岩-次生缝网多尺度介质流体产量变化规律, 得到了页岩气藏不同尺度介质流体跨尺度传质表征方法的适应性.

2 页岩气藏体积压裂水平井表征单元体模型

页岩气藏发育有机质孔隙、无机基岩孔隙及闭合天然裂缝(图1(c)), 储层实施压裂开发后改造区域天然裂缝张开并交错扩展, 形成交错复杂缝网系统(图1(b)). 因此体积压裂页岩气藏储层存在气体运移机制迥异的多重介质结构: 体积压裂未波及区域(USRV)存在微纳米级干酪根有机质孔隙以及无机基岩孔隙. 气体在干酪根有机质和无机基岩中气体运移机制不同, 将干酪根有机质和无机基岩等效成一种介质不能反映不同介质气体运移机制的影响. 体积压裂波及改造区域(SRV)发育微纳米级干酪根有机质孔隙、无机基岩孔隙以及较大尺度的次生缝网系统等三重介质, 其中干酪根有机质和无机基岩与USRV相似, 而次生缝网系统尺度相对较大, 气体在3种介质中运移规律相差较大. 考虑体积压裂页岩气藏储层介质分布特征, 分别截取SRV区域和USRV区域微小单元体(图1), 构建离散介质、瞬态窜流双重介质以及拟稳态窜流双重

介质模型描述干酪根有机质、无机基岩以及次生裂缝网络之间气体跨尺度传质运移机制.

2.1 离散介质表征单元体模型

页岩气藏体积压裂水平井USRV区域发育干酪根有机质和无机基岩双重介质, SRV区域内发育干酪根有机质、无机基岩以及次生裂缝网络三重介质, 采用离散介质模型描述USRV干酪根有机质-无机基岩、SRV区域无机基岩-次生缝网流体跨尺度运移机制. 假设USRV内无机基岩、SRV内次生裂缝网络均匀正交离散于储层中, 分别构建USRV干酪根-无机基岩离散介质模型(图2(a))、SRV无机基岩-次生缝网离散介质模型(图2(b)), 耦合不同介质中气体运移机制(干酪根中考虑黏性滑脱流、努森扩散、表面扩散及朗格缪尔吸附解吸, 无机基岩中考虑黏性滑脱流、努森扩散, 次生裂缝中考虑黏性滑脱流), 忽略高压下真实气体效应、岩石应力敏感性 & 开发过程中吸附层厚度变化等因素的影响, 建立页岩气藏不同区域离散介质表征单元体模型. 模型中只考虑水平方向气体运移, 上下边界封闭, 水平方向存在压力梯度, 不考虑气体垂向上流动.

干酪根有机质中气体以自由气和吸附气两种形式赋存, 干酪根中气体运移形态包括考虑滑移效应的黏

图1 (网络版彩图)页岩气藏压裂水平井储层特征示意图^[69]

图 2 (网络版彩图)USRV干酪根-无机基岩离散介质模型(a)和SRV无机基岩-次生缝网离散介质模型(b)

性流、努森扩散、表面扩散以及朗格缪尔吸附解吸, 耦合可得干酪根中气体运移控制方程^[9,69]:

$$\begin{aligned} & \frac{\partial}{\partial t} \left(\frac{p_k}{ZRT} \left(\phi_k + \varepsilon_{ks} (1 - \phi_k) c_{\mu s} \frac{ZRT}{(p_L + p_k)} \right) \right) \\ &= \frac{\partial}{\partial x} \left(\frac{p_k}{ZRT} \frac{1}{\mu_g} \left(\left(1 + \sqrt{\frac{8\pi RT}{M}} \frac{\mu_g}{p_k r_k} \left(\frac{2}{f_{ks}} - 1 \right) \right) \frac{\phi_k r_k^2}{8\tau_k} \right. \right. \\ & \left. \left. + \frac{\phi_k}{\tau_k} \frac{2r_k}{3} \sqrt{\frac{8ZRT}{\pi M}} C_g \mu_g + \mu_g \varepsilon_{ks} (1 - \phi_k) \right. \right. \\ & \left. \left. \cdot D_s \frac{c_{\mu s} ZRT}{(p_L + p_k)^2} \right) \frac{\partial p_k}{\partial x} \right), \end{aligned} \quad (1)$$

其中, ϕ_k 为干酪根固有孔隙度; p_k 为干酪根孔隙压力, MPa; Z 为气体压缩因子; R 为通用气体常数, $8.314 \times 10^{-6} \text{ MJ K}^{-1} \text{ mol}^{-1}$; T 为地层温度, K; ε_{ks} 为单位岩心体积中干酪根固体体积; M 为页岩气分子质量, kg/mol; μ_g 为气体黏度, mPa s; r_k 为干酪根中纳米尺度孔隙直径, m; τ_k 为干酪根中孔隙迂曲修正系数; C_g 为气体压缩系数, MPa⁻¹; D_s 为干酪根表面吸附气扩散系数, m²/s; $c_{\mu s}$ 干酪根表面朗格缪尔最大吸附浓度, mol/m³; p_L 为朗格缪尔压力, MPa; f_{ks} 为干酪根角动量调节系数(TMAG), 与页岩气在干酪根有机质纳米孔隙壁面上扩散反射有关, 变化范围为0~1.

Javadpour^[11]2009年提出表观渗透率的方法耦合表征页岩气藏气体不同运移机制, 国内外学者对其进行了大量研究^[12-15,52,67]. 考虑本文得到的干酪根介质气体运移控制方程, 可以得到干酪根有机质中耦合多种

气体运移机制的表观渗透率和孔隙度表达式:

$$\begin{aligned} k_{app_k} &= \frac{\phi_k}{\tau_k} \frac{2r_k}{3} \sqrt{\frac{8ZRT}{\pi M}} C_g \mu_g \\ &+ \mu_g \varepsilon_{ks} (1 - \phi_k) D_s \frac{c_{\mu s} ZRT}{(p_L + p_k)^2} \\ &+ \left(1 + \sqrt{\frac{8\pi RT}{M}} \frac{\mu_g}{p_k r_k} \left(\frac{2}{f_{ks}} - 1 \right) \right) \frac{\phi_k r_k^2}{8\tau_k}, \end{aligned} \quad (2)$$

$$\phi_{app_k} = \phi_k + \varepsilon_{ks} (1 - \phi_k) c_{\mu s} \frac{ZRT}{(p_L + p_k)}, \quad (3)$$

其中, k_{app_k} 为耦合多种运移机制的干酪根有机质表观渗透率, m²; ϕ_{app_k} 为耦合自由气和吸附气的干酪根有机质表观孔隙度.

无机基岩中页岩气主要以自由气形式赋存, 气体在USRV及SRV无机基岩微尺度孔隙介质中运移形态包括考虑滑移效应的黏性流以及努森扩散, 耦合可得无机基岩中气体运移控制方程为^[9,69]

$$\begin{aligned} & \frac{\partial}{\partial t} \left(\phi_m \frac{p_m}{ZRT} \right) \\ &= \frac{\partial}{\partial x} \left(\frac{p_m}{ZRT} \frac{1}{\mu_g} \left(\frac{\phi_m}{\tau_m} \frac{2r_m}{3} \sqrt{\frac{8ZRT}{\pi M}} C_g \mu_g + \frac{\phi_m r_m^2}{8\tau_m} \right. \right. \\ & \left. \left. \times \left(1 + \sqrt{\frac{8\pi RT}{M}} \frac{\mu_g}{p_m r_m} \left(\frac{2}{f_{ms}} - 1 \right) \right) \right) \frac{\partial p_m}{\partial x} \right), \end{aligned} \quad (4)$$

其中, ϕ_m 为无机基岩孔隙度; p_m 为无机基岩孔隙压力, MPa; r_m 为无机基岩内微米尺度孔隙直径, m; τ_m 为无机基岩中孔隙迂曲修正系数; f_{ms} 为无机基岩角动量调

节系数(TMAC), 与页岩气在无机基岩微米级孔隙壁上扩散反射有关, 变化范围为0~1.

同理可得耦合气体黏性滑移流和努森扩散的无机基岩表观渗透率:

$$k_{app_m} = \frac{\phi_m}{\tau_m} \frac{2r_m}{3} \sqrt{\frac{8ZRT}{\pi M}} C_g \mu_g + \left(1 + \sqrt{\frac{8\pi RT}{M}} \frac{\mu_g}{p_m r_m} \left(\frac{2}{f_{ms}} - 1 \right) \right) \frac{\phi_m r_m^2}{8\tau_m}, \quad (5)$$

其中, k_{app_m} 为耦合多种运移机制的无机基岩表观渗透率, m^2 .

气体在次生裂缝中以自由气形式赋存, 次生裂缝宽度相对较大, 努森扩散和滑移效应影响可以忽略不计, 气体在SRV次生裂缝中主要存在黏性流, 其运移控制方程为

$$\frac{\partial \left(\phi_f \frac{p_f}{ZRT} \right)}{\partial t} = \frac{p_f}{\mu_g ZRT} \frac{f_w^2}{8} \nabla p_f, \quad (6)$$

其中, ϕ_f 为次生裂缝孔隙度; p_f 为次生裂缝内孔隙压力, MPa; f_w 为次生裂缝宽度, m.

根据模型基本假设条件, 可得USRV离散介质模型中干酪根团块和SRV离散介质模型中无机基岩团块垂直两端及水平左侧外边界为封闭边界, 水平右侧边界为定压边界. 不同尺度介质交界面为气体跨尺度传质边界, 气体在不同尺度介质边界处运移时满足流量连续性原则, 即:

外边界条件

$$\begin{cases} \left. \frac{\partial p_\zeta}{\partial x} \right|_{x=0} = 0, \\ p_\zeta \Big|_{x=L} = p_{ini} - L \times dp, \\ \left. \frac{\partial p_\zeta}{\partial y} \right|_{y=0} = \left. \frac{\partial p_\zeta}{\partial y} \right|_{y=L} = 0. \end{cases} \quad (7)$$

交界面边界条件

$$\begin{cases} k_{app_k} \frac{\partial p_k}{\partial \Gamma_{USRV}} = k_{app_m} \frac{\partial p_m}{\partial \Gamma_{USRV}}, \\ k_{app_m} \frac{\partial p_m}{\partial \Gamma_{SRV}} = \frac{f_w^2}{8} \frac{\partial p_f}{\partial \Gamma_{SRV}}, \end{cases} \quad (8)$$

其中, L 为表征单元体(REV)边长, m; dp 为REV内压力梯度, MPa/m; 下标 ζ 代表不同介质, USRV离散介质模

型中分别代表干酪根和无机基岩, SRV离散裂缝模型中分别代表无机基岩和次生裂缝; Γ_{USRV} 为USRV离散介质模型中干酪根团块和无机基岩交界面; Γ_{SRV} 为SRV离散介质模型中无机基岩团块和次生裂缝交界面.

2.2 双重介质表征单元体模型

双重介质模型需要将离散介质模型中不连续分布的“基质”和“裂缝”等效成双重连续性介质, 根据模型基本假设、不同介质尺寸及数量分布特征, 对图2中离散介质模型进行连续性等效处理. 以图2(a)干酪根-无机基岩离散介质模型为例, 等效双重介质模型中干酪根-无机基岩渗透率和孔隙度分别为

$$\begin{aligned} k_{equ_k} &= k_{app_k} \times \frac{f_k n_k}{L_{KM}} \\ &= \left[\left(1 + \sqrt{\frac{8\pi RT}{M}} \frac{\mu_g}{p_k r_k} \left(\frac{2}{f_{ks}} - 1 \right) \right) \frac{\phi_k r_k^2}{8\tau_k} + \frac{\phi_k}{\tau_k} \frac{2r_k}{3} \sqrt{\frac{8ZRT}{\pi M}} C_g \mu_g + \mu_g \varepsilon_{ks} (1 - \phi_k) \right. \\ &\quad \left. \cdot D_s \frac{c_{\mu s} ZRT}{(p_L + p_k)^2} \right] \times \frac{f_k n_k}{L_{KM}}, \end{aligned} \quad (9)$$

$$\begin{aligned} \phi_{equ_k} &= \phi_{app_k} \times \frac{(f_k n_k)^2}{L_{KM}^2} \\ &= \frac{p_k}{ZRT} \left(\phi_k + \varepsilon_{ks} (1 - \phi_k) c_{\mu s} \frac{ZRT}{(p_L + p_k)} \right) \\ &\quad \times \frac{(f_k n_k)^2}{L_{KM}^2}, \end{aligned} \quad (10)$$

$$\begin{aligned} k_{equ_m} &= k_{app_m} \times \frac{f_m n_m}{L_{KM}} \\ &= \left[\left(1 + \sqrt{\frac{8\pi RT}{M}} \frac{\mu_g}{p_m r_m} \left(\frac{2}{f_{ms}} - 1 \right) \right) \frac{\phi_m r_m^2}{8\tau_m} + \frac{\phi_m}{\tau_m} \frac{2r_m}{3} \sqrt{\frac{8ZRT}{\pi M}} C_g \mu_g \right] \times \left(1 - \frac{f_k n_k}{L_{KM}} \right), \end{aligned} \quad (11)$$

$$\phi_{equ_m} = \phi_m \times \frac{(f_m n_m)^2}{L_{KM}^2} = \phi_m \times \left(1 - \frac{(f_k n_k)^2}{L_{KM}^2} \right), \quad (12)$$

其中, k_{equ_k} 为双重介质干酪根有机质等效渗透率, m^2 ; f_k 为离散介质模型中干酪根有机质团块特征尺寸, m; n_k 为离散介质表征单元体模型中干酪根有机质团块数目; L_{KM} 为干酪根-无机基岩表征单元体模型边长,

m ; ϕ_{equ_k} 为双重介质模型中干酪根有机质等效孔隙度; k_{equ_m} 为双重介质无机基岩等效渗透率, m^2 ; f_m 为离散介质模型中无机基岩团块特征尺寸, m ; n_m 为离散介质表征单元体模型中无机基岩团块数目; ϕ_{equ_m} 为双重介质

模型中无机基岩等效孔隙度。

基于不同介质等效渗透率和孔隙度, 可以得到离散介质模型的等效多重介质渗流数学模型。其中干酪根-无机基岩双重介质模型渗流方程组为

$$\begin{aligned} \frac{\partial}{\partial t} \left(\frac{p_k}{ZRT} \phi_{\text{app}_k} \frac{(f_k n_k)^2}{L_{\text{KM}}^2} \right) &= \frac{\partial}{\partial x} \left(\frac{p_k}{ZRT} \frac{k_{\text{app}_k}}{\mu_g} \frac{f_k n_k}{L_{\text{KM}}} \frac{\partial p_k}{\partial x} \right) - N_{km}, \quad \frac{\partial p_k}{\partial x} \bigg|_{x=0} = \frac{\partial p_k}{\partial x} \bigg|_{x=L_{\text{KM}}} = 0, \quad \frac{\partial p_m}{\partial x} \bigg|_{x=0} = 0, \\ p_m \big|_{x=L_{\text{KM}}} &= p_{\text{ini}} - L_{\text{KM}} \times dp, \quad \frac{\partial p_k}{\partial y} \bigg|_{y=0} = \frac{\partial p_k}{\partial y} \bigg|_{y=L_{\text{KM}}} = 0, \quad \frac{\partial p_m}{\partial y} \bigg|_{y=0} = \frac{\partial p_m}{\partial y} \bigg|_{y=L_{\text{KM}}} = 0, \\ \frac{\partial}{\partial t} \left(\frac{p_m}{ZRT} \phi_m \left(1 - \frac{(f_k n_k)^2}{L_{\text{KM}}^2} \right) \right) &= \frac{\partial}{\partial x} \left(\frac{p_m}{ZRT} \frac{k_{\text{app}_m}}{\mu_g} \left(1 - \frac{f_k n_k}{L_{\text{KM}}} \right) \frac{\partial p_m}{\partial x} \right) + N_{km}, \end{aligned} \quad (13)$$

其中, N_{km} 为干酪根有机质向无机基岩质量窜流量, kg/s ; p_{ini} 为页岩储层初始压力, MPa 。

无机基岩-次生缝网双重介质模型渗流方程组为

$$\begin{aligned} \frac{\partial}{\partial t} \left(\frac{p_m}{ZRT} \phi_m \left(1 - \frac{(f_w n_f)^2}{L_{\text{MF}}^2} \right) \right) &= \frac{\partial}{\partial x} \left(\frac{p_m}{ZRT} \frac{k_{\text{app}_m}}{\mu_g} \left(1 - \frac{f_w n_f}{L_{\text{MF}}} \right) \frac{\partial p_m}{\partial x} \right) - N_{fm}, \quad \frac{\partial p_m}{\partial x} \bigg|_{x=0} = \frac{\partial p_m}{\partial x} \bigg|_{x=L_{\text{MF}}} = 0, \\ \frac{\partial p_f}{\partial x} \bigg|_{x=0} &= 0, \quad p_f \big|_{x=L_{\text{MF}}} = p_{\text{ini}} - L_{\text{MF}} \times dp, \quad \frac{\partial p_m}{\partial y} \bigg|_{y=0} = \frac{\partial p_m}{\partial y} \bigg|_{y=L_{\text{MF}}} = 0, \quad \frac{\partial p_f}{\partial y} \bigg|_{y=0} = \frac{\partial p_f}{\partial y} \bigg|_{y=L_{\text{MF}}} = 0, \\ \frac{\partial}{\partial t} \left(\frac{p_f}{ZRT} \phi_f \frac{(f_w n_f)^2}{L_{\text{MF}}^2} \right) &= \frac{\partial}{\partial x} \left(\frac{p_f}{ZRT} \frac{f_w^2 n_f}{8 L_{\text{MF}}} \frac{\partial p_f}{\partial x} \right) + N_{mf}, \end{aligned} \quad (14)$$

其中, N_{fm} 为无机基岩向次生裂缝质量窜流量, kg/s ; L_{MF} 为无机基岩-次生缝网表征单元体模型边长, m 。

双重介质模型中流体跨尺度传质规律可以采用拟稳态窜流和瞬态窜流两种方式进行表征。以干酪根-无机基岩之间窜流为例进行分析, 当气体从小尺度的干酪根有机质向相对大尺度的无机基岩发生跨尺度传质时, 如果认为气体传质能瞬间达到拟稳态, 则其跨尺度传质可以采用拟稳态窜流方程表征:

$$N_{km} = \sigma_{\text{PSS}} \frac{p_k}{ZRT} \frac{k_{\text{equ}_k}}{\mu_g} \frac{f_k n_k}{L_{\text{KM}}} (p_k - p_m), \quad (15)$$

其中, σ_{PSS} 为干酪根有机质团块形状因子, m^{-2} 。

如果认为气体传质不能在短时间内达到稳态, 则采用瞬态窜流描述干酪根有机质与无机基岩之间的跨尺度传质。Zimmerman等人^[64]利用压力对形状因子进行修正, 得到了瞬态窜流方程:

$$\begin{aligned} N_{km} &= \sigma_{\text{PSS}} \frac{(p_{\text{ini}} - p_m)^2 - (p_{\text{ini}} - p_k)^2}{2(p_{\text{ini}} - p_k)(p_m - p_k)} \\ &\quad \cdot \frac{p_k}{ZRT} \frac{k_{\text{equ}_k}}{\mu_g} \frac{f_k n_k}{L_{\text{KM}}} (p_k - p_m). \end{aligned} \quad (16)$$

2.3 模型计算求解

采用有限元求解建立的离散介质、瞬态窜流双重

介质及拟稳态窜流双重介质表征单元体模型, 以干酪根有机质-无机基岩离散介质表征单元体模型为例说明求解流程. 依次对方程(1)~(4)和(7)进行有限元求解, 求解时采用隐式无机基岩压力 p_m 显示干酪根有机质压

力 p_k , 对 p_m 和 p_k 先后交替求解. 首先基于Euler向前时间差分格式进行离散, 可以得到 $n+1$ 时刻无机基岩压力值 p_m^{n+1} 和干酪根有机质压力 p_k^{n+1} :

$$\frac{\phi_m}{ZRT} \frac{p_m^{n+1} - p_m^n}{t^{n+1} - t^n} = \frac{\partial}{\partial x} \left(\frac{p_m^n}{ZRT \mu_g} \left(\left(1 + \sqrt{\frac{8\pi RT}{M}} \frac{\mu_g}{p_m^n r_m} \left(\frac{2}{f_{ms}} - 1 \right) \right) \frac{\phi_m r_m^2}{8\tau_m} + \frac{\phi_m 2r_m}{\tau_m 3} \sqrt{\frac{8ZRT}{\pi M}} C_g \mu_g \right) \frac{\partial p_m^{n+1}}{\partial x} \right), \quad (17)$$

$$\frac{\phi_k + \varepsilon_{ks}(1 - \phi_k) c_{\mu s} \frac{ZRT}{(p_L + p_k^n)} \frac{p_k^{n+1} - p_k^n}{t^{n+1} - t^n}}{ZRT} = \frac{\partial}{\partial x} \left(\frac{p_k^n}{ZRT \mu_g} \left(\left(1 + \sqrt{\frac{8\pi RT}{M}} \frac{\mu_g}{p_k^n r_k} \left(\frac{2}{f_{ks}} - 1 \right) \right) \frac{\phi_k r_k^2}{8\tau_k} + \frac{\phi_k 2r_k}{\tau_k 3} \sqrt{\frac{8ZRT}{\pi M}} C_g \mu_g + \mu_g \varepsilon_{ks} (1 - \phi_k) D_s \frac{c_{\mu s} ZRT}{(p_L + p_k^n)^2} \right) \frac{\partial p_k^{n+1}}{\partial x} \right). \quad (18)$$

利用标准伽辽金方法推导有限元积分弱形式, 在此基础上利用Gauss部分积分公式求解得到无机基岩团块单元体特性矩阵, 进一步化简可得无机基岩团块及干酪根有机质团块的有限元支配方程为

$$\left(A_m - \frac{R_m}{t^{n+1} - t^n} \right) P_m^{n+1} + \frac{R_m}{t^{n+1} - t^{n+1}} P_m^n = 0, \quad (19)$$

$$\left(A_k - \frac{R_k}{t^{n+1} - t^n} \right) P_k^{n+1} + \frac{R_k}{t^{n+1} - t^{n+1}} P_k^n = 0, \quad (20)$$

其中,

$$\mathbf{N}_e = [N_1, N_2, N_3], \quad \mathbf{P}_{me} = [p_{m1}, p_{m2}, p_{m3}],$$

$$\mathbf{P}_m = [p_{m1}, p_{m2}, \dots, p_{mN_p}]^T, \quad \mathbf{P}_{me'} = \left[\frac{1}{3} \quad \frac{1}{3} \quad \frac{1}{3} \right] \mathbf{P}_{me},$$

$$\nabla \mathbf{N}_e = \begin{bmatrix} \frac{\partial N_1}{\partial x} & \frac{\partial N_2}{\partial x} & \frac{\partial N_3}{\partial x} \\ \frac{\partial N_1}{\partial y} & \frac{\partial N_2}{\partial y} & \frac{\partial N_3}{\partial y} \end{bmatrix},$$

$$R_m = \frac{\phi_m}{ZRT} \iint_{\Omega_e} \nabla \mathbf{N}_e^T \mathbf{N}_e d\Omega_e,$$

$$A_m = \iint_{\Omega_e} \nabla \mathbf{N}_e^T \frac{\mathbf{P}_{me'}}{\mu_g ZRT} \cdot \left(\left(1 + \sqrt{\frac{8\pi RT}{M}} \frac{\mu_g}{p_m^n r_m} \left(\frac{2}{f_{ms}} - 1 \right) \right) \frac{\phi_m r_m^2}{8\tau_m} + \frac{\phi_m 2r_m}{\tau_m 3} \sqrt{\frac{8ZRT}{\pi M}} C_g \mu_g \right) \nabla \mathbf{N}_e d\Omega_e,$$

$$\mathbf{P}_{ke} = [p_{k1}, p_{k2}, p_{k3}],$$

$$\mathbf{P}_k = [p_{k1}, p_{k2}, \dots, p_{kN_p}]^T,$$

$$R_k = \frac{\phi_k + \varepsilon_{ks}(1 - \phi_k) c_{\mu s} \frac{ZRT}{(p_L + p_k^n)}}{ZRT} \iint_{\Omega_e} \nabla \mathbf{N}_e^T \mathbf{N}_e d\Omega_e,$$

$$A_k = \iint_{\Omega_e} \nabla \mathbf{N}_e^T \frac{P_{ke'}}{\mu_g ZRT} \cdot \left(\left(1 + \sqrt{\frac{8\pi RT}{M}} \frac{\mu_g}{p_k^n r_k} \left(\frac{2}{f_{ks}} - 1 \right) \right) \frac{\phi_k r_k^2}{8\tau_k} + \frac{\phi_k 2r_k}{\tau_k 3} \sqrt{\frac{8ZRT}{\pi M}} C_g \mu_g + \mu_g \varepsilon_{ks} (1 - \phi_k) D_s \frac{c_{\mu s} ZRT}{(p_L + p_k^n)^2} \right) \nabla \mathbf{N}_e d\Omega_e,$$

$$\mathbf{P}_{ke'} = \left[\frac{1}{3} \quad \frac{1}{3} \quad \frac{1}{3} \right] \mathbf{P}_{ke}.$$

对式(19)和(20)采用Newton-Raphson方法进行交替迭代求解, 可得任意时刻无机基岩团块和干酪根有机质团块压力值, 从而可以进一步得到表征单元体模型中气体产量变化规律.

3 页岩气藏多重介质流体跨尺度传质表征方法分析

基于体积压裂改造页岩气藏储层不同区域离散介质、瞬态双重介质、拟稳态双重介质表征单元体模型, 本文以北美典型页岩气藏储层作为研究对象, 参考

表 1 北美典型页岩气藏储层参数

页岩气藏参数	数值	页岩气藏参数	数值
无机基岩特征尺寸 (m)	0.5	干酪根表面朗格缪尔最大吸附浓度 ($\text{m}^3 \text{kg}^{-1}$)	3.1×10^{-3}
干酪根团块特征尺寸 (m)	0.5	离散介质中无机基岩团块数目	10
次生裂缝特征尺寸 (m)	0.001	通用气体常数 ($\text{J kg}^{-1} \text{mol}^{-1}$)	8.314
气体压缩系数 (MPa^{-1})	0.5	REV压力梯度 (MPa m^{-1})	0.1
干酪根孔径 (nm)	50	干酪根固有孔隙度	0.01
无机基岩孔隙度	0.05	无机基岩孔径 (nm)	1500
气体黏度 (mPa s)	0.0184	干酪根表面扩散系数 ($10^{-4} \text{m}^2 \text{s}^{-1}$)	0.01
气体摩尔质量 (kg mol^{-1})	0.016	朗格缪尔压力 (MPa)	13.78
储层温度 (K)	338	角动量调节系数	0.8
单位岩心体积中干酪根固体体积	0.5	干酪根孔隙迂曲度	2
无机基岩孔隙迂曲度	2	REV初始压力 (MPa)	50

相关文献中公开储层参数^[12,15,70-73], 归纳总结得到本文模型计算数据, 分析不同跨尺度传质表征方法计算得到的表征单元体产量变化规律.

3.1 双重介质不同窜流模式分析

双重介质模型流体从低渗介质窜流到高渗介质, 窜流量受两种介质之间压差、渗透率以及基质团块大小及形状的影响. 同时页岩气藏中气体密度、介质表观渗透率等受介质孔隙压力影响较大, 对窜流量产生较大的影响. 从窜流方程的角度出发, 以干酪根-无机基岩双重介质模型为例, 计算不同孔隙压力及介质间压差时页岩气藏窜流量, 如图3所示. 从图中可以看出:

图 3 (网络版彩图)双重介质模型不同窜流方式时窜流量分析

干酪根与无机基岩压差相同时, 储层越接近原始地层压力, 基于瞬态窜流方程计算得到的窜流量越大于拟稳态方法得到的窜流量, 即生产早期窜流模式对窜流量影响较大; 干酪根、无机基岩压差相差越大, 即介质之间渗透率相差越大, 生产早期不同窜流表征方法得到的窜流量相差越大, 窜流量差异持续时间越长. 同时, 随着干酪根有机质孔隙压力的下降, 相同介质压差时窜流量越来越小, 其主要原因是页岩气藏干酪根表观渗透率和气体密度受压力影响比较大, 随着孔隙压力的降低, 干酪根表观渗透率和气体密度均下降, 从而引起窜流量下降.

3.2 干酪根-无机基岩流体跨尺度传质表征方法分析

体积压裂页岩气藏储层中广泛发育干酪根有机质和无机基岩, USRV区域内气体由低尺度孔隙的干酪根有机质运移至发育相对大尺度孔隙无机基岩, 然后从无机基岩经过长距离运移至体积压裂产生的次生缝网. 同时SRV区域气体由干酪根有机质孔隙运移至无机基岩后, 通过近距离运移至次生缝网. 气体在干酪根有机质和无机基岩中运移特征对页岩气藏体积压裂水平井生产动态具有重要的影响. 干酪根有机质和无机基岩中气体赋存形式不同、介质属性差异较大, 笔者分别采用前文建立的干酪根-无机基岩离散介质、瞬态窜流双重介质及拟稳态窜流双重介质表征单元体

模型描述页岩气藏干酪根有机质-无机基岩流体跨尺度传质特征, 分析表观渗透率、介质含量对不同表征方法计算结果的影响, 结果如图4和5所示. 干酪根、无机基岩表观渗透率是孔隙尺寸、角动量调节系数、孔隙度、迂曲度、表面扩散系数(无机基岩中表面扩散系数可认为是0)等储层性质的函数, 其中孔隙尺寸是主要影响因素. 通过变化孔隙尺寸分析不同渗透率时3种表征方法得到的表征单元体产量变化规律, 可以看出: 随着无机基岩与干酪根有机质表观渗透率比值逐渐增大, 3种方法得到的瞬时产量相差逐渐增大, 其中离散介质计算得到的产量最大, 拟稳态窜流计算得到的产量最小. 当渗透率相差较小时, 无机基岩内压力下降较慢, 窜流发生时间较晚, 初始生产时刻3种方法描述得到的产量相差不大. 当渗透率相差较大时, 无机基岩内压力下降很快, 窜流发生时间较早, 初始生产时刻3种方法得到的产量有一定差别. 生产一段时间后, 干酪根有机质内气体运移量逐渐增大, 3种方法得到的产量之差逐渐增大, 此时瞬态窜流和拟稳态窜流

计算结果逐渐接近. 从累积产量(Q)曲线上可以看出, 生产早期离散介质模型得到产量最大, 拟稳态窜流模型得到产量最低, 生产时间足够长时, 3种描述方法得到的产量基本相同.

储层中干酪根和无机基岩介质含量决定离散介质模型中两种介质团块特征尺寸相对大小以及双重介质模型等效孔渗参数. 对比分析不同介质团块特征尺寸时3种方法得到的产量变化规律, 可以看出: 当前储层参数下, 干酪根介质含量大于无机基岩时, 生产初期离散介质模型产量大于双重介质模型产量, 随着生产时间的增长, 3种方法得到的产量逐渐接近, 累积产量在早期差别较大, 随着时间的增长逐渐接近, 最终趋于相等. 当干酪根介质含量小于无机基岩时, 生产初期3种方法得到的产量基本相等, 随着生产时间的增长, 由于窜流影响离散介质模型计算得到的产量与双重介质模型差别逐渐增大, 瞬态窜流模型计算得到的产量略高于拟稳态窜流模型. 当生产时间足够长时, 3种方法描述得到的产量基本相等. 其原因在于无机基岩含量较

图4 (网络版彩图)不同表观渗透率时干酪根-无机基岩流体生产动态对比

图5 (网络版彩图)不同介质含量时干酪根-无机基岩流体生产动态对比

图 6 (网络版彩图)不同表观渗透率时次生裂缝-无机基岩多尺度介质流体生产动态对比

高时,生产初期无机基岩孔隙内压力下降较慢,窜流发生时间较晚,因而3种方法早期产量基本相等,反之则相差较大。

综合分析可知,页岩气藏干酪根有机质-无机基岩系统中采用离散介质、瞬态双重介质、拟稳态双重介质描述得到的表征单元体产量变化规律基本相似,考虑到计算效率等因素,在页岩气藏数值模拟中宜采用瞬态窜流或拟稳态窜流双重介质模型表征干酪根有机质-无机基岩流体跨尺度传质机制。

3.3 无机基岩-次生缝网流体跨尺度传质表征方法分析

页岩气藏体积压裂形成高导流能力次生裂缝网络,气体在无机基岩和次生裂缝中赋存形式相同,运移机制相似,由于两者之间尺度差异较大,同样不能等效成一种介质进行处理。本文分别采用无机基岩-次生缝网离散介质、瞬态窜流双重介质及拟稳态窜流双重介质表征单元体模型描述页岩气藏无机基岩-次生缝网流体跨尺度传质特征,通过变化次生裂缝尺寸分析不同渗透率时3种表征方法得到的表征单元体产量变化规律,如图6所示。可以看出:现有储层参数下,3种方法得到的产量差别较大。离散介质模型计算得到的初期产量最高,产量下降速度最快,拟稳态窜流双重介质模型计算得到的产量最小,下降速度最慢。随着生产时间的增长,不同窜流模式时双重介质模型计算得到的产量很快趋于相等,而离散介质模型计算得到的产量仍高于双重介质模型。当生产时间足够长时,3种描述方法计算得到的累积产量相等。

综合前文分析,对于次生裂缝发育的SRV区域,由于次生裂缝与无机基岩导流能力相差较大,采用双重介质模型不能准确表征无机基岩-次生缝网跨尺度流体传质特征,页岩气藏数值模拟器中宜采用离散缝网耦合干酪根-无机基岩双重介质模型描述干酪根有机质-无机基岩-次生缝网多重介质流体运移规律。USRV区域宜采用瞬态窜流或拟稳态窜流双重介质模型表征干酪根有机质-无机基岩双重介质流体运移规律。

4 结论

(1) 基于体积压裂改造页岩气藏储层多尺度介质分布特征、多尺度介质气体运移特性,以储层不同区域微小单元体为研究对象,分别建立离散介质、拟稳态窜流双重介质、瞬态窜流双重介质表征单元体模型,对比分析了不同储层条件和裂缝参数时基于离散介质模型与不同窜流模式双重介质模型的流体产量变化规律。

(2) 储层生产早期不同窜流模式对窜流量影响较大,介质之间渗透率相差越大,生产早期不同窜流表征方法得到的窜流量相差越大,窜流量差异持续时间越长。同时,随着干酪根有机质孔隙压力的下降,介质之间压差相同时窜流量越来越小。

(3) 页岩气藏数值模拟器中宜采用离散缝网耦合干酪根-无机基岩双重介质模型描述SRV区域干酪根有机质-无机基岩-次生缝网多重介质流体运移规律。USRV区域宜采用瞬态窜流或拟稳态窜流双重介质模型表征干酪根有机质-无机基岩双重介质流体运移规律。

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Characterization methods for mass transfer of multiple media in shale gas reservoirs

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Shale gas reservoirs are abundant in multi-scale pore media and have strong heterogeneity. Gas migration mechanism in different scale pores is complex. Understanding the applicability of mass transfer characterization method for multi-media fluid is of great significance to develop numerical simulation of shale gas reservoirs. On the basis of multi-scale media distribution characteristics and the gas migration characteristics in multi-scale media of shale gas reservoirs, this paper establishes the discrete media REV model, transient-cross-flow dual-media REV model, and pseudo-state-cross-flow dual-media REV model for microcells in different regions of reservoirs. The flow behavior of the microcells calculated by the above three models is compared with reservoir conditions and fracture parameters. The suitable range of different mass transfer characterization methods for multiple media is proposed. The results showed that the cross-flow mode has a great effect on mass transfer in the early period. The greater the difference of dual media, the bigger the difference of mass transfer calculated by different cross-flow mode, the longer the duration of the difference of mass transfer. The transient-cross-flow dual-media model, and pseudo-state-cross-flow dual-media model can both accurately describe the mass transfer between porous kerogen and inorganic matrix. Mass transfer between inorganic matrix and secondary fractures should be described by discrete media model. The discrete fracture network coupled porous kerogen-inorganic matrix dual medium model can be more accurately for description of gas migration in shale gas reservoirs with stimulated reservoir volume. The model has important theoretical significance for developing numerical simulator for shale gas reservoirs.

shale gas reservoirs, discrete media, multi-media, mass transfer

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