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页岩油藏多重孔隙介质耦合流动数值模拟

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摘要:页岩孔隙类型多样,微纳米尺度孔隙发育,借助分段压裂水平井技术能够实商业化开采。原油分子与孔隙壁面作用较甲烷分子更加复杂,目前页岩油在无机和有机纳米孔中的运移机制尚不清楚。准确模拟页岩油微观运移机制和多重孔隙介质间耦合流动对页岩油藏产能评价和生产预测具有重要意义。结合润湿特性,考虑液体吸附、速度滑移及物性变化等机制,引入复杂结构参数(迂曲度、孔隙度和有机孔含量),建立了微纳米多孔介质液体表观渗透率模型,研究了不同运移机制对微纳米多孔介质表观渗透率影响。在此基础上,建立了基质-天然裂缝-人工裂缝耦合的页岩油藏分段压裂水平井数学模型,利用有限元方法求解,进行产能影响因素分析。结果表明,孔隙半径小于10 nm时,微纳米孔隙速度滑移影响明显,而孔隙半径大于100 nm时,微观运移机制作用可以忽略;有机孔隙含量越小、裂缝条数越多则分段压裂水平井产能越大;最优的缝网模式为缝网无间距且不重叠。本研究的重点是丰富微纳米孔隙内油气运移理论,为页岩油藏开发模拟研究提供理论方法。

关键词:缝网模式;微观运移;裂缝;微纳米孔隙;跨尺度流动;分段压裂;数值模拟;页岩油

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Numerical simulation of shale oil coupled flow in multi-pore media

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Abstract: Shale reservoirs are characterized by various pores with micro- and nano-pores well developed. Commercial shale oil development can be achieved by means of staged fracturing in horizontal wells. The interaction between oil molecules and pore wall is more complex than that between methane molecules and pore wall, but it is still unclear about the migration mechanism of shale oil in inorganic and organic nano-pores at present. Accurate simulation of the microscopic migration mechanisms of shale oil and the coupled flow in multi-pore media is of great significance to productivity evaluation and production prediction in shale oil reservoirs. Considering wettability and mechanisms of liquid adsorption, velocity slip and physical property change, we established the apparent permeability model for fluids in micro- and nano-scale multi-pore media based on the complex structural parameters (including tortuosity, porosity and organic pore content), to explore the effects of different migration mechanisms on the apparent permeability of micro- and nano-scale multi-pore media. Subsequently, the mathematical model with matrix, natural fracture and artificial fracture coupled was set up for multistage fractured horizontal wells in shale oil reservoirs. Besides, the finite element method was used to solve the model, and to analyze the factors affecting productivity. The results show that when the pore radius is less than 10 nm, the effect of velocity slip in micro- and nano-pores is significant, while when the pore radius is greater than 100 nm, the effect of microscopic migration mechanisms may be neglected. The less the number of organic pores and the more the number of fractures, the greater the productivity of multistage fractured horizontal wells will be. The optimal fracture network is that has neither spacing nor overlapping between the adjacent fractures. The highlight of the study is to enrich the theories on oil and gas migration in micro- and nano-pores, so as to contribute to the development simulation of shale reservoirs with

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theoretical methods.

Key words: fracture network, microscopic migration, fracture, nano-pore, cross-scale flow, multistage fracturing, numerical simulation, shale oil

常规资源短缺加速了页岩油气等非常规资源的开发。页岩油储量丰富,潜力巨大,受到世界各国越来越多的关注,其主要特点是油气成藏机理和储集空间类型与常规油气资源不同。页岩储层纳米孔隙发育、渗透率极低,烃类流体同时存在于有机和无机两类孔隙内,流体运移机制更为复杂[1-3],达西定律不再适用。目前,针对纳米通道内原油运移规律的研究多集中于分子动力学模拟(MDS)领域[4-5]。考虑原油微观运移机制的表观渗透率模型是页岩油藏宏观数值模拟、产量预测等理论[6-7]的基础。

借助高精度扫描电镜表征页岩孔隙结构,结果表明:尺寸在 1 ~ 200 nm 的纳米孔隙发育,多数孔隙半径小于 5 nm[8]。通过 X - 射线衍射进行矿物分析发现,页岩典型组成可分为:油湿干酪根(OM)和水湿的石英、粘土(IM)等,如图 1[9] 所示。目前,学者利用实验和数值模拟方法,如 MDS 和格子玻尔兹曼等方法,研究了甲烷气体在页岩多孔介质内的运移机制,提出了几种基于努森数和微孔隙结构的气体表观渗透率模型[10-11]。与甲烷分子不同,液烃分子平均自由程较小,且液 - 固分子的相互作用更强[12],导致流体运移机制更为复杂。实验和 MDS[13] 方法证实液烃运移在孔隙壁面出现速度滑移现象,且滑移边界条件与润湿性有关,与无滑移边界条件有显著差异[4,14-16]。Majumder 等[17] 观察到水、己烷、乙醇和烷烃通过多孔碳纳米管(CNT)复合膜的流速比哈根 - 泊肃叶(HP)方程[15,17]计算的流速大 4 ~ 5 个数量级。Holt 等[18] 通过由直径小于 2 nm 的碳纳米管组成的微制备膜测量了水的传输速度,计算得到增强因子为 3 个数量级。近年,物理实验模拟研究虽涵盖了直径为 0.8 ~ 44 nm,长度为 2 ~ 280 μm,压力为 0.1 ~ 100 MPa 等条件。但物理实验模拟实现较为困难,因此,MDS 被广泛用于研究流体在纳米孔和近壁区域传输的流体力学特性。Barrat 和 Bocquet[16] 利用 MDS 研究了具有滑移和无滑移边界条件的微尺度孔隙内流体的水动力特性,发现玻璃体系内汞的滑移长度超过 30 分子直径。Falk 等[17] 应用 MDS 计算不同直径和几何形状 CNT 中液体流动的摩擦系数,与无滑移的 HP 流量相比,流量增强倍数为 1 ~ 3 个数量级。前期研究多采用单相水为对象,温度或压力无法反映页岩储层条件。Wang 等[4-5] 利用 MDS 研究了无机和有机纳米孔(1.7 ~ 11.2 nm)的液烃运移机制,并计算了速度分布、表观粘度和滑移长度,采用滑移长度和表观粘度两种模型来描述液烃在 OM 内的运移。

本文将页岩孔隙迂曲度、孔隙度和有机孔含量等结构参数引入到页岩基质宏观参数的数学表征中,并考虑无机纳米孔隙内流速增强效果、近壁与体相流体密度及粘度的差异,建立了耦合多种运移机制的页岩油藏表观渗透率模型。然后将表观渗透率模型应用到页岩油藏分段压裂水平井模型,分析了产能影响因素,形成了页岩油藏分段压裂水平井多重孔隙介质耦合模拟方法。

1 页岩油藏表观渗透率模型

1.1 无机孔隙内液烃运移机制

无机孔隙主要由粘土、石英等矿物构成,液烃在无机孔隙内的运移规律可参考水在碳纳米管内的运移规律。根据润湿关系,单相水在碳纳米管内运移形态可分为 5 种,如图 2 所示。亲水壁面,水分子与壁面作用力强,形成难流动的近壁面区域(图 2a 蓝色区域)和无滑移边界,如图 2(a)和(b)所示;中性壁面,无滑移边界仍适用,近壁面流体粘度和密度发生变化(红色箭头所示),如图 2(c)所示;疏水壁面,壁面对水分子排斥增强,使近壁面流体粘度和密度比体相流体小且出现滑移,如图 2(d)和(e)所示。

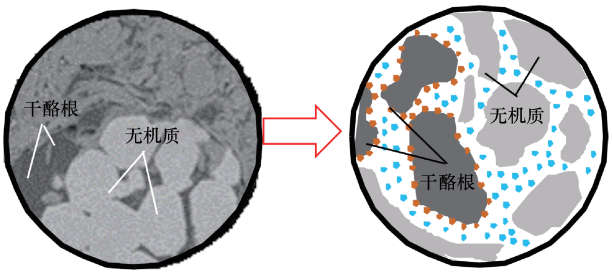

图 1 2D 页岩有机和无机孔隙结构表征示意图[9]

Fig. 1 2 - D structural characterization of organic and inorganic pores in shales[9]

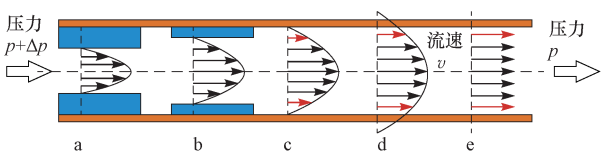

图 2 单相水在碳纳米管内运移示意图

Fig. 2 A schematic diagram showing single-phase water migration in carbon nanotubes

通过修正 Hagen – Poiseuille(HP)方程来描述考虑速度滑移的流体运移速度:

$$v_{\mathrm{b}}(r) = \frac{(R^2 - r^2)\Delta p}{4\mu_{\mathrm{b}}L} + c_1, 0 \leqslant r \leqslant R - \delta \quad (1)$$

式中:R 为孔隙半径,m;r 为孔隙内任一点与轴线距离,m;Δp 为压差,MPa;L 为孔隙长度,m;v_{b} 为体相流体流速,m/s;μ_{b} 为体相流体粘度,mPa·s;c_1 为与速度滑移相关的参数,m/s;δ 为近壁面流体厚度,m。

近壁面流体流速可表示为:

$$v_{\mathrm{w}}(r) = \frac{(R^2 - r^2)\Delta p}{4\mu_{\mathrm{w}}L} + c_2, R - \delta \leqslant r \leqslant R \quad (2)$$

式中:v_{w} 为近壁面流体流速,m/s;μ_{w} 为近壁面流体粘度,mPa·s;c_2 为速度滑移相关的参数,m/s。

根据牛顿内摩擦定律,孔隙中心流速最大且速度梯度为零,假设体相流体与近壁面流体交界处速度和剪切力连续,则模型边界条件为:

$$\begin{cases} \left.\dfrac{\partial v_{\mathrm{b}}}{\partial r}\right|_{r=0} = 0 \\ v_{\mathrm{b}}|_{r=R-\delta} = v_{\mathrm{w}}|_{r=R-\delta} \\ \mu_{\mathrm{b}} \left.\dfrac{\partial v_{\mathrm{b}}}{\partial r}\right|_{r=R-\delta} = \mu_{\mathrm{w}} \left.\dfrac{\partial v_{\mathrm{w}}}{\partial r}\right|_{r=R-\delta} \\ -\lambda \left.\dfrac{\partial v_{\mathrm{w}}}{\partial r}\right|_{r=R} = v_{\mathrm{w}}|_{r=R} \end{cases} \quad (3)$$

若近壁面流体粘度和厚度确定,则滑移长度可表示为[18]:

$$\lambda = \frac{2\mu_{\mathrm{w}}L}{R\Delta p} v_{\mathrm{w}}|_{r=R} \quad (4)$$

孔壁处速度与压力梯度和分子表面扩散系数的关系为[19]:

$$v_{\mathrm{w}}|_{r=R} = \frac{D_{\mathrm{s}}}{W_{\mathrm{A}}}\Delta p \quad (5)$$

式中:W_{A} 表示近壁面区域流体与孔壁单位表面积的作用能,J/m²;D_{s} 为分子表面扩散系数,m²/s。D_{s} 和 W_{A} 可通过实验或分子模拟获得。

定义速度滑移系数 C 为:

$$C = \frac{LD_{\mathrm{s}}}{W_{\mathrm{A}}} \quad (6)$$

则 v_{b} 和 v_{w} 的表达式分别为:

$$\begin{cases} v_{\mathrm{b}}(r) = \dfrac{\mu_{\mathrm{w}}(R^2 - r^2) + (2R\delta - \delta^2)(\mu_{\mathrm{b}} - \mu_{\mathrm{w}})}{4L\mu_{\mathrm{w}}\mu_{\mathrm{b}}}\Delta p + \dfrac{C\Delta p}{L}, 0 \leqslant r \leqslant R - \delta \\ v_{\mathrm{w}}(r) = \left(\dfrac{R^2 - r^2}{4\mu_{\mathrm{w}}} + C\right)\dfrac{\Delta p}{L}, R - \delta \leqslant r \leqslant R \end{cases} \quad (7)$$

对 r 从 0 到 $R-\delta$ 积分,得体相体积流量:

$$Q_{\mathrm{b}} = \int_0^{R-\delta} v_{\mathrm{b}} A \mathrm{d}r = \frac{\pi\Delta p\,(R-\delta)^2}{8L}\left[\frac{4R\delta - 2\delta^2}{\mu_{\mathrm{w}}} + \frac{(R-\delta)^2}{\mu_{\mathrm{b}}} + 8C\right] \quad (8)$$

对 r 从 $R-\delta$ 到 R 积分,得近壁面体积流量:

$$Q_{\mathrm{w}} = \int_{R-\delta}^{R} v_{\mathrm{w}} A \mathrm{d}r = \frac{\pi\Delta p}{8L\mu_{\mathrm{w}}}\left[(2R\delta - \delta^2)^2 + 8\mu_{\mathrm{w}}C(2R\delta - \delta^2)\right] \quad (9)$$

则无机孔隙内流体质量流量可表示为:

$$q_{\mathrm{in}} = \frac{\pi\Delta p\rho_{\mathrm{b}}\,(R-\delta)^2}{8L}\left[\frac{4R\delta - 2\delta^2}{\mu_{\mathrm{w}}} + \frac{(R-\delta)^2}{\mu_{\mathrm{b}}} + 8C\right] + \frac{\pi\Delta p\rho_{\mathrm{w}}(2R\delta - \delta^2)}{8L}\left(\frac{2R\delta}{\mu_{\mathrm{w}}} - \frac{\delta^2}{\mu_{\mathrm{w}}} + 8C\right) \quad (10)$$

上式(8)—(10)中:q_{in} 为无机孔内质量流量,kg/s;Q_{b} 为体相体积流量,m³/s;Q_{w} 为近壁面体积流量,m³/s;ρ_{b} 为体相流体平均密度,kg/m³;ρ_{w} 为近壁面流体平均密度,kg/m³。

引入多孔介质内流体流动的修正系数 $\xi = \phi/\tau$[54],ϕ 为孔隙度,τ 为迂曲度。则多孔介质内质量流量为:

$$J_{\mathrm{in}} = J_{\mathrm{b}} + J_{\mathrm{w}} = \frac{\Delta p}{8L}\left\{\begin{array}{l} \xi_{\mathrm{b}}\rho_{\mathrm{b}}\left[\dfrac{4R\delta - 2\delta^2}{\mu_{\mathrm{w}}} + \dfrac{(R-\delta)^2}{\mu_{\mathrm{b}}} + 8C\right] + \\ \xi_{\mathrm{w}}\rho_{\mathrm{w}}\left(\dfrac{2R\delta - \delta^2}{\mu_{\mathrm{w}}} + 8C\right) \end{array}\right\} \quad (11)$$

式中:J_{in} 为无机孔内质量流量,kg/(m²·s);J_{b} 为体相质量流量,kg/(m²·s);J_{w} 为近壁面质量流量,kg/(m²·s);ξ_{b} 为体相流体运移修正系数;ξ_{w} 为近壁面流体运移修正系数。体相流体有效孔隙度 ϕ_{b} 和近壁面流体有效孔隙度 ϕ_{w} 为:

$$\begin{cases} \phi_{\mathrm{b}} = \phi\left(1 - \dfrac{\delta}{R}\right)^2 \\ \phi_{\mathrm{w}} = \phi\left[1 - \left(1 - \dfrac{\delta}{R}\right)^2\right] \end{cases} \quad (12)$$

1.2　干酪根有机孔隙内液烃运移机制

分子模拟结果表明,烃类与干酪根有机孔壁有较

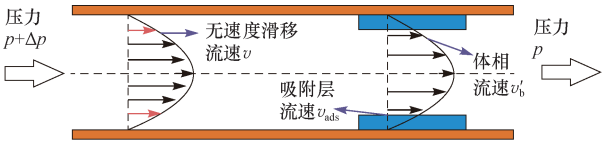

图3 干酪根有机孔内流体运移示意图

Fig. 3 A schematic diagram showing the fluid migration in organic pores of kerogen

强作用力,从而产生物理吸附。当孔径小于1.8 nm时,烃类分子几乎全部吸附在有机孔壁上[20]。受吸附层影响,在壁面处产生无滑移现象。体相与近壁面流体的速度分布如图3所示。

与无机孔隙内的质量流量推导过程相同,干酪根有机孔内体积流量表示为:

$$q_{or}=\frac{\pi\Delta p}{8L}\begin{Bmatrix}\rho_b(R-\delta')^2\left[\dfrac{4R\delta'-2\delta'^2}{\mu_{ads}}+\dfrac{(R-\delta')^2}{\mu_b}+8C_{or}\right]+\\ \rho_{ads}(2R\delta'-\delta'^2)\left(\dfrac{2R\delta'-\delta'^2}{\mu_{ads}}+8C_{or}\right)\end{Bmatrix} \tag{13}$$

式中:q_{or}为有机孔中质量流量,kg/s;δ'为吸附层厚度,m;μ_{ads}为吸附流体的平均粘度,mPa·s;ρ_{ads}为吸附流体平均密度,kg/m^3;C_{or}为有机孔内流体运移滑移系数,nm^2/(mPa·s)。

由于壁面处不考虑速度滑移,则C_{or}为0,干酪根有机多孔介质质量流量可表示为:

$$\begin{aligned}J_{or}&=J_b+J_{ads}\\&=\frac{\Delta p}{8L}\begin{Bmatrix}\dfrac{\xi_b'\rho_b}{\mu_b}\left[\dfrac{\mu_b}{\mu_{ads}}(4R\delta'-2\delta'^2)+(R-\delta')^2\right]+\\ \dfrac{\xi_{ads}'(2R\delta'-\delta'^2)\rho_{ads}}{\mu_{ads}}\end{Bmatrix}\end{aligned} \tag{14}$$

式中:J_{or}为干酪根有机孔内质量流量,kg/(m^2·s);J_{ads}为干酪根有机孔吸附层质量流量,kg/(m^2·s);ξ_b'和ξ_{ads}'分别为有机孔体相和吸附层的多孔介质修正系数。其中,体相和吸附层的有效孔隙度分别为:

$$\begin{cases}\phi_b'=\phi\left(1-\dfrac{\delta'}{R}\right)^2\\ \phi_{ads}'=\phi\left[1-\left(1-\dfrac{\delta'}{R}\right)^2\right]\end{cases} \tag{15}$$

1.3 页岩油藏表观渗透率模型的建立

假设孔壁流体无速度滑移,则流量为:

$$J_v=\rho_o\frac{\phi R^2\Delta p}{8\tau L\mu_o} \tag{16}$$

式中:J_v为质量流量,kg/(m^2·s);ρ_o为平均密度,kg/(m^2·s);μ_o为平均粘度,mPa·s。

不考虑流体粘度和密度随压力和温度变化,令ρ_b=0.9 kg/m^3,ρ_w=0.8 kg/m^3,ρ_o=0.9 kg/m^3,μ_b=1.5 mPa·s,μ_w=1.3 mPa·s,μ_o=1.5 mPa·s,ρ_{ads}=1.0 kg/m^3,μ_{ads}=1.7 mPa·s,δ'=0.98 mm,δ=0.1 nm;ϕ=0.05,τ=2,L=50 μm,Δp=5 MPa,C=1 200 nm^2/(mPa·s)。

根据分子模拟结果,近壁面处厚度约为0.1 nm,即假设速度滑移系数,可得无机和有机多孔介质内流体质量流量与孔隙半径关系曲线,如图4所示。由图4a看出,当R<10 nm时,体相质量流量J_b逐渐增大,近壁面的质量流量J_w减小但不能忽略;当10 nm<R<100 nm时,近壁面处质量流量相比体相质量流量可忽略不计;当R>200 nm时,体相质量流量和总质量流量基本相同,近壁面处的质量流量的影响可忽略不计。而由图4b看出,当R<2 nm时,体相流体与吸附层流体共同影响有机孔中的质量流量,孔径越小,体相质量流量越小,吸附层质量流量变化幅度较小,故吸附层的质量流量占总质量流量的比例较高;当R>10 nm时,吸附层内的质量流量远小于体相质量流量,可忽略不计,而体相质量流量与HP方程算得的流量基本相同。

假设页岩油藏表观渗透率为k_a,则多孔介质总质量流量可写为:

$$J_t=-\frac{\rho_o k_a}{\mu_o}\nabla p \tag{17}$$

将式(11)和式(14)线性相加后代入式(17),可得:

从式(18)看出,页岩油表观渗透率体现了有机孔含量、吸附层厚度、速度滑移长度、体相及近壁面原油密度和粘度、孔隙度、迂曲度及等效流动半径等参数的影响。

$$\begin{aligned}k_a=&\frac{\phi\mu_o(1-\beta)}{8\tau\rho_o R^2}\left\{\rho_b(R-\delta)^2\left[\frac{4R\delta-2\delta^2}{\mu_w}+\frac{(R-\delta)^2}{\mu_b}+8C\right]+\rho_w(2R\delta-\delta^2)\left(\frac{2R\delta-\delta^2}{\mu_w}+8C\right)\right\}+\\&\frac{\phi\mu_o\beta}{8\tau\rho_o R^2}\left\{\rho_b(R-\delta')^2\left[\frac{4R\delta'-2\delta'^2}{\mu_{ads}}+\frac{(R-\delta')^2}{\mu_b}\right]+\frac{\rho_{ads}}{\mu_{ads}}(2R\delta'-\delta'^2)^2\right\}\end{aligned} \tag{18}$$

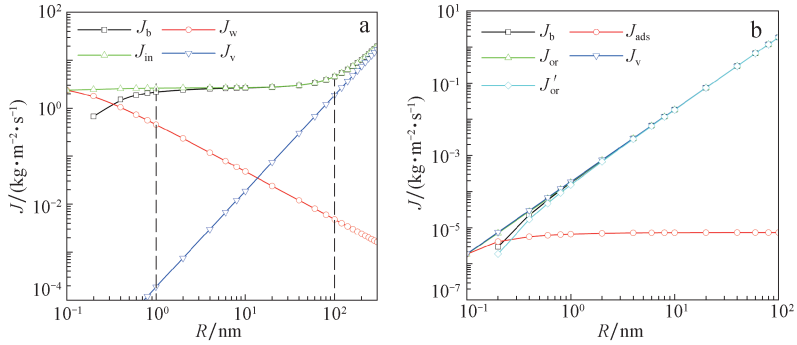

图 4　不同孔径下多孔介质质量流量随孔隙半径变化

Fig. 4　Variation of mass flux in multi-pore media with pore radius under different pore sizes

a. 无机多孔介质质量流量;b. 干酪根有机多孔介质质量流量

2　页岩油藏分段压裂水平井跨尺度耦合模型

单条裂缝由于在一定时间内的压力波及范围较小,日产油量衰减很快,难以起到增产的效果。因此,需进行多级压裂。压裂水平井技术可以在储层内产生复杂的裂缝网络,沟通页岩中的微裂缝,增大储层的动用面积以及导流能力。基质和微裂缝用双重介质模型描述,压裂缝网用离散裂缝模型显式处理。建立考虑微观运移基质的页岩油藏分段压裂水平井双孔双渗模型。

模型基本假设如下:①盒装封闭各向同性储层中心一口分段压裂水平井;②有限导流能力人工裂缝穿透整个储层,垂直于水平井筒且均匀对称分布;③基质和天然裂缝内均考虑原油微观运移机制,人工裂缝内流动服从达西定律。

2.1　基质 – 天然裂缝 – 人工裂缝耦合数学模型

人工裂缝的外边界 Γ_F 与天然裂缝系统压力处处相等,内边界 Γ_I 为定井底压力,则人工裂缝内的流动数学模型为:

$$\begin{cases} C_{oF}\phi_{oF}\rho_{oF}\dfrac{\partial p_{oF}}{\partial t} = \nabla\left(\rho_{oF}\dfrac{k_{oF}}{\mu_{oF}}\nabla p_{oF}\right) + \\ q_{oF}\delta(M - M') \\ p_{oF}\big|_{t=0} = p_{oini} \\ p_{of}\big|_{\Gamma_F} = p_{oF}\big|_{\Gamma_F} \\ p_{oF}\big|_{\Gamma_I} = p_{wf} \end{cases} \tag{19}$$

基质和微裂缝控制方程、初始条件和边界条件分别为:

$$\begin{cases} C_{om}\phi_{om}\rho_{om}\dfrac{\partial p_{om}}{\partial t} = \nabla\left(\rho_{om}\dfrac{k_{om,a}}{\mu_{om}}\nabla p_{om}\right) - q_o \\ C_{of}\phi_{of}\rho_{of}\dfrac{\partial p_{of}}{\partial t} = \nabla\left(\rho_{of}\dfrac{k_{of,a}}{\mu_{of}}\nabla p_{of}\right) + q_o - \\ q_{of}\delta(M - M') \end{cases} \tag{20}$$

$$\begin{cases} p_{om}\big|_{t=0} = p_{of}\big|_{t=0} = p_{oini} \\ p_{of}\big|_{\Gamma_F} = p_{oF}\big|_{\Gamma_F} \\ \left.\dfrac{\partial p_{om}}{\partial \mathbf{n}}\right|_{\Gamma_O} = \left.\dfrac{\partial p_{of}}{\partial \mathbf{n}}\right|_{\Gamma_O} = 0 \end{cases} \tag{21}$$

式中:C_{om}为基质原油综合压缩系数,MPa^{-1};ϕ_{om}为基质孔隙度,无因次;ρ_{om}为基质原油密度,kg/m^3;p_{om}为基质压力,MPa;$k_{om,a}$为基质表观渗透率,m^2;μ_{om}为基质原油平均粘度,mPa · s;q_o为基质 – 裂缝间的窜流量,$kg/(m^3 \cdot s)$;C_{of}为天然裂缝原油压缩系数,MPa^{-1};ϕ_{of}为天然裂缝孔隙度,无因次;ρ_{of}为天然裂缝原油密度,kg/m^3;p_{of}为天然裂缝系统压力,MPa;$k_{of,a}$为考虑速度滑移时天然裂缝表观渗透率,m^2;μ_{of}为天然裂缝原油平均粘度,mPa · s;q_{of}为裂缝系统源汇项,$kg/(m^3 \cdot s)$。C_{oF}为人工裂缝原油压缩系数,MPa^{-1};ϕ_{oF}为人工裂缝孔隙度,无因次;ρ_{oF}为人工裂缝原油密度,kg/m^3;p_{oF}为人工裂缝压力,MPa;k_{oF}为人工裂缝渗透率,m^2;μ_{oF}为人工裂缝原油平均粘度,mPa · s;q_{oF}为裂缝系统源汇项,$kg/(m^3 \cdot s)$。

2.2　模型求解

式(19)—式(21)构成考虑微观运移的页岩油藏分段压裂水平井双孔双渗数值流动模型。则基质和天然裂缝、人工裂缝 Gauss 部分积分后单元特性矩阵如式(22)所示:

$$\begin{cases}
\iiint_{\Omega_e} C_{om}\phi_{om}\rho_{om}\,\mathbf{N}_{e,m}^T\mathbf{N}_{e,m}\mathrm{d}\Omega_e\,\dfrac{\mathbf{P}_{ome}^{n+1}-\mathbf{P}_{ome}^{n}}{t^{n+1}-t^{n}} \\
\quad=-\iiint_{\Omega_e}\nabla\mathbf{N}_{e,m}^T\dfrac{\rho_{om}k_{om,a}\mathbf{N}_{e,m}\mathbf{P}_{ome}^{n}}{\mu_{om}}\nabla\mathbf{N}_{e,m}\mathrm{d}\Omega_e\,\mathbf{P}_{ome}^{n+1}- \\
\quad\iiint_{\Omega_e}\mathbf{N}_{e,m}^T\dfrac{\sigma_m\rho_{om}k_{om,a}\mathbf{N}_{e,m}\mathbf{P}_{ome}^{n}}{\mu_{om}}\mathbf{N}_{e,m}\mathrm{d}\Omega_e \\
\quad(\mathbf{P}_{ome}^{n+1}-\mathbf{P}_{ofe}^{n+1}) \\
\iiint_{\Omega_e} C_{of}\phi_{of}\rho_{of}\,\mathbf{N}_{e,f}^T\mathbf{N}_{e,f}\mathrm{d}\Omega_e\,\dfrac{\mathbf{P}_{ofe}^{n+1}-\mathbf{P}_{ofe}^{n}}{t^{n+1}-t^{n}} \\
\quad=-\iiint_{\Omega_e}\nabla\mathbf{N}_{e,f}^T\dfrac{\rho_{of}k_{of,a}\mathbf{N}_{e,f}\mathbf{P}_{ofe}^{n}}{\mu_{of}}\nabla\mathbf{N}_{e,f}\mathrm{d}\Omega_e\,\mathbf{P}_{ofe}^{n+1}+ \\
\quad\iiint_{\Omega_e}\mathbf{N}_{e,f}^T\dfrac{\sigma_m\rho_{of}k_{om,a}\mathbf{N}_{e,f}\mathbf{P}_{ofe}^{n}}{\mu_{om}}\mathbf{N}_{e,f}\mathrm{d}\Omega_e\cdot \\
\quad(\mathbf{P}_{ome}^{n+1}-\mathbf{P}_{ofe}^{n+1})+\iiint_{\Omega_e}\mathbf{N}_{e,f}^T q_{of}^{n+1}\delta(M-M')\mathrm{d}\Omega_e\cdot \\
a_f\iint_{\Omega_{e,F}} C_{oF}\phi_{oF}\rho_{oF}\,\mathbf{N}_{e,F}^T\mathbf{N}_{e,F}\mathrm{d}\Omega_{e,F}\,\dfrac{\mathbf{P}_{oFe}^{n+1}-\mathbf{P}_{oFe}^{n}}{t^{n+1}-t^{n}} \\
\quad=-a_f\iint_{\Omega_{e,F}}\nabla\mathbf{N}_{e,F}^T\dfrac{k_{oF}\rho_{oF}\mathbf{N}_{e,F}\mathbf{P}_{oFe}^{n}}{\mu_{OF}}\nabla\mathbf{N}_{e,F}\mathrm{d}\Omega_{e,F}\mathbf{P}_{oFe}^{n+1}+ \\
\quad a_f\iint_{\Omega_{e,F}}\mathbf{N}_{e,F}^T q_{oF}^{n+1}\delta(M-M')\mathrm{d}\Omega_{e,F}
\end{cases} \tag{22}$$

假设人工裂缝仅与天然裂缝沟通，流体从页岩基质流入天然裂缝，然后从天然裂缝流入人工裂缝，并从天然裂缝与人工裂缝流入井筒。若页岩油藏节点数为 N_p 个，基质和天然裂缝系统压力可表示为：

$$\begin{cases}
\mathbf{P}_{ome}=[p_{ome1},\quad p_{ome2},\quad \cdots,\quad p_{omeN_p}]^T \\
\mathbf{P}_{ofe}=[p_{ofe1},\quad p_{ofe2},\quad \cdots,\quad p_{ofeN_p}]^T
\end{cases} \tag{23}$$

基质和天然裂缝系统均利用四面体单元描述，人工裂缝从三维简化到具有一定开度的二维面单元，利用二维三角形单元描述，并用有限元方法进行模型求解，人工裂缝和基质、天然裂缝形成连续的介质系统，则基质、天然裂缝和人工裂缝系统单元总平衡方程组的时间域离散形式可表示为：

$$\begin{cases}
\left(\mathbf{A}_m+\dfrac{\mathbf{B}_m}{t^{n+1}-t^{n}}+\mathbf{C}\right)\mathbf{P}_{ome}^{n+1} \\
\quad=\dfrac{\mathbf{B}_m}{t^{n+1}-t^{n}}\mathbf{P}_{ome}^{n}+\mathbf{C}\mathbf{P}_{ofe}^{n} \\
\left(\mathbf{A}_f+\dfrac{\mathbf{B}_f}{t^{n+1}-t^{n}}+\mathbf{C}\right)\mathbf{P}_{ofe}^{n+1} \\
\quad=\mathbf{Q}^{n+1}+\dfrac{\mathbf{B}_f}{t^{n+1}-t^{n}}\mathbf{P}_{ofe}^{n}+\mathbf{C}\mathbf{P}_{ome}^{n}
\end{cases} \tag{24}$$

式中：$\mathbf{A}_m=\iiint_{\Omega_e}\nabla\mathbf{N}_{e,m}^T\dfrac{\rho_{of}k_{om,a}\mathbf{N}_{e,m}\mathbf{P}_{ome}^{n}}{\mu_{om}}\nabla\mathbf{N}_{e,m}\mathrm{d}\Omega_e$；

$\mathbf{B}_m=\iiint_{\Omega_e}C_{om}\phi_{om}\rho_{of}\mathbf{N}_{e,m}^T\mathbf{N}_{e,m}\mathrm{d}\Omega_e$；

$\mathbf{C}=\iiint_{\Omega_e}\dfrac{\rho_{of}\sigma_m k_{om,a}\mathbf{N}_{e,m}\mathbf{P}_{ome}^{n}}{\mu_{om}}\mathbf{N}_{e,m}^T\mathbf{N}_{e,m}\mathrm{d}\Omega_e$

$\mathbf{N}_{e,F}=[N_1\quad N_2\quad N_3]^T$；

$\mathbf{N}_{e,m}=\mathbf{N}_{e,f}=[N_1\quad N_2\quad N_3\quad N_4]^T$；

$\mathbf{A}_f=\iiint_{\Omega_e}\nabla\mathbf{N}_{e,f}^T\dfrac{\rho_{of}k_{of,a}\mathbf{N}_{e,f}\mathbf{P}_{ofe}^{n}}{\mu_{of}}\nabla\mathbf{N}_{e,f}\mathrm{d}\Omega_e+$

$a_f\iint_{\Omega_{e,F}}\nabla\mathbf{N}_{e,F}^T\dfrac{\rho_{oF}k_{oF}\mathbf{N}_{e,F}\mathbf{P}_{oFe}^{n}}{\mu_{oF}}\nabla\mathbf{N}_{e,F}\mathrm{d}\Omega_{e,F}$；

$\mathbf{B}_f=\iiint_{\Omega_e}C_{of}\phi_{of}\rho_{of}\mathbf{N}_{e,f}^T\mathbf{N}_{e,f}\mathrm{d}\Omega_e+$

$a_f\iint_{\Omega_{e,F}}C_{oF}\phi_{oF}\rho_{oF}\mathbf{N}_{e,F}^T\mathbf{N}_{e,F}\mathrm{d}\Omega_{e,F}$；

$\mathbf{Q}^{n+1}=\iiint_{\Omega_e}\mathbf{N}_{e,f}^T q_{of}^{n+1}\delta(M-M')\mathrm{d}\Omega_e+$

$a_f\iint_{\Omega_{e,F}}\mathbf{N}_{e,F}^T q_{oF}^{n+1}\delta(M-M')\mathrm{d}\Omega_{e,F}$；

$\mathbf{P}_{oFe}=[p_{oF1}\quad p_{oF2}\quad p_{oF3}]^T$；

$\mathbf{P}_{ome}=[p_{om1}\quad p_{om2}\quad p_{om3}\quad p_{om4}]^T$；

$\mathbf{P}_{ofe}=[p_{of1}\quad p_{of2}\quad p_{of3}\quad p_{of4}]^T$；

$$\nabla\mathbf{N}_{e,m}=\nabla\mathbf{N}_{e,f}=\begin{bmatrix}\dfrac{\partial N_1}{\partial x}&\dfrac{\partial N_2}{\partial x}&\dfrac{\partial N_3}{\partial x}&\dfrac{\partial N_4}{\partial x}\\ \dfrac{\partial N_1}{\partial y}&\dfrac{\partial N_2}{\partial y}&\dfrac{\partial N_3}{\partial y}&\dfrac{\partial N_4}{\partial y}\\ \dfrac{\partial N_1}{\partial z}&\dfrac{\partial N_2}{\partial z}&\dfrac{\partial N_3}{\partial z}&\dfrac{\partial N_4}{\partial z}\end{bmatrix};$$

$$\nabla\mathbf{N}_{e,F}=\begin{bmatrix}\dfrac{\partial N_1}{\partial x}&\dfrac{\partial N_2}{\partial x}&\dfrac{\partial N_3}{\partial x}\\ \dfrac{\partial N_1}{\partial y}&\dfrac{\partial N_2}{\partial y}&\dfrac{\partial N_3}{\partial y}\\ \dfrac{\partial N_1}{\partial z}&\dfrac{\partial N_2}{\partial z}&\dfrac{\partial N_3}{\partial z}\end{bmatrix}。$$

利用式(24)隐式向后差分，可以得到各时刻基质和天然裂缝系统的压力值。

3 产能影响因素分析

基于上述模型，研究分段压裂水平井生产动态和产能影响因素。模型网格剖分和模拟参数分别如图 5 和表 1 所示，基质表观渗透率计算参数如 1.3 节，研究人工裂缝条数、天然裂缝间距、缝网间距等因素对储层产油量影响。

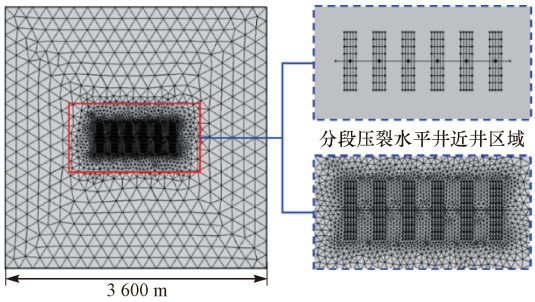

图 5　模拟区域网格划分

Fig. 5　Meshing of the simulated region

3.1　基质有机孔隙含量和人工裂缝条数影响

图 6a 表示了基质有机孔隙含量对页岩油藏分段压裂水平井日产油量和累积产油量的影响。可见,有机孔隙含量影响分段压裂水平井初期日产油量,但不明显。有机孔隙含量越高,则分段压裂水平井日产油量和累积产油量越低,这是由于有机孔隙含量越高,原油物理吸附量越大,导致分段压裂水平井产油量越低,原油越难被采出;无机孔隙含量越高,分段压裂水平井产油量越高,说明无机孔隙在页岩油藏开发中占主要地位。

表 1　页岩油藏压裂水平井模型参数

Table 1　Model parameters of fractured horizontal wells in the shale oil reservoir

基本参数	参数值	基本参数	参数值
油藏面积/m^2	3 600	天然裂缝孔隙度	1×10^{-3}
油藏厚度/m	1	天然裂缝开度/m	5×10^{-6}
初始压力/MPa	10	天然裂缝间距/m	0.05
储层温度/℃	50	布缝方式	均匀等长
井底压力/MPa	1	人工裂缝段数	6
井筒长度/m	1 200	人工裂缝半长/m	200
迂曲度	2	人工裂缝间距/m	200
孔隙半径/nm	1	人工裂缝开度/m	5×10^{-4}
井筒半径/m	0.05	人工裂缝孔隙度	0.38
流体粘度/mPa·s	1.1	缝网带宽/m	80
原油体积系数	1.2	储层改造区域面积/(m·m)	2 000×1 000
有机孔含量	0.5	储层改造区域厚度/m	10
基质孔隙度	0.05	未改造区域裂缝孔隙度	1×10^{-4}
基质压缩系数/MPa^{-1}	3.5×10^{-4}	未改造区域微裂缝间距/m	0.1
微裂缝压缩系数/MPa^{-1}	3.5×10^{-3}		

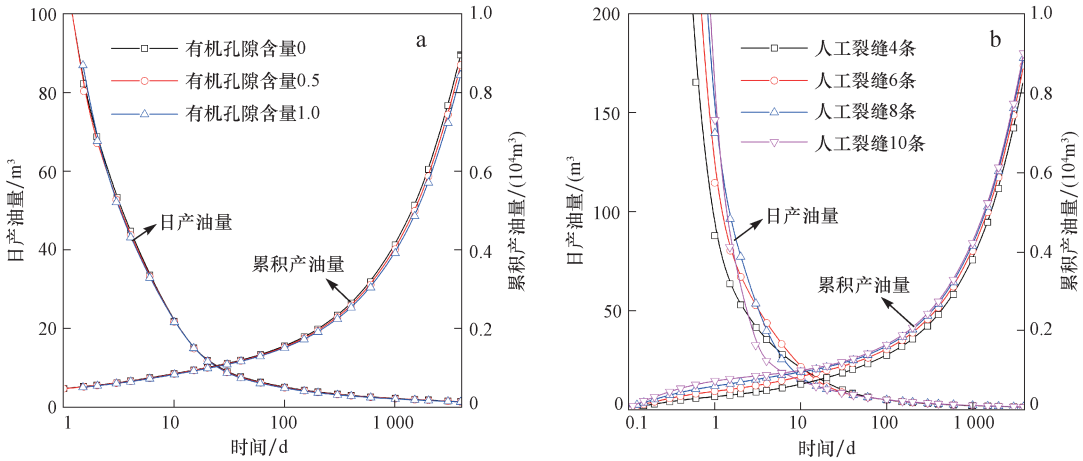

图 6　基质有机孔含量及天然裂缝间距对产油量影响

Fig. 6　Impacts of orgainc pore content in matrix and spacing among natrural fractures on oil production

a. 基质有机孔隙含量影响;b. 人工裂缝条数影响

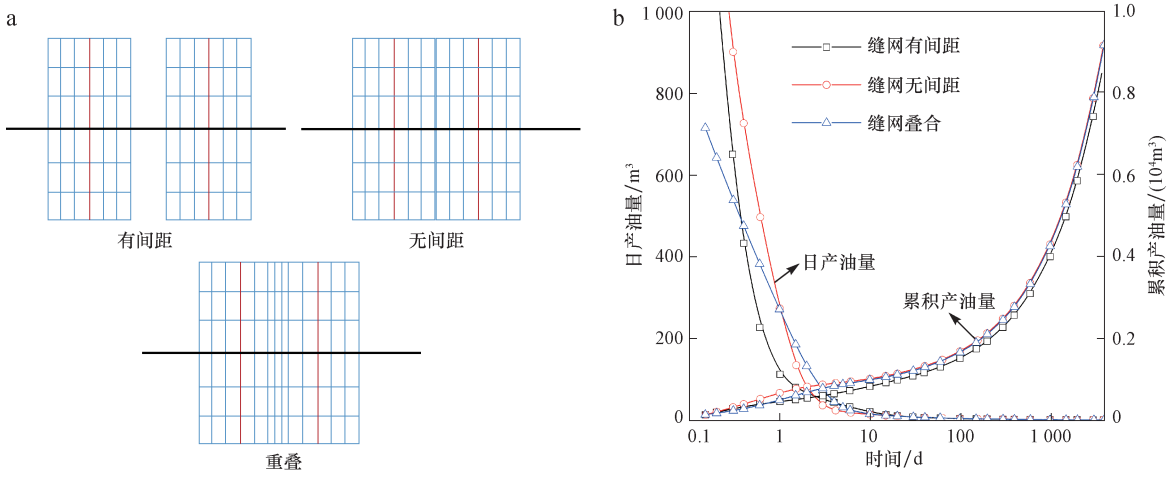

图 7 不同缝网间距示意图及对产油量的影响

Fig. 7 A schematic map showing different spacings of fracture network, and their influences on oil production

a. 不同缝网间距改造模式示意图;b. 不同缝网间距改造模式产油量变化

改变人工裂缝条数从 4 条增至 10 条,日产油量和累产油量如图 6b 所示。人工裂缝条数主要影响分段压裂水平井初期的日产油量。人工裂缝为 4 条时,第一天的日产量为 85 m^3/d,而 8 条人工裂缝的第一天日产量超过 200 m^3/d。到 100 d 时,不同人工裂缝条数的日产量基本相同,说明压力波已经波及到整个油藏,产量不再受裂缝条数的影响。同时可发现,8 条和 10 条人工裂缝对应的日产量曲线基本重合,考虑到经济效益,8 条人工裂缝为最佳的压裂方案。

3.2 缝网间距

假设人工裂缝网络裂缝条数不变,改变带宽来模拟 3 种改造模式(图 7a)。不同的缝网间距对应不同的改造模式,也就有不同的改造体积(SRV)。缝网间距对产油量的影响如图 7b 所示。缝网有间距时,缝网间的区域内没有人工裂缝,流动的快慢只取决于微裂缝导流能力;缝网无间距或缝网重合时,人工裂缝间存在重叠,整体形成一个大的缝网结构,区域内的裂缝连通性好。从产油曲线上可以发现,当缝网无间距或缝网有重叠时,早期的日产量都高于缝网有间距的情形,说明缝网与缝网的相互重叠可增加裂缝的导流能力,提高产油量。

4 结论

在前期 MDS、实验和理论研究基础上,建立了富有机页岩油藏表观渗透率模型,对纳米尺度孔隙内原油运移机制进行表征。模型考虑了润湿性、速度滑移、物理吸附、孔隙结构参数和有机孔含量。有机孔隙考虑了物理吸附,无机孔隙考虑了速度滑移和近壁流动。孔隙半径 < 10 nm 时,表观渗透率比固有渗透率大得多,而孔隙半径 > 100 nm 时,吸附和速度滑动对原油运移影响基本可忽略。同时,将建立的页岩油表观渗透率模型引入到页岩油藏分段压裂水平井宏观流动模型,形成页岩油藏基质 - 天然裂缝 - 人工裂缝多重孔隙介质耦合数学模型,分析了产能影响因素,有机孔隙含量越小,人工裂缝条数越大,则分段压裂水平井产能越大,同时压裂缝网模式为缝网无间距且不叠合时最优。

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