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# 页岩气藏体积压裂有效改造体积计算方法

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**摘要:** 页岩气藏矿场压裂实践表明, 储层有效改造体积(effective stimulated reservoir volume, 简称 ESRV)是影响页岩气藏体积压裂水平井生产效果的关键因素, ESRV 的准确计算对页岩气藏压裂方案评价与体积压裂水平井产量预测具有重要作用。基于页岩储层改造体积(stimulated reservoir volume, 简称 SRV)多尺度介质气体运移机制, 建立了 SRV 区域正交离散裂缝耦合双重介质基质团块来表征单元体渗流模型(representation elementary volume, 简称 REV), 并结合北美页岩储层实例研究了次生裂缝间距、宽度等缝网参数对页岩气藏气体运移规律的影响。在此基础上根据 SRV 区域次生裂缝分布特征, 采用分形质量维数定量表征裂缝间距分布规律, 结合页岩气藏次生裂缝间距对基质团块内流体动用程度的影响规律, 得到了页岩气藏体积压裂 ESRV 计算方法。结果表明 SRV 区域次生裂缝间距对基质团块内吸附及自由气影响较大, 次生裂缝间距小于 0.20 m 时可以实现 SRV 区域基质团块内流体向各方向裂缝的“最短距离”渗流。选取北美典型页岩储层生产井体积压裂数据进行 ESRV 计算, 页岩气藏目标井 ESRV 占体积压裂 SRV 的 37.78%。因此 ESRV 受改造区域次生裂缝分布规律及 SRV 有效裂缝间距界限的影响, 是储层固有性质及人工压裂因素综合作用的结果。

**关键词:** 页岩气藏; 体积压裂; 有效改造体积; 裂缝间距; 石油地质。

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## A New Approach to Calculate Effective Stimulated Reservoir Volume in Shale Gas Reservoir

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**Abstract:** Hydraulic fracturing practices in shale reservoirs show that effective stimulated reservoir volume (ESRV) significantly affects the production of hydraulic fractured well. Therefore, estimating ESRV is an important prerequisite for the evaluation and production prediction of hydraulic fracturing wells in shale reservoirs. This paper introduces a representation elementary volume (REV) of orthogonal discrete fracture coupled dual-porosity matrixflow model to predict the volumetric flux of gas in shale reservoirs. The influence of fracture space and fracture width on gas migration was studied. Considering fractal characteristics of the fracture network in stimulated reservoir volume (SRV), fractal dimension was used to quantitatively evaluate the fracture space distribution. Combining the effective fracture space and fractal characteristic of fracture network, a new approach was proposed to evaluate the ESRV in shale reservoirs. The approach was used in Eagle Ford shale gas reservoir and the results show that the fracture space has a great influence on migration of adsorbed gas. Fracture network has a contribution to enhance absorbed and free gas recovery ratio when the fracture space is less than 0.20 m. The ESRV was evaluated in this paper and the results indicate that

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the ESRV accounts for 37.78% of the total SRV in shale gas reservoir. The ESRV was influenced by both secondary fracture distribution and effective fracture space, as a result of reservoir intrinsic property and hydraulic fracturing practices.

**Key words:** shale gas reservoir; volume fracturing; effective stimulated reservoir volume; fracture space; petroleum geology.

## 0 引言

页岩气藏发育微纳米级孔隙介质,天然裂缝闭合,渗透率极低(nD 级别),气体运移速度较慢,很难获得经济产量(Kang *et al.*, 2011; Shabro *et al.*, 2011; Islam and Patzek, 2014; Yuan and Wood, 2015; Sheng *et al.*, 2015; 吴松涛等, 2015)。近年来,水平井体积压裂技术的大规模应用提高了页岩储层流体渗流速度,实现了页岩气藏的经济开发(吴奇等, 2012; 杜保健等, 2014; 樊建明等, 2015; Yuan and Wood, 2015),为我国非常规油气资源开发提供了技术保障(吴奇等, 2012; 刘晓旭等, 2013; 苏玉亮等, 2014)。页岩储层体积压裂在形成压裂主裂缝的同时,压裂液沿压裂裂缝壁面纵向延伸并沟通天然裂缝,使得天然裂缝开启交错,最终在压裂裂缝周围形成复杂裂缝网络,称为储层改造体积(stimulated reservoir volume, 简称 SRV)(Mayerhofer *et al.*, 2010; 王文东等, 2013; 杜保健等, 2014; Guo *et al.*, 2014)。SRV 区域基质团块内流体向各方向次生裂缝“最短距离”渗流(吴奇等, 2012; 苏玉亮等, 2014),改造区域成为体积压裂生产井 20 a 估算采出程度的主要生产潜力区(Anderson *et al.*, 2010; Stalgorova and Mattar, 2012; Fan, 2015)。实际生产数据表明,非常规储层体积压裂生产井实际产量与根据 SRV 体积计算得到的产量相差较大,SRV 区域存在有效和无效渗流区域(Anderson *et al.*, 2010; Stalgorova and Mattar, 2012),因此深入研究有效改造体积(effective SRV, 简称 ESRV)对页岩储层体积压裂方案优化设计及生产动态预测更具有实际意义。

非常规 SRV 常采用微地震检测、裂缝扩展模型等方法来计算,前人认为裂缝波及到的区域即为改造体积(Maxwell *et al.*, 2002; Denney, 2005; Ren *et al.*, 2016)。对于微纳米尺度孔喉发育的页岩储层,改造区域基质团块内流体很难动用,裂缝间距较大时,基质团块内流体动用程度很小,增产效果可以忽略不计(Bustin *et al.*, 2008; King, 2010)。近两年来国内学者们对体积压裂有效改造体积影响因素开始逐步研究。段瑶瑶等(2015)采用 Eclipse 数值模拟软件,以苏里格致密气藏为例对体积改造生产效

果进行研究,结果表明基质渗透率和裂缝网络间距对体积改造的有效性起关键作用;崔明月等(2014)研究提出采用包含次生裂缝密度以及次生裂缝体积的多因素耦合参数来表征储层改造程度。体积压裂可实现 SRV 缝网区域基质团块内流体向各方向裂缝的“最短距离”渗流,页岩气藏基质发育微纳米级孔喉,基质中包含干酪根有机质及无机基岩,气体运移机制复杂且运移距离短,因此需要研究页岩气藏基质团块内“最短距离”对流体渗流的影响,即体积压裂 SRV 区域基质团块内流体充分运移的有效裂缝间距界限。

页岩储层层理发育、储层非均质强、天然裂缝的不规则分布以及原始地应力场等因素导致 SRV 区域次生裂缝分布规律复杂(Olson, 2008; Olson and Taleghani, 2009; 康永尚等, 2016)。学者们采用 wiremesh(Xu *et al.*, 2009, 2010; Meyer and Bazan, 2011)、UFM(Weng *et al.*, 2011; Weng, 2015)等模型对 SRV 裂缝分布规律进行了大量研究,但是上述方法均是基于一定理想性的假设,没有考虑到实际储层特征。学者们通过研究次生裂缝分布规律发现,采用分形理论可以准确描述 SRV 区域次生裂缝分布规律(Xu *et al.*, 2008, 2016; Cai and Yu, 2010, 2011; Yang *et al.*, 2014; Wang *et al.*, 2015)。Zhou *et al.*(2016)基于微地震解释数据,采用 L-system 方法反演得到了 SRV 次生裂缝二维分布形态;Fan and Ettehadtavakkol(2017)采用分形质量维数定量表征了体积压裂水平井 SRV 区域次生裂缝密度分布规律,并通过 Barnett 页岩储层渗透率、孔隙度等实际分布特征验证了次生裂缝的分形分布特征。

本文基于页岩气藏体积压裂 SRV 区域多尺度介质(干酪根有机质、无机基岩、次生裂缝)分布特征及气体渗流特性,建立了正交离散裂缝耦合双重介质基质团块表征单元体(representation elementary volume, 简称 REV)渗流模型,分析了裂缝间距对基质团块流体动用程度的影响,得到了页岩气藏体积压裂 SRV 区域基质团块内流体充分运移的有效裂缝间距界限,在此基础上结合次生裂缝分形分布特征,提出了页岩气藏体积压裂有效改造体积的计算方法。

# 1 页岩气藏体积压裂 SRV 有效裂缝间距界限研究

## 1.1 REV 渗流模型

**1.1.1 REV 物理模型** 基于页岩气藏储层特征及体积压裂水平井储层改造特征(图 1a),截取改造区域微小单元体,建立正交离散裂缝耦合双重介质基质团块 REV 渗流物理模型,如图 1b 所示:实际储层改造区域缝网分布较为复杂,将其典型化为垂直交叉的裂缝网络.缝网将改造区域储层分割成正方体的基质团块,基质团块物性与页岩气藏初始性质相同,即基质团块中发育微纳米尺度的干酪根有机质和无机基岩(Sheng *et al.*, 2015; Yuan *et al.*, 2015)(图 1c).无机基岩中主要分布游离相气体分子,无机基岩内部发育微纳米级孔喉,气体在其中的运移主要包括努森扩散和粘性流;干酪根有机质内部发育纳米级有机粒内孔隙,页岩气主要以吸附相和游离相的方式储集在有机质中(Javadpour, 2009; Swami *et al.*, 2013)(图 1d),气体在有机质中运移形态主要包括有机质骨架表面的扩散、纳米级有机粒孔隙内部的努森扩散和粘性流(Javadpour *et al.*, 2007; Javadpour, 2009; Civan, 2010; Akkutlu and Fathi, 2012; 陈晓明等, 2012).生产过程中在缝网压力与基质团块内压力的相互作用下,干酪根中储集的气体将

会通过干酪根内部运移、干酪根—无机基岩跨尺度传质、无机基岩内部运移、无机基岩—缝网跨尺度传质、缝网内部运移的路径流动至井底(Sheng *et al.*, 2015; Yuan *et al.*, 2015; Yan *et al.*, 2016),不考虑地应力等因素变化对流体运移的影响.

**1.1.2 REV 数学模型建立** 假设表征单元体  $x$  方向存在压力梯度  $dp$ ,缝网内气体在压力梯度作用下由左向右流动, $y, z$  方向上无压力梯度,气体在这两个方向上无流动.根据以上假设,建立 REV 数学模型:考虑气体在有机质骨架表面的表面扩散、纳米级有机粒孔隙内部努森扩散和滑脱粘性流(Javadpour *et al.*, 2007; Javadpour, 2009; Civan, 2010; Akkutlu and Fathi, 2012; 陈晓明等, 2012; Sheng *et al.*, 2015)以及双重介质基质团块中气体从干酪根向无机基质中的拟稳态窜流,可得干酪根中气体运移控制方程:

$$\frac{\partial \left( \varphi_k \frac{p_k}{ZRT} \right)}{\partial t} + \frac{\partial (\epsilon_{ks} (1 - \varphi_k) c_{\mu})}{\partial t} = \nabla \cdot \left( \begin{aligned} & \frac{p_k}{ZRT} \left( 1 + \sqrt{\frac{8\pi RT}{M}} \frac{\mu_g}{p_k r_k} \left( \frac{2}{f} - 1 \right) \right) \frac{\varphi_k r_k^2}{\tau_k} \frac{1}{8} \nabla p_k \\ & + \frac{\varphi_k}{\tau_k} \frac{2r_k}{3} \sqrt{\frac{8ZRT}{\pi M}} \frac{p_k}{ZRT} C_g \nabla p_k \\ & + \epsilon_{ks} (1 - \varphi_k) D_s \frac{c_{\mu s} p_k}{(p_L + p_k)^2} \nabla p_k \end{aligned} \right) - N_{km}, \quad (1)$$

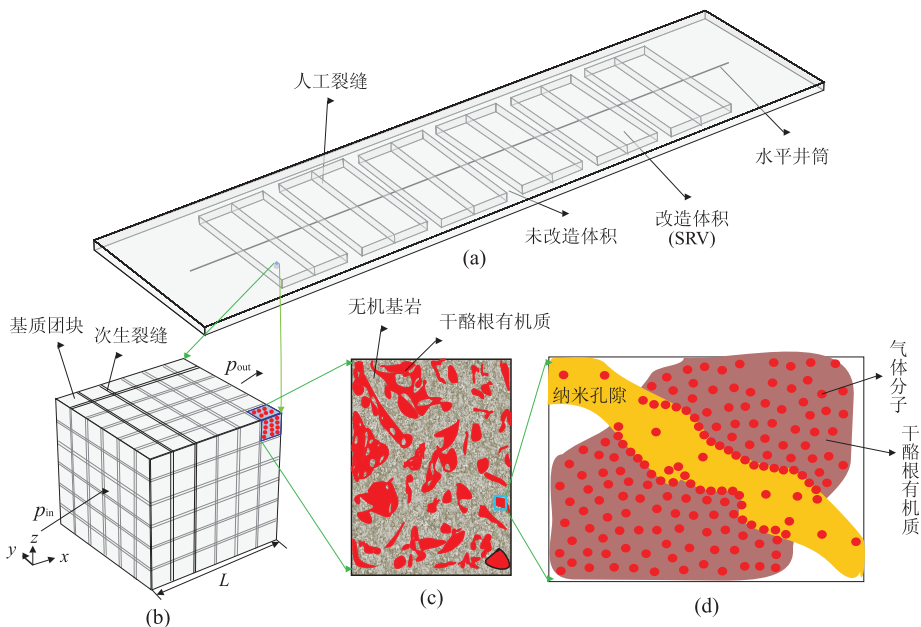


图 1 页岩储层 SRV 区域表征单元体渗流模型

Fig.1 Representative elementary volume flow model of SRV region in shale reservoirs

图 d 据 Javadpour(2009)

其中,  $\varphi_k$  为干酪根孔隙度;  $p_k$  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,  $8.314 \times 10^{-6}$  MJ/(K · mol);  $T$  为地层温度, K;  $\epsilon_{ks}$  为单位岩心体积中干酪根固体的体积;  $c_\mu$  为单位干酪根固体体积中吸附气的量, mol/m<sup>3</sup>;  $M$  为页岩气分子质量, kg/mol;  $\mu_g$  为气体粘度, mPa · s;  $r_k$  为干酪根中孔隙直径, m;  $\tau_k$  为干酪根中孔隙迂曲修正系数;  $C_g$  为气体压缩系数, MPa<sup>-1</sup>;  $D_s$  为干酪根表面吸附气扩散系数, m<sup>2</sup>/s;  $c_{\mu s}$  为干酪根表面朗格缪尔最大吸附浓度, mol/m<sup>3</sup>;  $p_L$  为朗格缪尔压力, MPa;  $N_{km}$  为单位体积干酪根有机质与无机基岩之间窜流量, mol/(m<sup>3</sup> · s);  $f$  为角动量调节系数, 与页岩气在流管管壁上扩散反射有关, 变化范围为 0~1.

不考虑气体从干酪根向裂缝的流动, 则干酪根介质边界条件:

$$\nabla p_k |_{\zeta} = 0, \quad (2)$$

其中,  $\zeta$  为基质团块边界.

假设基质团块中干酪根向无机基岩发生拟稳态窜流, 则干酪根-无机基岩跨尺度传质控制方程为 (Sheng *et al.*, 2015):

$$N_{km} = \sigma_k \frac{p_k}{ZRT\mu_g} \cdot \left( \begin{aligned} & \epsilon_{ks} (1 - \varphi_k) D_s \frac{c_{\mu s} ZRT}{(p_L + p_k)} \bar{\mu}_g \\ & + \frac{\varphi_k}{\tau_k} \frac{2r_k}{3} \sqrt{\frac{8ZRT}{\pi M}} C_g \mu_g + \left( 1 + \sqrt{\frac{8\pi RT}{M}} \frac{\mu_g}{p_k r_k} \left( \frac{2}{f} - 1 \right) \right) \end{aligned} \right) \cdot (p_k - p_m), \quad (3)$$

其中,  $\sigma_k$  为干酪根单元体形状因子, m<sup>-2</sup>;  $p_m$  为无机基岩孔隙压力, MPa.

考虑气体在无机基岩微纳级孔喉中发生努森扩散和滑脱粘性流 (Javadpour *et al.*, 2007; Javadpour, 2009; Akkutlu and Fathi, 2012; Sheng *et al.*, 2015) 以及干酪根中气体流入, 则无机基岩中气体运移控制方程:

$$\frac{\partial(\varphi_m \frac{p_m}{ZRT})}{\partial t} = \nabla \cdot \left( \begin{aligned} & \frac{\varphi_m}{\tau_m} \frac{2r_m}{3} \sqrt{\frac{8ZRT}{\pi M}} \frac{p_m}{ZRT} C_g \nabla p_m \\ & + \frac{p_m}{ZRT} \left( 1 + \sqrt{\frac{8\pi RT}{M}} \frac{\mu_g}{p_m r_m} \left( \frac{2}{f} - 1 \right) \right) \frac{\varphi_m}{\tau_m} \frac{r_m^2}{8} \nabla p_m \end{aligned} \right) + N_{km}, \quad (4)$$

其中,  $\varphi_m$  为无机基岩孔隙度;  $p_m$  为无机基岩内孔隙压力, MPa;  $\tau_m$  为无机基岩中孔隙迂曲修正系数;  $r_m$  为无机基岩中孔隙直径, m.

根据物理模型假设, 无机基岩外边界条件为:

$$\begin{cases} p_m |_{x=0} = p_{in}; \\ p_m |_{x=L} = p_{in} - L \times dp; \\ \left. \frac{\partial p_m}{\partial y} \right|_{y=0} = \left. \frac{\partial p_m}{\partial y} \right|_{y=L} = 0; \\ \left. \frac{\partial p_m}{\partial z} \right|_{z=0} = \left. \frac{\partial p_m}{\partial z} \right|_{z=L} = 0; \end{cases} \quad (5)$$

其中,  $p_{in}$  为 REV 入口压力, MPa;  $L$  为 REV 边长, m;  $dp$  为 REV 内压力梯度, MPa/m.

气体在裂缝中主要存在粘性流, 其运移控制方程:

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

其中,  $\varphi_f$  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.

根据物理模型假设, 缝网外边界条件为:

$$\begin{cases} p_f |_{x=0} = p_{in}; \\ p_f |_{x=L} = p_{in} - L \times dp; \\ \left. \frac{\partial p_f}{\partial y} \right|_{y=0} = \left. \frac{\partial p_f}{\partial y} \right|_{y=L} = 0; \\ \left. \frac{\partial p_f}{\partial z} \right|_{z=0} = \left. \frac{\partial p_f}{\partial z} \right|_{z=L} = 0; \end{cases} \quad (7)$$

缝网内边界条件:

$$p_f |_{\zeta} = p_m |_{\zeta}, \quad (8)$$

模型初始条件:

$$p_f = p_m = p_k = p_{ini}, \quad (9)$$

其中,  $p_{ini}$  为储层原始压力, MPa.

**1.1.3 模型求解** 采用有限元数值方法对 REV 数学模型进行求解. 首先选取四面体单元对 REV 物理模型进行离散, 基于 Euler 时间差分格式, 分别建立基质团块、板状缝网特性矩阵, 对模型进行求解, 可以得到 REV 内不同赋存状态气体产量变化规律. 本文以北美 Barnett 典型页岩气藏储层为研究对象, 参考相关文献中的公开储层参数 (段永刚等, 2015; Sheng *et al.*, 2015; Javadpour *et al.*, 2007), 归纳总结得到本文模型计算数据, 如表 1 所示.

北美页岩储层统计资料表明, 页岩储层 SRV 缝网区域裂缝间距 (天然裂缝或次生裂缝) 通常大于 5 cm, 且很少达到米尺度以上 (Bustinet *et al.*, 2008; King, 2010). 笔者分别计算了裂缝间距为 0.03、0.05、0.07、0.10、0.15、0.20、0.50 和 1.00 m 时气体产出情况 (图 2a). 定义产出比例为累积产出气量与气体总储量的比值, 如图 2a 所示, 气体产出比

表 1 Barnett 页岩气藏储层参数

Table 1 Reservoir parameters of Barnett shale gas reservoir

参数	数值	参数	数值
次生裂缝宽度(m)	0.001	REV 入口压力(MPa)	15
气体压缩系数(MPa <sup>-1</sup> )	0.05	REV 压力梯度(MPa·m <sup>-1</sup> )	0.05
干酪根孔径(nm)	50	干酪根孔隙度	0.2
无机基岩孔隙度	0.1	无机基岩孔径(nm)	100
REV 水平方向裂缝条数	5	次生裂缝孔隙度	0.02
REV 垂直方向裂缝条数	5	次生裂缝间距(m)	0.05
气体粘度(mPa·s)	0.018 4	干酪根表面扩散系数(10 <sup>-4</sup> m <sup>2</sup> ·s <sup>-1</sup> )	5
气体摩尔质量(kg·mol <sup>-1</sup> )	0.016	朗格缪尔压力(MPa)	13.78
储层温度(K)	338	干酪根固体形状因子(m <sup>-2</sup> )	0.5
单位岩心体积中干酪根固体体积	0.5	角动量调节系数	0.8
无机基岩孔隙迂曲度	5	干酪根孔隙迂曲度	5
干酪根表面朗格缪尔最大吸附浓度(m <sup>3</sup> ·kg <sup>-1</sup> )	3.1×10 <sup>-3</sup>	REV 初始压力(MPa)	50

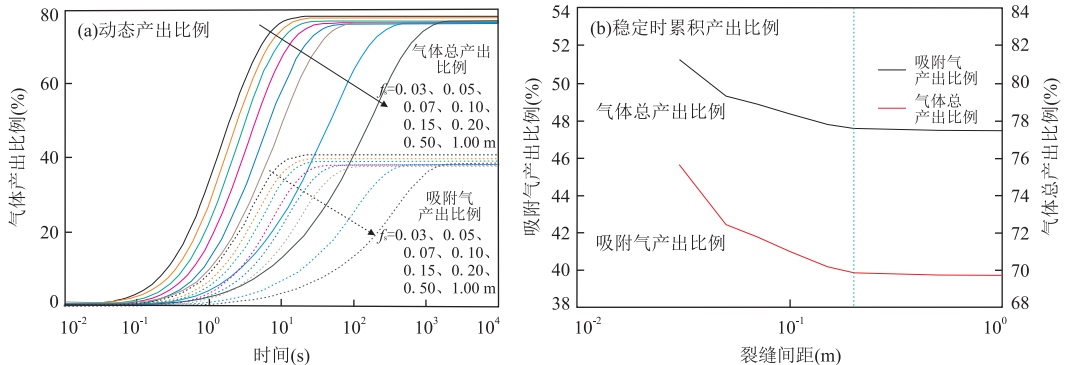


图 2 不同裂缝间距下吸附气及总气体产出比例曲线

Fig.2 Production curves of absorbed gas and total gas with different fracture spaces

例随生产时间的增加呈现先快速增长后平缓的趋势,最后均趋于稳定.随着裂缝间距的增大,气体产出比例增长速度逐渐变小,且变化幅度越来越大,吸附气产出比例的增长速度略小于气体总产出比例的增长速度.裂缝间距越小,气体产出比例越早达到稳定状态;达到稳定状态时,裂缝间距越小,气体产出比例越高,吸附气产出比例受裂缝间距的影响较大.其主要原因在于页岩储层基质团块非常致密,发育纳米级孔隙,渗透率极低,基质团块内流体很难动用,裂缝间距较大时,基质团块内流体很难实现向裂缝的“最短距离”渗流,因此基质团块内流体动用程度很小.同时吸附气赋存于纳米级有机粒孔隙内部,与自由气相比更难运移,因此吸附气产出比例的增长速度略小于气体总产出比例的增长速度.对比稳定状态时不同裂缝间距下气体产出比例(图 2b),可以看出当裂缝间距大于 0.20 m 时,裂缝间距继续增加而气体产出比例则不再下降.因此本模型参数下当裂缝间距大于 0.20 m 时,裂缝对 SRV 区域气体增产贡献程度可以忽略不计,即该气藏体积压裂

SRV 有效裂缝间距界限为 0.20 m.

## 1.2 页岩气藏 SRV 有效裂缝间距界限影响因素研究

页岩气有效流动不仅受储层性质(孔喉尺寸、基质团块渗透率、气体扩散性质等)的影响,同时还受生产改造参数(地层压力、压力梯度、裂缝宽度等)的影响.本节从流体渗流角度考虑不同生产改造参数对气体运移规律的影响,不考虑地质力学、流固耦合等因素对渗流的影响.北美 Barnett 页岩储层统计数据结果表明,页岩储层体积压裂改造区域次生裂缝宽度一般在 0.3~1.0 mm 之间.基于以上基础数据,分析不同裂缝宽度(0.1、0.5 和 1.0 mm)、地层压力(10、15 和 20 MPa)以及压力梯度(0.01、0.05 和 0.10 MPa/m)对 SRV 有效裂缝间距界限的影响(图 3~图 5).

如图 3~图 5 所示,当裂缝间距大于 0.20 m 时,裂缝间距继续增加气体产出比例不再下降.因此本模型参数下当裂缝间距大于 0.20 m 时,裂缝对 SRV 区域气体增产贡献程度可以忽略不计,即该气藏体

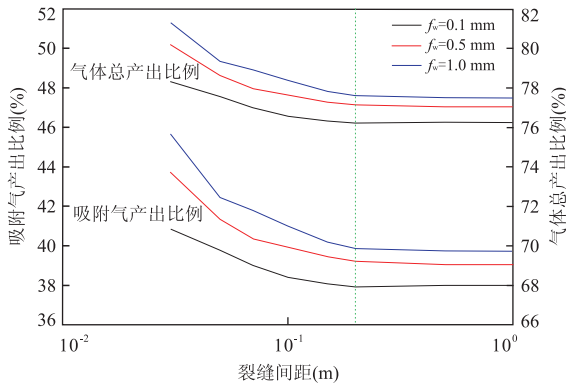


图 3 裂缝宽度对 SRV 有效裂缝间距界限影响

Fig.3 Effect of fracture width on effective fracture space of SRV

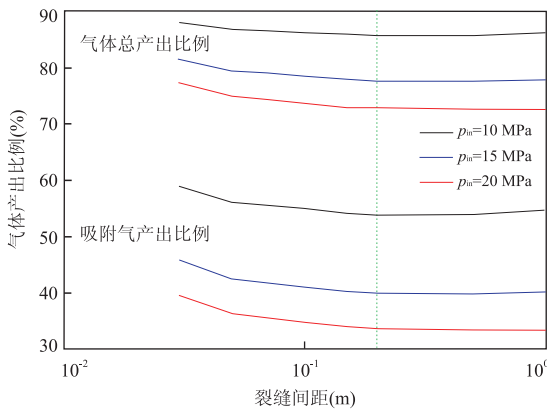


图 4 地层压力对 SRV 有效裂缝间距界限影响

Fig.4 Effect of reservoir pressure on effective fracture space of SRV

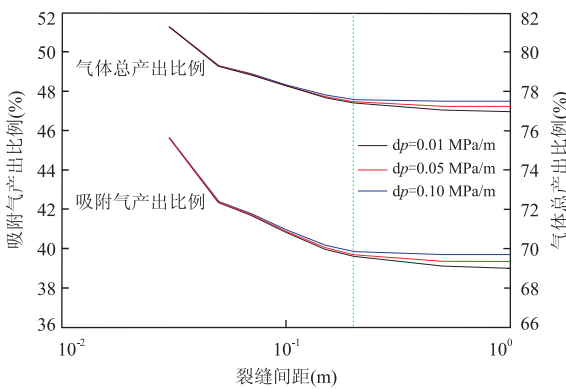


图 5 压力梯度对 SRV 有效裂缝间距界限影响

Fig.5 Effect of pressure gradient on effective fracture space of SRV

积压裂 SRV 有效裂缝间距界限为 0.20 m。裂缝宽度、地层压力、压力梯度对气体产出比例均有一定影响,但对 SRV 有效裂缝间距界限影响很小。裂缝宽度越大,气体产出量越高,裂缝间距越小,裂缝宽度对气体产量的影响越大。地层压力对气体产量影响

较大,地层压力越低,REV 单元压力与储层原始压力差值越大,气体产出量越高。裂缝间距越小,地层压力对气体产量的影响越大,但变化程度不大;REV 内压力梯度对气体产量随裂缝间距的增大而增大,当裂缝间距小于 SRV 有效裂缝间距界限时,压力梯度对气体产量影响很小,可以忽略不计;当裂缝间距大于 0.20 m 时,压力梯度对气体产量的影响逐渐增加。

## 2 页岩气藏体积压裂 ESRV 评价方法

体积压裂改造区域裂缝分布规律复杂。Fan (2015)、Fan and Ettehadtavakkol(2017)对改造区域缝网研究发现:距离压裂裂缝越远,次生裂缝数量越少,次生裂缝间距越大,可以采用分形分叉理论进行描述(图 6)。页岩气藏体积压裂 SRV 有效裂缝间距界限研究表明,当次生裂缝间距增加到一定程度之后,SRV 对增产效果影响很小。次生裂缝间距小于 SRV 有效裂缝间距界限的改造区域为 ESRV。假设 SRV 区域任意与压裂裂缝平行的平面内次生裂缝均匀分布且穿透整个储层,则 Fan and Ettehadtavakkol(2017)提出分形缝网模型来表征 SRV 区域裂缝的非均匀分布特征,其通过分形质量维数来表征体积压裂改造区域次生裂缝密度分布规律:

$$N_f(y) = N_i \left( \frac{y}{\omega_F} \right)^{-d_f+1}, \quad (10)$$

其中, $N_f$  为  $[y, y_c]$  范围内裂缝总条数; $N_i$  为 SRV 区域内裂缝总条数; $\omega_F$  为压裂裂缝半宽, m;  $d_f$  为 SRV 区域次生裂缝分形质量维数,表征裂缝分布复杂程度(Fan and Ettehadtavakkol, 2017),其可采用盒维数法来估算(Korvin, 1992; Miao *et al.*, 2015),其值在 1.3~1.7 之间(Korvin, 1992; Fan and Ettehadtavakkol, 2017)。

Fan and Ettehadtavakkol(2017)对 Barnett 页岩生产井体积压裂微地震数据建模分析,得到实际储层次生裂缝孔隙度、渗透率以及裂缝密度分布规律,将其与分形质量维数方法计算的裂缝密度及孔渗分布规律进行对比,获得了较好的一致性,从而验证了裂缝分形分布特征的正确性。在此基础上,对上式进行求导,可以得到改造区域内不同位置处次生裂缝密度分布规律:

$$\rho_f = N_i (d_f - 1) \frac{y^{-d_f}}{\omega_F^{-d_f+1}}, \quad (11)$$

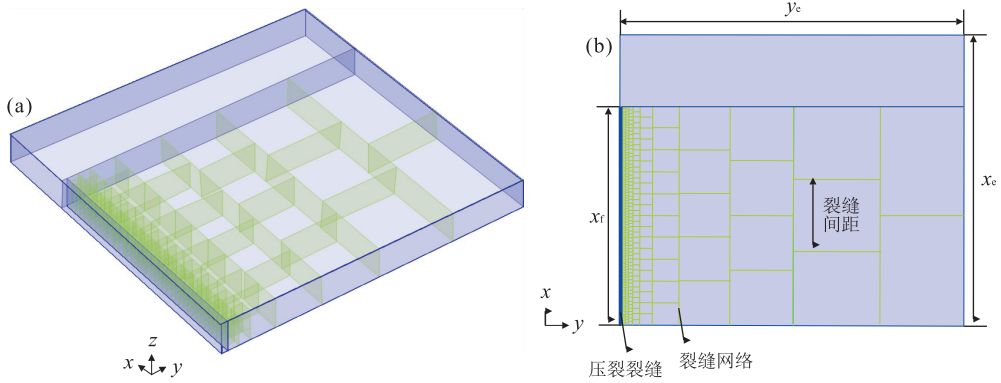


图 6 体积压裂 SRV 次生裂缝分布

Fig.6 Secondary fracture distribution of SRV

a. 三维图; b. 俯视图

根据裂缝密度分布规律,可以得到裂缝间距分布公式为:

$$f_s = \frac{1}{N_t(d_t - 1)} \frac{y^{d_t}}{\omega_F^{d_t - 1}} \quad (12)$$

笔者综合文献调研得到的 Barnett 页岩储层参数及压裂改造数据 (Fan and Ettehadtavakkol, 2017),假设改造区域内次生裂缝总条数为 20 000 条,压裂裂缝半宽为 1 cm,次生裂缝分形质量维数为 1.35,裂缝半长为 150 m,储层厚度为 60 m,计算 SRV 区域内次生裂缝间距分布规律(图 7)。次生裂缝间距为 0.2 m 时对应的 ESRV 有效带宽为 64.8 m,而微地震等手段监测得到的 SRV 改造带宽为 171.5 m,因而对于本文采用的储层相关数据,该页岩气藏有效改造体积占体积压裂改造体积的 37.78%,该结果与现场矿场压裂实践认识基本吻合。

页岩储层体积压裂 ESRV 受改造区域次生裂缝分布规律及 SRV 有效裂缝间距界限的影响,SRV 有效裂缝间距界限受基质团块渗透率、微观孔隙结

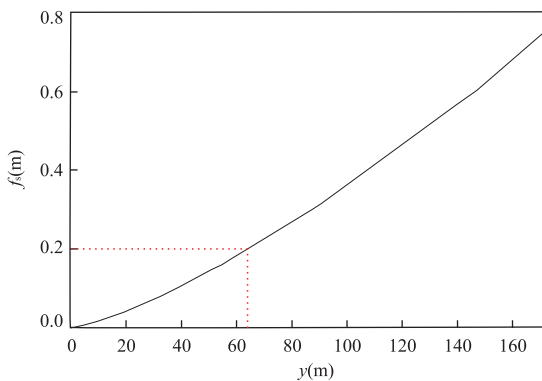


图 7 体积压裂 SRV 区域次生裂缝间距分布规律

Fig.7 Secondary fracture space distribution in SRV region

构、气体吸附解吸特性等储层性质参数影响,是储层的固有性质参数;次生裂缝分布规律受液量、排量、压裂规模等压裂施工参数以及储层天然裂缝发育程度、岩石物性参数等因素影响,是储层固有性质及人工压裂因素综合作用的结果。同时 ESRV 现场实例计算应建立在裂缝监测的基础上,反演裂缝的具体形态,并结合生产资料等历史数据计算并验证有效裂缝间距界限,确定储层体积压裂 ESRV 具体形态及大小,并通过生产井产能数据进行验证,有效改造体积对非常规储层压裂方案评价与产量预测具有重要作用,需要进一步深入研究。

### 3 结论

(1)本文基于页岩气藏体积压裂 SRV 区域多尺度介质(干酪根有机质、无机基岩、次生裂缝)分布特征及气体渗流特性,建立了缝网多重介质 REV 渗流模型,并采用有限元方法对该模型进行数值求解,得到了 REV 内不同赋存状态气体产量变化规律。

(2)以北美 Barnett 页岩气藏典型生产井作为研究对象,采用 REV 渗流模型研究了裂缝间距对基质团块流体动用程度的影响,结果表明该生产井体积压裂 SRV 有效裂缝间距界限为 0.20 m,当 SRV 区域次生裂缝间距大于 0.20 m 时,次生缝网对气体增产贡献很小;次生裂缝宽度、地层压力、压力梯度等参数对 SRV 区域气体增产比例有影响,对 SRV 区域裂缝间距增产界限影响很小,而从地质力学角度耦合分析时,地层压力、压力梯度对有效裂缝间距界限影响将会改变,需要进一步深入研究。

(3)基于分形理论表征 SRV 区域次生裂缝分布规律,采用分形质量维数定量表征了改造区域内不

同位置处次生裂缝间距,结果表明裂缝间距随着与压裂裂缝之间距离的增加呈指数增长趋势。

(4)本文提出了裂缝间距增产界限结合次生裂缝分布规律的页岩气藏体积压裂水平井 ESRV 计算评价方法,并以 Barnett 页岩生产井为例进行计算.结果表明次生裂缝间距为 0.20 m 时对应的 ESRV 有效带宽为 64.8 m,而微地震监测得到的 SRV 改造带宽为 171.5 m,该页岩气藏有效改造体积占体积压裂改造体积的 37.78%。

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