页岩气井体积压裂技术在我国的应用建议

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摘 要 页岩气因其储层渗透率超低、气体赋存状态多样等特点,决定了采用常规的压裂形成单一裂缝的增产改造技术已不能适应页岩气藏的改造,必须探索研究新型的压裂改造技术,方能使其获得经济有效地开发。为此,在总结分析美国页岩气储层的岩性、物性、天然裂缝与力学性质特征的基础上,依据复杂裂缝形成机理,提出了压裂形成复杂缝网、增大改造体积的基本地层条件的观点,归纳了直井和水平井体积压裂改造工艺技术方法等。实践表明:页岩气储层获得体积压裂后不仅初期产量高,而且更有利于长期稳产;在我国压裂增产改造将是开发页岩气最重要的技术手段。建议分海相、陆相两大类型开展体积压裂适应性、体积压裂优化设计技术与实施工艺技术、压后监测与评估技术等攻关研究。

关键词 页岩气 体积压裂 缝网 剪切裂缝 水压裂 监测 建议
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1 页岩气基本特征

美国 Fort Worth、Illinois 盆地等 5 大盆地生产页岩气,占美国产气量的 95% 以上,页岩气开采深度普遍小于 3 000 m,其储层典型特征为: ①石英含量大于 28%,一般为 40%~50%,遭受破坏时会产生复杂的缝网; ②页岩气储层致密,孔隙度为 4.22%~6.51%,基质渗透率在 1.0 mD 以下; ③页岩微裂缝发育,页岩气在裂缝网络系统不发育情况下,很难成为有效储层; ④页岩气有机质丰度高,厚度大,有机碳含量一般大于 2%,成熟度为 1.4%~3.0%,干酪根以腐泥—混合型为主,有效厚度一般在 15~91 m; ⑤页岩脆性系数高,容易形成剪切裂缝,如 Barnett 页岩杨氏模量为 34 000~44 000 MPa,泊松比为 0.2~0.3; ⑥页岩气主要有吸附态、溶解态和游离态 3 种赋存状态,其赋存状态要求有大的改造体积,这样才会获得高产[1-2]。

2 页岩气井体积压裂技术

体积压裂是指在水力压裂过程中,使天然裂缝不断扩张和脆性岩石产生剪切滑移,形成天然裂缝与人工裂缝相互交错的裂缝网络,从而增加改造体积,提高初始产量和最终采收率。

页岩气储层渗透率超低,厚度大,天然裂缝发育,气体主要以吸附态吸附在有机质表面,常规改造形成单一裂缝很难获得好的增产效果。数值模拟研究表明[3],页岩气储层改造的体积(SRV, 10^6 ft^3; 1 ft^3 = 0.028 317 m^3,下同)越大,压后增产效果越好(图 1)。但要实现体积改造,除地层要具备体积压裂的基本条件外,压裂改造工艺方法也十分关键。

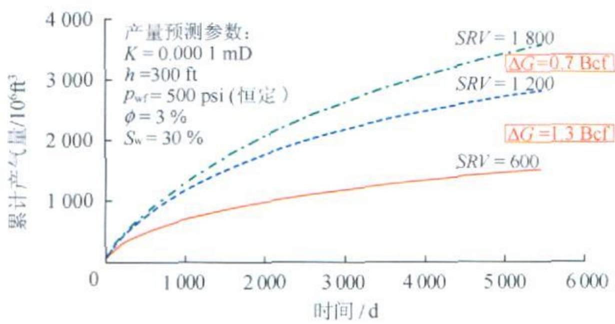

图 1 页岩气不同改造体积下累计产量预测曲线图
(1 psi= 6.895 kPa; 1 ft= 0.304 8 m)

2.1 页岩气体积改造的地层条件

1) 天然裂缝发育,且天然裂缝方位与最小主地应力方位一致。在此情况下,压裂裂缝方位与天然裂缝方位垂直,容易形成相互交错的网络裂缝。

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2) 岩石硅质含量高(大于 35%), 脆性系数高。岩石硅质(石英和长石) 含量高, 使得岩石在压裂过程中产生剪切破坏, 不是形成单一裂缝, 而是有利于形成复杂的网状缝, 从而大幅度提高了裂缝体积。

3) 敏感性不强, 适合大型滑溜水压裂。弱水敏地层, 有利于提高压裂液用液规模, 同时使用滑溜水压裂, 滑溜水黏度低, 可以进入天然裂缝中, 迫使天然裂缝扩展到更大范围, 大大扩大改造体积。图 2 为滑溜水压裂和交联冻胶压裂改造范围的比较曲线。

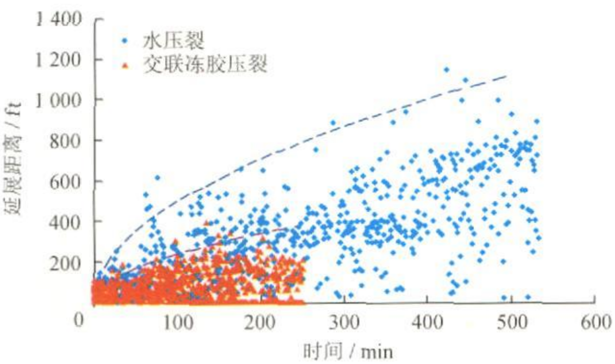

图 2　滑溜水压裂和交联冻胶压裂改造范围的比较图

2.2　页岩气井体积压裂工艺技术

2.2.1　直井滑溜水大型压裂技术

2.2.1.1　压裂工艺

压裂工艺体现了“两大、两小”特征, 其中“两大”是指: ①大排量, 施工排量 10 m^3/ min 以上; ②大液量, 单井用液量 2 271~ 5 678 m^3。“两小”是指: ①小粒径支撑剂, 支撑剂一般采用70/ 100目和40/ 70目陶粒, ②低砂比, 平均砂液比为 3% ~ 5%, 最高砂液比不超过 10.0%。

2.2.1.2　压裂液体系

压裂液体系以滑溜水为主, 滑溜水可以采用阴离子聚合物, 也可以用低浓度瓜胶。

2.2.2　水平井分簇射孔分段压裂技术

2.2.2.1　分簇射孔技术

为了压裂形成网状裂缝、提高改造体积, 采用分簇射孔技术, 每级分 4~ 6 簇射孔, 每簇长度 0.46~ 0.77 m, 簇间距 20~ 30 m, 孔密 16~ 20 孔/ m, 孔径 13 mm, 相位角 60°或者 180°。

2.2.2.2　分段压裂技术施工参数

施工排量为 12.7~ 19.0 m^3/ min; 压裂液为滑溜水或低浓度胶液, 每段用量 2 000~ 5 000 m^3; 支撑剂单井用量为 60~ 190 m^3, 100 目支撑剂 30~ 360 kg/ m^3 斜坡递增浓度, 40/ 70 目支撑剂 30~ 600 kg/ m^3 斜坡递增浓度。

2.2.2.3　分段压裂技术施工步骤

施工步骤为: ①第一段采用油管或连续油管传输射孔, 提出射孔枪; ②从环空进行第一段压裂; ③凝胶冲洗井筒; ④用液体泵送电缆+ 射孔枪+ 桥塞工具入井; ⑤电引爆座封桥塞, 射孔枪与桥塞分离, 试压(约过射孔段 25 m); ⑥拖动电缆带射孔枪至射孔段, 射孔, 拖出电缆; ⑦压裂第二层, 重复步骤 ④~ ⑦, 实现多层分段压裂。

2.2.2.4　压后桥塞处理

压后用连续油管磨铣或 ∅73 mm+ ∅101.6 mm 的 5 刃刀钻掉桥塞, 合层排液求产。

2.3　页岩气体积改造效果

采用上述方法, 通过井下微地震波测试, 证实页岩气直井滑溜水大规模压裂和水平井分簇射孔分段压裂形成网络裂缝, 提高了压裂改造效果(图 3)。

在Barnett 页岩19口有井下微地震监测资料的

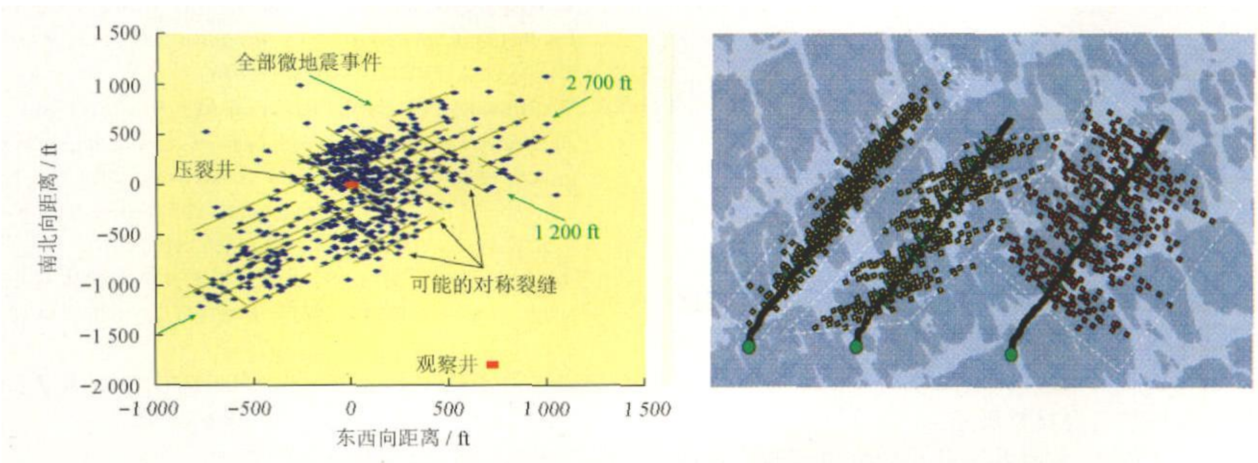

图 3　直井与水平井井下微地震波裂缝监测结果图

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井,改造后的体积与压后 6 个月和 3 a 累计产量的比较曲线见图 4。由图 4 可见: 19 口井的压裂改造体积在 5.3×10^6~ 52.7×10^6 m^3,且压后 4 个月的累计产量随着改造体积的增加而增加,压后 3 a 增加的幅度更大,这充分说明改造体积对页岩气压后产量的重要作用。

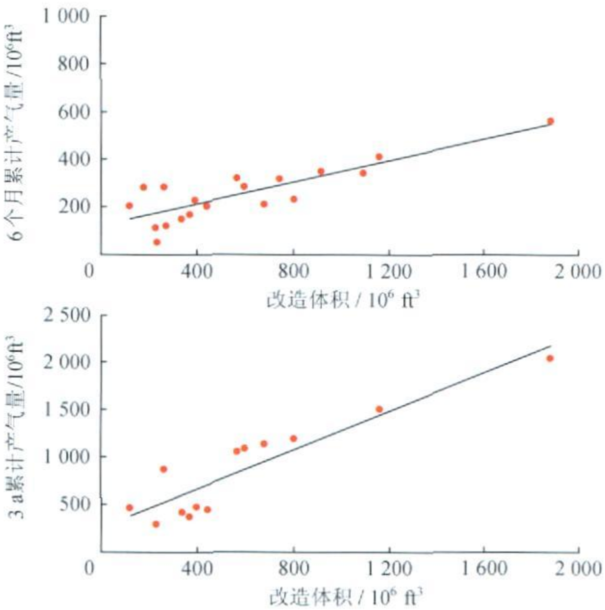

图 4　**Barnett** 页岩 **19** 口井压后累计产量与改造体积的关系图

3　对国内页岩气井压裂改造技术的建议

我国古生界海相和中新生界陆相均发现页岩气[4],海相页岩以南方、华北等 3 大地区为主,陆相页岩分布于松辽、准噶尔等 5 大盆地,主要盆地和地区的页岩气资源量为 15×10^{12}~ 30×10^{12} m^3,因沉积环境与条件的差异,各盆地与地区页岩气非均质性非常强。因此,各盆地与地区页岩气对压裂改造技术适应性,将是一个长期研究与探索的过程,不可能一蹴而就,建议分海相与陆相两大页岩气类型展开体积压裂技术攻关研究与试验。

1) 复杂裂缝形成的机理研究: ①岩性、物性、力学性质与天然裂缝条件; ②最大与最小主地应力差异; ③剪切裂缝形成机制。

2) 体积压裂工艺技术方面: ①体积压裂油藏数值模拟研究; ②水力裂缝间距与导流能力优化[5]; ③体积压裂实施与控制技术研究,包括同步压裂技术等。

3) 体积压裂适合材料研究。

4) 先试验直井,在直井试验成功取得经验后再向水平井拓展。

5) 裂缝监测技术方面要大力发展井下微地震监测技术,以评价页岩气压裂复杂裂缝扩展情况,指导现场压裂设计与评估效果。

4　结论与认识

1) 页岩气在国外得到了很好的开发利用,而国内页岩气开发研究则处于起步阶段,亟待攻关研究其增产改造技术。

2) 页岩气主要采用压裂投产方式开发,包括直井滑溜水大型压裂和水平井分簇射孔分段压裂,改造思路为形成复杂缝网的体积改造技术。

3) 页岩气水平井主体体积压裂技术为可钻式桥塞封隔分段压裂,包括分段电缆簇射孔技术,高排量、滑溜水、大规模、低砂比压裂施工技术,可钻式桥塞封隔技术等。

4) 国内页岩气有丰富的资源量,要得到有效的开发利用,压裂增产改造技术尤为关键,建议首先在直井上开展体积压裂技术,探索工艺、液体、施工参数的适应性和评价压后效果,取得成功后向水平井发展。

5) 为发展国内页岩气水平井体积压裂技术,应重点研究泵送可钻式桥塞分段压裂技术,包括研制可钻式桥塞,研究电缆分级射孔技术,电引爆桥塞座封技术等配套技术。

参　考　文　献

[1] CIPOLLA C L, WARPINSKI N R, MAYERHOFER M J, et al. The relationship between fracture complexity, reservoir properties, and fracture treatment design[C] // SPE Annual Technical Conference and Exhibition, 21-24 September 2008, Denver, Colorado, USA: SPE, 2008, SPE 115769.

[2] MAYERHOFER M J, LOLON E P, WARPINSKI N R, et al. What is stimulated rock volume? [C] // SPE Shale Gas Production Conference, 16-18 November 2008. Fort Worth, Texas, USA: SPE, 2008, SPE 119890.

[3] WARPINSKI N R, MAYERHOFER M J, VINCENT M C, et al. Stimulating unconventional reservoirs: maximizing network growth while optimizing fracture conductivity[C] // SPE Unconventional Reservoirs Conference, 10-12 February 2008. Keystone, Colorado, USA: SPE, 2008, SPE 114173.

[4] 朱华,姜文利,边瑞康,等. 页岩气资源评价方法体系及其应用——以川西坳陷为例[J]. 天然气工业, 2009, 29(12): 130-134.

[5] 陈作,王振铎,曾华国. 水平井分段压裂工艺技术现状及展望[J]. 天然气工业, 2007, 27(9): 78-80.

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Transient pressure analysis of infinite conductivity fractured wells for shale gas

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NATUR. GAS IND. VOLUME 30, **ISSUE** 10, **pp.** 26-29, 10/25/2010. **(ISSN** 1000-0976; **In Chinese)**

Abstract: Although recoverable resources of shale gas are very abundant in China, very low or even no natural productivity can be obtained for most of the wells in shale gas reservoirs, and productivity will be available only when some stimulation measures are taken during the shale gas development. Therefore, based on a study on the fracturing of conventional gas reservoirs, in view of the characteristics of pressure drawdown, desorption, diffusion, and fluid flow during the output of shale gases, we start from the filtration theory and adopt the Quasi steady state Fick diffusion according to the point source function method, to study the single-phase flow of shale gases in the matrix and fractures. Based on the above, we set up an evaluation model on the infinite conductivity fractured well of shale gas reservoirs, to discuss the influences of parameters, such as adsorption coefficient, fracture storage coefficient, and cross flow coefficient on the pressure performance and analyze the dynamic characteristics of the fractured wells in shale gas reservoirs together with some estimation methods of parameters. As a result, the problem of indeterminable dynamic parameters of shale gas reservoirs is thus resolved and typical curves of fractured wells in shale gas reservoirs are drawn for the first time. This study will provide technical support for the high-efficiency development of shale gas reservoirs.

Key words: shale gas, fractured well, infinite conductivity fracture, adsorption coefficient, analysis, diffusion, mathematical model

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Proposals for the application of fracturing by stimulated reservoir volume (SRV) in shale gas wells in China

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Abstract: Due to ultra-low permeability and various states of gas occurrence, shale gas reservoirs require a large fracture network to maximize well performance. In shale reservoirs, where complex network structures in multiple planes are created, the concepts of single-fracture half-length and conductivity are insufficient to describe stimulation performance. Based on an analysis of lithologic, petrophysical, mechanical properties, and natural fractures of shale gas reservoirs in the USA, this paper introduces what is the concept of using stimulated reservoir volume (SRV) as a correlation parameter for well performance and summarizes how the SRV fracturing methods affects production acceleration and ultimate recovery of vertical and horizontal shale gas wells. From American field practices, we learn that the SRV can not only accelerate the early-stage productivity but maintain steady production of the ultralow-

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permeability shale gas reservoirs. Moreover, we suggest that key projects on the adaptability of SRV fracturing, optimal fracture design and operation, post-frac monitoring and assessment should be performed respectively in the marine-facies and continental-facies shale gas development.

Key words: shale gas, stimulated reservoir volume fracture network, shearing fracture, water frac, monitor, proposal
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An analysis of hydraulic fracturing technology in shale gas wells and its application

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Abstract: Shale gas wells can obtain favorable production only after reservoir stimulation due to their small porosity and low permeability of shale gas reservoirs. At present, hydraulic fracturing is one of the core technologies commonly used in shale gas development. Based on an analysis of the principle of hydraulic fracturing technology in shale gas development and its field practices in other countries, this paper analyzes the characteristics and applicability of a variety of hydraulic fracturing technologies, which include multi-stage fracturing, water fracturing, hydrojet fracturing, refracturing, and simultaneous fracturing. This paper also discusses the roles of natural fracture systems and fracturing fluid preparation in hydraulic fracturing. Moreover, it is suggested from studies that shale gas exploration and development in China should start from refracturing in old wells and hydraulic fracturing in new wells at present. Through a review on the data of many old wells in the southern and southwestern Sichuan Basin, it is concluded that the old wells with shale gas shows can be fractured by modern hydraulic fracturing; from foreign experiences, nitrogen foam fracturing can be used for the exploratory shallow wells or those with favorable pay zones as deep as less than 1500 m; while water fracturing can be used for the wells with pay zones as deep as 1500 - 3000 m; but no further development will be taken into consideration for those wells with pay zones as deep as more than 3000 m.

Key words: shale gas, exploitation technology, reservoir stimulation, hydraulic fracturing, application, analysis, burial depth
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An experimental study of gas mass-transfer for fractured tight sand gas reservoirs

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