页岩气储层水平井与压裂工程基础问题探讨

李根生^{①②*}, 盛茂^{①②}, 田守增^{①②}, 葛洪魁^{①②}, 黄中伟^{①②}, 宋先知^{①②}

① 油气资源与探测国家重点实验室(中国石油大学(北京)), 北京 102249;

② 中国石油大学(北京)石油工程学院油气井工程系, 北京 102249

* 联系人, E-mail: ligs@cup.edu.cn

2015-11-06 收稿, 2016-02-17 修回, 2016-02-17 接受, 2016-06-12 网络版发表

国家自然科学基金重大国际(地区)合作项目(51210006)和国家自然科学基金重大项目(51490652)资助

摘要 水平井钻井和压裂改造是页岩气高效开发的关键技术, 我国页岩气储层水平井与压裂工程面临诸多工程与地质挑战: (1) 钻头适应性差, 破岩效率低, “一趟钻”难突破; (2) 层理裂隙发育, 井眼垮塌和井漏问题突出, 坍塌周期明显; (3) 压裂缝网形成机制仍需深入认识, 复杂裂缝系统的压裂设计理论有待完善. 指出页岩气储层岩石破碎机理与高效破岩、长水平段井壁失稳机理与控制、复杂缝网形成机制与调控等是亟需解决的关键基础问题. 探索工作流体(钻井、完井、压裂流体)与页岩之间的多重耦合作用机理, 建立流体-固体、力学-化学耦合的理论模型将是未来研究的重点和难点, 具体包括: (1) 考虑页岩自发渗吸、水膜润滑裂缝面、岩石脆性等条件下的页岩破碎机理; (2) 考虑水岩反应、力学-化学耦合作用的页岩长水平段井壁失稳机理; (3) 压裂液作用下的流体压力分配与多裂缝竞争开裂机制. 针对关键基础问题综述了研究进展和发展趋势, 对促进我国页岩气储层水平井与压裂工程的科学发展有一定借鉴作用.

关键词 页岩气, 水平井, 岩石破碎, 井壁失稳, 水力压裂

页岩气是近年来全球非常规油气资源开发利用的重点, 美国规模化应用水平井与压裂工程技术, 实现了页岩气大规模商业开采, 开启了页岩气革命并席卷全球. 据美国能源署报告^[1], 2004年以来美国页岩气年产量持续增加, 2015年增加到全年天然气总量的56%, 跃居成为全球第一大天然气生产国. 中国在这场革命中抓住机遇、稳中求进, 截至2015年我国探明页岩气储量超5000亿立方米, 年产能65亿立方米(数据来源于中国地质调查局油气资源调查中心). 页岩气革命所带来的能源结构巨变离不开技术革新和与之相关的基础理论进步, 特别是水平井与压裂工程发展水平.

近年来, 我国围绕水平井与压裂工程的关键基础理论与技术问题开展了大量工作, 其中技术关键

包括钻头优选与高效破岩、井眼轨迹设计与控制、井壁稳定性控制、长水平段固井质量控制、压裂工艺与参数优化设计等. 在基础理论研究方面, 正在开展页岩非线性地质力学表征与评价、多重耦合下的页岩安全优质钻井、页岩地层复杂裂缝扩展与控制、页岩气多尺度渗流与开采等方面研究^[2~4]; 在关键技术革新方面, 正在开展优快钻井、丛式三维水平井与工厂化作业、高性能环保钻井液、长水平段固井、无水压裂新方法、地质与工程一体化等方面的研究与探索^[5~7], 已初步形成我国页岩水平井与压裂工程技术体系, 钻井压裂成本与建井周期(包括钻井与压裂完井)稳步降低. 以涪陵页岩气田为例, 截至2015年, 单井钻井压裂成本从最初的上亿元降至5000万元左右, 平均建井周期由原先108天缩短至66天^[8], 缩短建井周

引用格式: 李根生, 盛茂, 田守增, 等. 页岩气储层水平井与压裂工程基础问题探讨. 科学通报, 2016, 61: 2883–2890

Li G S, Sheng M, Tian S C, et al. Key issues and investigation of horizontal well drilling and multistage fracturing in shale gas reservoir (in Chinese). Chin Sci Bull, 2016, 61: 2883–2890, doi: 10.1360/N972015-00692

期近40%，钻井总进尺突破百万米。

与美国页岩气开采基础理论与技术相比，我国在理论模型与软件、工程设计理念与经验、关键技术可靠性等方面还存在一定差距，钻井压裂成本仍高于美国(2400~3600万元/井)。其原因一方面是相关基础理论研究起步较晚，滞后于工程技术进步；另一方面相比美国，我国页岩油气地质条件更加复杂，埋藏更深、地层年代更老，催生出一系列新的技术瓶颈与挑战。

1 页岩水平井与压裂工程面临的工程地质挑战

水平井与压裂工程是一个系统工程，面临工程和地质两方面的诸多挑战。工程方面：页岩水平井水平段长(约1500 m)，普遍存在钻柱摩阻和扭矩大、钻头破岩效率低、井眼轨迹控制难、钻井液携岩难度大、井壁稳定性差、固井质量不稳定等工程技术难题。地质方面：相比美国，我国页岩气储层地质条件更为复杂，埋藏深、地层老，构造改造强烈、断裂发育^[9]，导致岩石可钻性极差，井漏风险高，地层起裂压力高，井下环境更加复杂。综合我国涪陵、长宁-威远、昭通等国家级页岩气示范区钻完井情况^[10,11]，总结当前面临的突出问题：(1) 钻头适应性差，破岩效率低，“一趟钻”难以突破；(2) 层理裂隙发育，井眼垮塌和井漏问题突出，坍塌周期明显，井壁稳定性控制难度大；(3) 压裂缝网形成机制仍需深入认识，复杂裂缝系统的压裂设计理论有待完善。

上述问题制约了我国页岩气资源的高效开发进程，应重点解决页岩气储层岩石破碎机理与高效破岩、长水平段井壁失稳与控制、复杂缝网形成机制与调控等关键基础问题并取得突破。

2 页岩岩石破碎机理与高效破岩方法

钻井过程中影响岩石破碎的因素很多，地层岩性是其重要的客观因素。页岩以黏土矿物和石英为主，细粒沉积、研磨性强、可钻性差，力学-化学及流体-固体等多重耦合作用强烈，其破碎机理相比普通砂岩更加复杂。探讨流体与固体耦合作用、各向异性与非均质性、页岩脆性等对岩石破碎的影响。

2.1 考虑页岩瞬时吸水效应的流固耦合作用

页岩瞬时吸水是页岩与水基钻井液短暂接触，

页岩孔隙、吼道及微裂缝的表面瞬间吸附水分子，形成水膜的现象。其原因是页岩原始处于超干状态^[12]，初始含水饱和度低于应有的束缚水饱和度，孔隙表面未被水分子充满^[13]。当岩石表面接触到水分子时，在黏土矿物与水分子间的范德华力和钻井压差力共同作用下，水分子瞬间被吸入孔隙、裂缝。页岩瞬时吸水促进了流体与固体的耦合作用，对岩石破碎产生三方面作用：(1) 裂缝表面的水膜起到润滑缝面的作用，可降低缝面摩擦系数，在相同正应力作用下，裂缝更易于压剪破坏；(2) 黏土矿物吸水后水化膨胀，颗粒间黏聚力降低，岩石抗压强度明显降低，有实验表明，吸水后的抗压强度比吸水前降低35%^[14]；(3) 岩石经水分子润湿后，岩石表面自由能降低，即产生单位面积新鲜岩面所需要的破碎功降低。由此可见，瞬时吸水有利于页岩破碎，可以通过提高页岩瞬时吸水速率，降低岩石强度的方法来提高机械钻速。孙金声等人^[15]研制出快速钻井剂，平均提高机械钻速18%，验证了通过改善岩石瞬时吸水速率提高机械钻速的可行性。此外，超临界CO₂因表面张力为零，容易进入裂缝^[16,17]，可起到润滑缝面，降低岩石表面自由能的作用，有望提高页岩破碎效率。

2.2 页岩破碎的各向异性与非均质性

页岩具有典型的各向异性力学特性^[18]，导致岩石破碎功和钻头切削力同样具有各向异性，在二者共同作用下钻井井斜与方位发生漂移，特别是当井眼轴线与岩石层理方向具有一定夹角时^[19]，井眼轨迹难以控制。高德利课题组^[19,20]系统研究了岩石各向异性对钻头破岩和井眼轨迹的影响，建立了考虑岩石各向异性的三维钻速方程，通过优化钻压和钻头齿布置来克服井斜和方位漂移。目前页岩水平井轨迹设计也充分利用到地层自然造斜规律^[8]。

页岩地层非均质性(矿物组成、裂缝分布等)较强^[21,22]，细观弹性模量和岩石硬度呈非均匀分布^[23]，宏观表现为页岩层段岩石可钻性差异明显。岩石可钻性在井眼轴线方向上的非均质性使得钻头适应性不佳^[24]，需要研制个性化钻头克服岩石非均质性。Pessier等人^[25]针对非均质地层，提出PDC-牙轮复合钻头，兼顾冲击和剪切破岩，机械钻速提高2~4倍。

2.3 振动冲击破碎页岩新方法

页岩基质脆性矿物含量较高(普遍超过40%)^[26]，

在冲击载荷下易开裂^[27,28],这可能成为高效破碎页岩的突破口。利用钻头振动和高压脉冲射流对页岩基质产生周期性冲击,促使基质萌生裂纹→裂缝间相互贯通→岩块脱离母体,其破碎效率将成倍提高。闫铁课题组^[29]研究了砂岩在PDC钻头高频振动冲击作用下的响应特点和破岩效果,结果表明机械钻速成倍提高。本课题组^[30,31]提出在井下调制水力脉冲空化射流辅助钻井,可在岩石表面产生低频冲击,周期性改变井底应力状态^[32],促进裂缝萌生、贯通。该技术在宣页1井现场试验,在钻进地层相同相近工况下试验井段比同井相邻井段机械钻速平均提高105.3%^[33]。说明硬脆性页岩在振动冲击破岩方式下可获得较好破岩效果。

3 页岩长水平段井壁失稳机理与控制方法

页岩长水平段井壁稳定问题有其特殊性:(1)页岩气储层往往是总有机碳含量高、层理裂缝发育、岩石脆性较强的层理状页岩,这种页岩与传统的块状泥页岩和泥岩的失稳机理有较大差异;(2)黏土矿物水化膨胀被认为是泥岩井壁失稳的重要机理之一,然而,针对页岩气储层,黏土矿物水化膨胀可能不再是主要矛盾,裂缝和应力弱面成为影响井壁稳定性的主要因素;(3)页岩水平井井眼与页岩接触面积和接触时间相比直井均成倍增加,因此钻井液与井壁岩石相互作用的时间效应必须考虑,特别是自发渗吸作用诱发岩石强度折损不可忽视。基于以上三点认识,探讨影响页岩长水平段井壁失稳的因素及其作用机理。

3.1 钻井液促进井壁裂缝失稳扩展

水平井井壁除天然裂缝发育外,且钻进中钻头和钻杆会撞击井壁,造成诱导裂缝。钻井液在压差力、毛细管力和浓度差的作用下渗流进入裂缝,产生水力劈裂作用,裂缝失稳扩展贯通,最终导致井壁坍塌。其原因是页岩原始处于超干状态^[12,13],微裂缝在吸水之前润滑性差,岩石颗粒间黏聚力较强;当水相侵入后,缝面得到润滑,同时水岩反应降低岩石颗粒黏聚力,缝面摩擦力和岩石表面自由能均降低,促使裂缝拉张扩展和剪切滑移。因此,You等人^[34]提出封堵微裂缝、避免水或其他液相沿裂缝侵入是控制页岩井壁失稳的关键。

3.2 黏土水化膨胀产生微裂隙,损伤加剧

黏土矿物水化产生较高的膨胀应力,诱发井壁

垮塌,是泥岩井壁失稳的主要形式。然而,针对富有机质页岩,黏土矿物以伊利石为主,以我国典型龙马溪组页岩为例^[35],黏土矿物含量26.5%~59.5%(平均46.2%),其中伊利石占绝大多数(平均82.5%),脆性矿物含量超过40%,质地硬而脆。伊利石不易水化,因此,龙马溪组页岩的水化膨胀能力低于泥岩^[36]。Dehghanpour等人^[37]实验表明,黏土矿物水化膨胀对页岩井壁稳定的作用并不是膨胀应力使基质整体破坏,导致井壁垮塌,而是水化膨胀会在页岩基质中产生新的微裂隙。裂隙加剧了岩石的初始损伤,降低岩石强度,不利于井壁稳定。作用机理是黏土矿物水化膨胀使局部孔隙压力增大,基质膨胀挤压周围的天然裂缝,使得膨胀应力得以释放,这一过程中当局部拉应力超过岩石抗张强度时就会产生裂隙。

3.3 自发渗吸作用降低岩石强度

页岩井壁与钻井液接触时间长(短则几天,多则数十天),同时微纳米孔隙自发渗吸作用超强^[38],因此自发渗吸产生的累积效应不可忽略。渗吸进入的液相,特别是水相能显著改变岩石宏观力学性质,表现为页岩硬度随在水中浸泡时间的增加而降低^[39],岩石抗拉强度随含水饱和度升高而降低^[14]。自发渗吸降低岩石强度,促进井壁失稳。提出抑制钻井过程中自发渗吸作用的钻井液体系是解决这一问题的有效途径。

4 页岩复杂缝网形成机制与调控方法

页岩气储层因其脆性强、天然裂缝发育,压裂改造后形成复杂的裂缝网络系统^[40,41],这与均质砂岩储层形成双翼单裂缝有本质区别。然而,页岩压裂缝网的形成受天然裂缝与层理面、原地应力、地层各向异性与非均质性、压裂液性质、施工排量等诸多因素影响,裂缝扩展路径十分复杂。探讨页岩压裂缝网形成机制及其影响因素。

4.1 流体压力分配与多裂缝竞争开裂机制

缝网的形成其本质是压裂液作用下的多裂缝竞争开裂问题,受到不同方位裂缝的开启压力和压裂液压力分配控制。多裂缝竞争开裂条件下将出现裂缝非连续扩展^[42],并以地面泵压的起伏变化为特征。现场压裂施工曲线表明^[43],常规压裂地面泵压变化相对连续、平稳;非常规页岩压裂地面泵压存在明显

的跳跃和起伏,这正是多裂缝竞争开启的外在表现.

页岩多裂缝竞争开裂由两方面决定:其一,压裂液在复杂多裂缝系统中,流量和流体压力会按照流动法则分配到各分支裂缝中,使得各分支缝内流体压力各异;其二,页岩天然裂缝发育和各向异性使得各分支裂缝的开启压力有较大差异,同时缝面受到的局部地应力也不同.二者共同作用的结果是,各分支缝内流体净压力不同,一旦某个分支缝的流体净压力超过裂缝开启压力,裂缝随即扩展,能量得到释放,同时也抑制了其他分支裂缝的开裂.裂缝纤维暂堵是控制裂缝扩展路径的有效方法之一,用于页岩气储层改造表现出了良好的增产效果^[44].纤维暂堵剂人为改变了缝内流体压力分配和裂缝的开启压力,削弱优势裂缝的扩展,让更多的分支裂缝得以开裂,最终提高缝网的复杂程度.

4.2 天然裂缝与水压裂缝相互作用的力学机制

20世纪70年代,人们就认识到天然裂缝、地质不连续性对水力压裂裂缝扩展有重要影响^[45,46].当时的研究是为了避免天然裂缝带来的多裂缝扩展、加速压裂液滤失和支撑剂架桥堵塞等不利影响.然而,随着页岩缝网压裂概念的提出^[47,48],研究转向了如何激活、沟通更多的天然裂缝产生裂缝网络.

水压裂缝在逼近天然裂缝过程中,天然裂缝周围应力场受到水压裂缝尖端应力奇异场的干扰,天然裂缝因此可能发生剪切滑移^[49,50].在缝内水压力和局部地应力作用下,天然裂缝也可能发生压剪滑移,形成双翼剪切缝^[51].由于裂缝面粗糙,裂缝剪切滑移后形成自支撑裂缝,且水压裂缝与之沟通后转向继续扩展,因此,天然裂缝发生剪切滑移对缝网形成至关重要.裂缝是否能发生剪切滑移成为研究焦点之一,为此提出了多个理论判据^[52,53],考虑了原地应力、缝内流体净压力、裂缝逼近角、缝面摩擦力等因素.然而,现有判据仅考虑两条裂缝间的相互作

用,与页岩多裂缝扩展的实际情况仍有一定差距.

4.3 压裂液与岩石相互作用的力学-化学耦合机制

压裂液与页岩存在不同尺度下的强相互作用,在微观尺度下,压裂液在超强毛细管力作用下,被吸收进入储层岩石孔隙裂隙中,影响到气体在岩石表面的吸附、润湿和流体流动,与岩石矿物发生水化反应,改变岩石孔隙结构和岩石强度;在宏观尺度下,压裂液是传递水力能量和携带支撑剂的主要介质,首先,压裂液黏度决定水压力能否传递到缝尖,黏度越低,水压力越易于到达缝尖,同时裂缝复杂度随压裂液黏度减小而增强^[54];其次,压裂液可显著降低裂缝表面自由能和裂缝面的摩擦系数,使得岩石断裂韧性降低^[55],裂缝更容易发生剪切滑移.Yan等人^[56]实验对比了干裂缝和液体润滑条件下的裂缝面摩擦系数,发现有压裂液润滑条件下裂缝面摩擦系数从0.6降低至0.2,降幅显著.

5 结束语

页岩破碎机理与高效破岩、页岩长水平段井壁失稳机理与控制、页岩复杂缝网形成机制与调控是页岩气储层水平井与压裂工程中亟待解决的三个关键科学问题.页岩特殊的力学和化学性质给水平井与压裂工程基础研究提出了新的挑战.探索工作流体(钻井、完井、压裂流体)与页岩之间的多重耦合作用机理,建立流体-固体、力学-化学耦合的理论模型将是未来研究的重点和难点.井壁裂缝失稳扩展和自发渗吸作用是层理状页岩井壁失稳的主要诱因,应重点研究钻井条件下井壁裂缝失稳扩展微观作用机理及高效封堵方法.压裂液作用下的多裂缝竞争开裂是缝网形成的重要机制,应重点研究压裂液在复杂裂缝系统中压力分配规律和分支裂缝间开启压力变化规律,建立页岩压裂多裂缝竞争开裂扩展数学模型和数值模拟方法.

参考文献

- 1 EIA USA. Annual energy outlook 2015 with projections to 2040. United States Energy Information Administration, Washington, 2015, www.eia.gov/forecasts/aeo
- 2 Chen M, Ge H K, Zhao J Z, et al. The key fundamantals for the efficient exploitation of shale oil and gas and its relatd challenges (in Chinese). Pet Drill Tech, 2015, 43: 7-14 [陈勉, 葛洪魁, 赵金洲, 等. 页岩油气高效开发的关键基础理论与挑战. 石油钻探技术, 2015, 43: 7-14]
- 3 Ge H K, Wang X Q, Zhang Y. A technical approach to reduce shale gas development cost (in Chinese). Pet Drill Tech, 2013, 41: 1-5 [葛

- 洪魁, 王小琼, 张义. 大幅度降低页岩气开发成本的技术途径. 石油钻探技术, 2013, 41: 1–5]
- 4 Yao J, Sun H, Huang Z Q, et al. Key mechanical problems in the development of shale gas reservoirs (in Chinese). *Sci Sin-Phys Mech Astron*, 2013, 43: 1527–1547 [姚军, 孙海, 黄朝琴, 等. 页岩气藏开发中的关键力学问题. 中国科学: 物理学 力学 天文学, 2013, 43: 1527–1547]
 - 5 Lu B P. Sinopec engineering technical advance and its developing tendency in shale gas (in Chinese). *Pet Drill Tech*, 2013, 41: 1–8 [路保平. 中国石化页岩气工程技术进步及展望. 石油钻探技术, 2013, 41: 1–8]
 - 6 Li G S, Tian S C, Huang Z W, et al. Feasibility investigation of hydra-jet fracturing in unconventional gas reservoir (in Chinese). In: *Proceedings of Unconventional Gas Reservoir Stimulation Workshop*. Chengdu, 2011 [李根生, 田守嵘, 黄中伟, 等. 非常规气藏水力喷射压裂改造可行性探讨. 见: 非常规天然气储层高效改造工程技术论坛. 成都, 2011]
 - 7 Zeng Y J. Integration technology of geology & engineering for shale gas development (in Chinese). *Pet Drill Tech*, 2014, 42: 1–6 [曾义金. 页岩气开发的地质与工程一体化技术. 石油钻探技术, 2014, 42: 1–6]
 - 8 Ai J, Zhang J C, Zang Y B, et al. The key drilling technologies in Fuling shale gas field (in Chinese). *Pet Drill Tech*, 2014, 42: 9–15 [艾军, 张金成, 臧艳彬, 等. 涪陵页岩气田钻井关键技术. 石油钻探技术, 2014, 42: 9–15]
 - 9 Dong D Z, Zou C N, Yang Y, et al. Process and prospects of shale gas exploration and development in China (in Chinese). *Acta Petrol Sin*, 2012, 33: 107–114 [董大忠, 邹才能, 杨桦, 等. 中国页岩气勘探开发进展与发展前景. 石油学报, 2012, 33: 107–114]
 - 10 Zhou X H. Drilling & completion techniques used in shale gas horizontal wells in Jiaoshiba block of Fuling area (in Chinese). *Pet Drill Tech*, 2013, 41: 26–30 [周贤海. 涪陵焦石坝区块页岩气水平井钻井完井技术. 石油钻探技术, 2013, 41: 26–30]
 - 11 Tang J G. Discussion on shale gas horizontal drilling technology in southern sichuan (in Chinese). *Pet Drill Tech*, 2014, 42: 47–51 [唐嘉贵. 川南探区页岩气水平井钻井技术. 石油钻探技术, 2014, 42: 47–51]
 - 12 Fang C H, Huang Z L, Wang Q Z, et al. Cause and significance of the ultra-low water saturation in gas-enriched shale reservoir (in Chinese). *Nat Gas Geosci*, 2014, 25: 471–476 [方朝合, 黄志龙, 王巧智, 等. 富含气页岩储层超低含水饱和度成因及意义. 天然气地球科学, 2014, 25: 471–476]
 - 13 Bennion D B, Thomas F, Ma T. Formation damage processes reducing productivity of low permeability gas reservoirs. In: *Proceedings of the SPE Rocky Mountain Regional/Low-Permeability Reservoirs Symposium and Exhibition*. Denver Colorado: Society of Petroleum Engineers, 2000
 - 14 Chenevert M E, Pernot V. Control of shale swelling pressures using inhibitive water-base muds. In: *Proceedings of the spe annual technical conference and exhibition*. New Orleans Louisiana: Society of Petroleum Engineers, 1998
 - 15 Sun J S, Yang Y P, An S M, et al. A study on the theory and technology of drilling fluids to increase ROP (in Chinese). *Drill Fluid Complet Fluid*, 2009, 262: 1–6 [孙金声, 杨宇平, 安树明, 等. 提高机械钻速的钻井液理论与技术研究. 钻井液与完井液, 2009, 262: 1–6]
 - 16 Shen Z H, Wang H Z, Li G S. Feasibility analysis of coiled tubing drilling with supercritical carbon dioxide (in Chinese). *Pet Explor Dev*, 2010, 37: 743–747 [沈忠厚, 王海柱, 李根生. 超临界 CO₂ 连续油管钻井可行性分析. 石油勘探与开发, 2010, 37: 743–747]
 - 17 Li G S, Wang H Z, Shen Z H, et al. Investigation and prospects of supercritical carbon dioxide jet in petroleum engineering. In: *Proceedings of the 10th Pacific Rim International Conference on Water Jet Technology*. Jeju, Korea: Water Jet Technology Association, 2013
 - 18 Heng S, Yang C H, Zhang B P, et al. Experimental research on anisotropic properties of shale (in Chinese). *Rock Soil Mech*, 2015, 36: 609–616 [衡帅, 杨春和, 张保平, 等. 页岩各向异性特征的试验研究. 岩土力学, 2015, 36: 609–616]
 - 19 Gao D L. The effect of an orthotropic formation on bore hole deviation (in Chinese). *Acta Petrolei Sin*, 1990, 11: 98–105 [高德利. 正交各向异性地层对井斜的影响. 石油学报, 1990, 11: 98–105]
 - 20 Gao D L. Adigraphmatic method for drilling characteristics of formation anisotropy and drill bit (in Chinese). *Acta Petrolei Sin*, 1994, 15: 126–132 [高德利. 钻头 and 地层各向异性钻井特性的一种表达方法. 石油学报, 1994, 15: 126–132]
 - 21 Suarez-rivera R, Deenadayalu C, Yang Y. Unlocking the unconventional oil and gas reservoirs: The effect of laminated heterogeneity in wellbore stability and completion of tight gas shale reservoirs. In: *Proceedings of the Offshore Technology Conference*. Houston Texas, 2009
 - 22 Jiang K X, Peng L, He W X, et al. Research of shale gas reservoir heterogeneity: A case of the Lower Cambrian Qiongzhusi formation of the Sichuan basin (in Chinese). *Mar Geol Front*, 2014, 30: 47–54 [江凯禧, 彭丽, 何文祥, 等. 页岩气储层非均质性研究——以四川盆地寒武统筇竹寺组为例. 海洋地质前沿, 2014, 30: 47–54]
 - 23 Chen P, Han Q, Ma T S, et al. Study of mechanical properties of shale based on micro-indentation test (in Chinese). *Pet Explor Dev*, 2015, 42: 1–9 [陈平, 韩强, 马天寿, 等. 基于微米压痕实验研究页岩力学特性. 石油勘探与开发, 2015, 42: 1–9]
 - 24 Zhang J H. Key drilling & completion techniques for shale gas horizontal wells in Pengshui block (in Chinese). *Pet Drill Tech*, 2013, 41: 9–15 [张锦宏. 彭水区块页岩气水平井钻井关键技术. 石油钻探技术, 2013, 41: 9–15]
 - 25 Pessier R, Damschen M. Hybrid bits offer distinct advantages in selected roller-cone and PDC-bit applications. *SPE Drill Complet*, 2011, 26: 96–103

- 26 Zou C N, Yang Z, Zhang G S, et al. Conventional and unconventional petroleum “orderly accumulation”: Concept and practical significance (in Chinese). *Pet Explor Dev*, 2014, 41: 14–26 [邹才能, 杨智, 张国生, 等. 常规-非常规油气“有序聚集”理论认识及实践意义. 石油勘探与开发, 2014, 41: 14–26]
- 27 Li Q H, Chen M, Jin Y, et al. Rock mechanical properties and brittleness evaluation of shale gas reservoir (in Chinese). *Pet Drill Tech*, 2012, 40: 17–22 [李庆辉, 陈勉, 金衍, 等. 页岩气储层岩石力学特性及脆性评价. 石油钻探技术, 2012, 40: 17–22]
- 28 Yuan J L, Deng J G, Zhang D Y, et al. Fracability evaluation of shale-gas reservoirs (in Chinese). *Acta Petrol Sin*, 2013, 34: 523–527 [袁俊亮, 邓金根, 张定宇, 等. 页岩气储层可压裂性评价技术. 石油学报, 2013, 34: 523–527]
- 29 Li W, Yan T, Zhang Z C, et al. Rock response mechanism and rock breaking test analysis for impact of high frequency vibration drilling tool (in Chinese). *Pet Drill Tech*, 2013, 41: 25–28 [李玮, 闫铁, 张志超, 等. 高频振动钻具冲击下岩石响应机理及破岩试验分析. 石油钻探技术, 2013, 41: 25–28]
- 30 Fu J S, Li G S, Shi H Z, et al. A novel tool to improve the rate of penetration—hydraulic-pulsed cavitating-jet generator. *SPE Drill Complet*, 2012, 27: 355–362
- 31 Shi H Z, Li G S, Wang X J, et al. Improving the rate of penetration by hydraulic pulsating-cavitating water jet under-balance pressure drilling (in Chinese). *Pet Explor Dev*, 2010, 37: 111–115 [史怀忠, 李根生, 王学杰, 等. 水力脉冲空化射流欠平衡钻井提高钻速技术. 石油勘探与开发, 2010, 37: 111–115]
- 32 Chang D Y, Li G S, Shen Z H, et al. Influence of waterjet impact load on bottom-hole rock stress field (in Chinese). *J China Univ Pet*, 2011, 35: 74–79 [常德玉, 李根生, 沈忠厚, 等. 射流冲击载荷对井底岩石应力场的影响. 中国石油大学学报, 2011, 35: 74–79]
- 33 Liu S, Li G S, Shi H Z, et al. Application of hydraulic pulsed jet generator for rop enhancement in shale gas well. In: *Proceedings of Offshore Mediterranean Conference and Exhibition*. Ravenna, Italy: Offshore Mediterranean Conference Press, 2015
- 34 You L, Kang Y, Chen Z, et al. Wellbore instability in shale gas wells drilled by oil-based fluids. *Int J Rock Mech Min Sci*, 2014, 72: 294–299
- 35 Wang Y M, Dong D Z, Li J Z, et al. Reservoir characteristics of shale gas in longmaxi formation of the lower silurian, southern Sichun (in Chinese). *Acta Petrol Sin*, 2012, 33: 551–561 [王玉满, 董大忠, 李建忠, 等. 川南下志留统龙马溪组页岩气储层特征. 石油学报, 2012, 33: 551–561]
- 36 Yang H L, Shen R C, Fu L. Composition and mechanical properties of gas shale (in Chinese). *Pet Drill Tech*, 2013, 41: 31–35 [杨恒林, 申瑞臣, 付利. 含气页岩组分构成与岩石力学特性. 石油钻探技术, 2013, 41: 31–35]
- 37 Dehghanpour H, Lan Q, Saeed Y, et al. Spontaneous imbibition of brine and oil in gas shales: Effect of water adsorption and resulting microfractures. *Energy Fuels*, 2013, 27: 3039–3049
- 38 Akbarabadi M, Piri M. Nanotomography of the spontaneous imbibition in shale. In: *Proceedings of the SPE/AAPG/SEG Unconventional Resources Technology Conference*. Denver, Colorado: Society of Petroleum Engineers Press, 2014
- 39 Liu X J, Xiong J, Liang L X, et al. Analysis of the wettability of Longmaxi formation shale in the south region of Sichuan basin and its influence (in Chinese). *Nat Gas Geosci*, 2014, 25: 1644–1652 [刘向君, 熊健, 梁利喜, 等. 川南地区龙马溪组页岩润湿性分析及影响讨论. 天然气地球科学, 2014, 25: 1644–1652]
- 40 Zhang X, Jiang T X, Jia C G, et al. Physical simulation of hydraulic fracturing of shale gas reservoir (in Chinese). *Pet Drill Tech*, 2013, 41: 70–74 [张旭, 蒋廷学, 贾长贵, 等. 页岩气储层水力压裂物理模拟试验研究. 石油钻探技术, 2013, 41: 70–74]
- 41 Zhang S C, Guo T K, Zhou T, et al. Fracture propagation mechanism experiment of hydraulic fracturing in natural shale (in Chinese). *Acta Petrol Sin*, 2014, 35: 496–503, 518 [张士诚, 郭天魁, 周彤, 等. 天然页岩压裂裂缝扩展机理试验. 石油学报, 2014, 35: 496–503, 518]
- 42 Daneshy A A. Off-balance growth: A new concept in hydraulic fracturing. *J Pet Tech*, 2003, 55: 78–85
- 43 Goma A M, Qu Q, Nelson S, et al. New insights into shale fracturing treatment design. In: *Proceedings of the SPE/EAGE European Unconventional Resources Conference and Exhibition*. Vienna, Austria: Society of Petroleum Engineers Press, 2014
- 44 Bustos O A, Powell A R, Olsen T N, et al. Fiber-laden fracturing fluid improves production in the bakken shale multi-lateral play. In: *Proceedings of the Rocky Mountain Oil & Gas Technology Symposium*. Denver Colorado: Society of Petroleum Engineers Press, 2007
- 45 Daneshy A A. Hydraulic fracture propagation in the presence of planes of weakness. In: *Proceedings of the SPE European Spring Meeting*. Amsterdam Netherlands: Society of Petroleum Engineers Press, 1974
- 46 Zoback M D, Rummel F, Jung R, et al. Laboratory hydraulic fracturing experiments in intact and pre-fractured rock. *Int J Rock Mech Min Sci Geomech Abstracts*, 1977, 14: 49–58
- 47 Mayerhofer M J, Lolon E, Warpinski N R, et al. What is stimulated reservoir volume? *SPE Prod Oper*, 2010, 25: 89–98
- 48 Wu Q, Xu Y, Wang X Q, et al. Volume fracturing technology of unconventional reservoirs: Connotation, optimization design and implementation (in Chinese). *Pet Explor Dev*, 2012, 39: 352–358 [吴奇, 胥云, 王晓泉, 等. 非常规油气藏体积改造技术——内涵, 优化设计与实现. 石油勘探与开发, 2012, 39: 352–358]
- 49 Olson J E, Bahorich B, Holder J. Examining hydraulic fracture-natural fracture interaction in hydrostone block experiments. In: *Proceedings of the SPE Hydraulic Fracturing Technology Conference*. Woodlands Texas: Society of Petroleum Engineers Press, 2012

- 50 Lee H P, Olson J E, Holder J, et al. The interaction of propagating opening mode fractures with preexisting discontinuities in shale. *J Geophys Res: Solid Earth*, 2015, 120: 169–181
- 51 Zhao Y L, Cao P, Wen Y D, et al. Damage fracture failure mechanism of compressive-shear rock cracks under seepage pressure (in Chinese). *J Cent S Univ (Sci Tech)*, 2008, 39: 838–844 [赵延林, 曹平, 文有道, 等. 渗透压作用下压剪岩石裂纹损伤断裂机制. 中南大学学报(自然科学版), 2008, 39: 838–844]
- 52 Potluri N, Zhu D, Hill A. The effect of natural fractures on hydraulic fracture propagation. In: *Proceedings of the SPE European Formation Damage Conference*. Sheveningen Netherlands: Society of Petroleum Engineers Press, 2005
- 53 Cheng W, Jin Y, Chen M, et al. A criterion for identifying hydraulic fractures crossing natural fractures in 3D space (in Chinese). *Pet Explor Dev*, 2014, 41: 336–340 [程万, 金衍, 陈勉, 等. 三维空间中水力裂缝穿透天然裂缝的判别准则. 石油勘探与开发, 2014, 41: 336–340]
- 54 Cipolla C L, Warpinski N R, Mayerhofer M, et al. The relationship between fracture complexity, reservoir properties, and fracture-treatment design. *SPE J*, 2010, 25: 438–452
- 55 Cao P, Yang H, Jiang X L, et al. Subcritical crack growth of rock during water-rock interaction (in Chinese). *J Cent S Univ (Sci Tech)*, 2010, 41: 649–654 [曹平, 杨慧, 江学良, 等. 水岩作用下岩石亚临界裂纹的扩展规律. 中南大学学报: 自然科学版, 2010, 41: 649–654]
- 56 Yan W, Ge H K, Wang D B. Frictional characteristics of shale and their influence on hydraulic stimulating fractures under the effect of fracturing fluids. In: *Proceedings of the China Shale Gas Conference*. Wuhan: China Shale Gas Conference Press, 2015

Key issues and investigation of horizontal well drilling and multistage fracturing in shale gas reservoir

LI GenSheng^{1,2}, SHENG Mao^{1,2}, TIAN ShouCeng^{1,2}, GE HongKui^{1,2},
HUANG ZhongWei^{1,2} & SONG XianZhi^{1,2}

¹ State Key Laboratory of Petroleum Resources and Prospecting (China University of Petroleum-Beijing), Beijing 102249, China;

² Department of Oil and Gas Well Engineering, College of Petroleum Engineering, China University of Petroleum-Beijing, Beijing 102249, China

Unconventional shale gas is rapidly increasing as an available source of natural gas in the world. Horizontal well drilling and multistage fracturing are two principle techniques of shale gas resources production. Benefiting most from these two techniques, the United States, Canada, and China have become only three countries to produce shale gas in commercial quantities. The key technical issues emerged in the horizontal drilling and fracturing involve the rock fragmentation issues, wellbore trajectory optimization and control, wellbore stability, cementing and its quality control for long horizontal lateral, and hydraulic fracturing design. Although some progress associated with those technical issues have been achieved in China, there are still many geologic and engineering challenges: (1) the low rate of penetration and fast bit wearing for both PDC and Cone bits are still the primary issues, which makes hard achieve the “one-trip” drilling; (2) wellbore collapse and lost circulation are serious with a certain collapsing period due to natural fractures system; (3) complex multi-fractures propagation behaviors still need to be understood and the fundamentals of fracturing design should be established after understanding multi-fractures propagation behaviors.

In this paper, three fundamental issues are proposed including the rock fragmentation and high-efficiency drilling techniques, the long lateral wellbore collapsing and its control techniques, and the complex multi-fractures propagation behaviors. The most important thing is to understand multi-physical coupling of work fluid (drilling mud, completion fluid, and fracturing fluid) and shale.

The future investigation would emphasize on three parts. (1) The effects of spontaneous imbibition, thin-film lubrication on micro-cracks faces, and brittleness on shale rock fragmentation: Drilling fluid suddenly flows into pores and micro-cracks due to the spontaneous imbibition. Then a thin-film lubrication layer occurs on the micro-cracks surfaces that reduces the interface friction of the cracks. Thus, the spontaneous imbibition is positive to accelerate the rock fragmentation. (2) The effects of rock-fluid interaction, hydro-mechanical-chemical coupling on wellbore collapsing behaviors: The reasons of shale collapse are different from those of the clay. The natural cracks and weak planes may be the primary contributors for shale collapse. Drilling fluid penetrates into natural cracks and weak planes under the differential pressure, capillary forces, and concentration difference. The fluid lubricates the crack surfaces and make them easier shear slip. Further, the rock-fluid interaction makes the clay minerals swell that reduces the cohesive strength of rock. Consequently, the hydro-mechanical-chemical coupling is strong enough to be considered. (3) The flow pressure assignment and multi-fractures competitive propagation within fracture network: Multi-fractures competitively propagate because of the diversity of the fracture opening pressure and fluid assignment. Fracturing fluid is self-assigned into branch fractures and fluid pressure is time and space dependent, making the net pressure of branch fractures diverse. Meanwhile, fracture opening pressures present the localized character due to the complex naturally fracture system and rock anisotropy. Thus, three fundamental issues should be studied involving the fluid assignment properties, the influence factors of fracture opening pressure, and the competitive propagation mechanisms.

This paper reviews the research progress of the key fundamental issues, and analyzes their possible mechanisms from views of shale rock characterization, hopefully to provide insights on current research status and future emphases.

shale gas, horizontal well, rock penetration, wellbore stability, hydraulic fracturing

doi: 10.1360/N972015-00692