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页岩气储层水平井与压裂工程基础问题探讨

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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

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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填满[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CO_2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侵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.

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

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Unconventional shale gas is rapidly increasing as an available source of natural gas in the worldwild. 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 undstanding multi-fractures propagation behaviors.

In this paper, three fundamental issues are proposed including the rock fragmentaion 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 spontanuous 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 spontanuous imbibition. Then a thin-film lubrication layer occurs on the micro-cracks surfaces that reduces the interface friction of the cracks. Thus, the spontanuous 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 veiws of shale rock charcterization, hopefully to provide insights on current research status and future emphases.

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

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