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评 述 页岩油气高效开发专题

页岩气开发: 岩石力学的机遇与挑战

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摘要 长水平段水平井和分段水力压裂技术是提高我国页岩气单井产量的关键技术. 随着页岩气勘探开发面向深层, 水平井钻完井面临安全钻进风险高、高效压裂难度大和单井产量低且递减快等难题, 问题的核心仍是发展页岩储层断裂、破坏和流动模型, 其本质仍为页岩气储层岩石力学问题. 受机理研究制约, 目前在页岩储层实验测试、裂缝系统与渗流、多场耦合和孔隙弹性等方面仍需要进一步研究与突破. 中国的页岩气开发虽然取得了阶段性的成果, 其面临的问题仍不容忽视, 发展岩石力学相关理论对页岩气开发关键技术有重要的指导意义. 同时, 低油价条件下清洁开发、降低工程成本和提高单井产量是贯穿页岩气全生产周期的关键问题. 本文重点分析页岩气储层力学特征评价、断裂与渗流和流固耦合等机理问题及其研究进展, 介绍页岩储层实验测试、井筒安全和高效开采等关键问题, 讨论未来的研究方向和热点.

关键词 页岩气, 岩石力学, 井壁稳定, 储层改造

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1 引言

随着社会对清洁能源的需求, 页岩气作为新型的清洁非常规天然气资源, 越来越受到关注. 北美作为页岩气革命的先驱, 规模化采用水平井和水力压裂技术使商业化生产页岩气变为现实. 特别是2016年美国在Marcellus气田实现了超长水平段(垂深3000 m, 井深8244 m, 5652 m, Purple Hayes 1号)、超深水平井(垂深4000 m, 井深超10000 m, 水平段1000 m, Scotts Run 591340)钻完井技术的突破, 解决了深层超高压页岩气水平井的技术难题, 大幅度提高了单井产量(年产量15×10^8 m^3), 有望实现天然气井口成本低至6分钱/m^3, 为美国深层页岩气高效开发提供有力的技术保障[1].

中国页岩气储量丰富, 地质资源量为80.21×10^{12} m^3, 可采资源量12.85×10^{12} m^3. 通过学习借鉴及自我研发, 基本具备了中深层(<3500 m)页岩气开发理论基础和相关技术. 截止2016年9月, 全国完钻页岩气井960口, 累积产气114×10^8 m^3, 完成国家"十二五"规划. 随着勘探开发深入, 深层页岩气资源是未来勘探开发的重点, 如四川盆地3500–4000 m页岩气资源量3.5×10^{12} m^3

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(3500 m以浅资源量的2倍多), 可采储量9×10^{11} m^3, 其开采已纳入国家页岩气发展“十三五”规划[2].

与浅层页岩气相比, 深层页岩埋深增加, 温度升高, 全岩矿物发生改变, 构造应力复杂, 应力差增大, 基质强度高, 各向异性和脆性减弱, 页岩弹塑性转换临界深度尚不明确, 给工程地质力学评价、安全钻进、高效压裂和长效开采带来一系列挑战. 如何通过岩石力学科学解决深层页岩开发相关技术难题, 是岩石力学的机遇和挑战[3].

2　地层力学特征的评价

2.1　脆性

页岩脆性是衡量页岩综合力学特征的关键指标, 对井壁稳定和水力压裂具有重要的影响. 现有的脆性评价方法繁多, 主要分为三大类: 实验描述、测井数据和地震解释类[4–7]. 考虑矿物组成, 忽略成岩作用影响, 不能反映页岩温度、压力和裂缝对脆性的影响, 相同矿物的页岩经历不同的成岩过程, 脆性可能差异性大[8]. 基于强度或硬度的脆性评价方法, 不能定量解释页岩剪切或张性裂缝密度规律, 不能揭示其在缝网发育过程中的作用机制. 采用同一组页岩三轴实验数据计算了4种脆度指数, 结果差异明显, 且不同指数与岩石强度或弹性参数均无明显相关性. 因此, 深入探索非连续结构页岩岩体变形破坏机制, 对于构建脆度评价新标准显得尤为重要.

2.2　可压性

可压性通常定义为储层可被有效压裂并增产的潜力[9]. 可压性预测多基于地球物理地震反演技术解释的岩石弹性参数, 如杨氏模量、泊松比和拉梅常数等. 相应的模型基本是这些弹性参数的数学组合. Varga等人[10]利用AVO同步反演方法得到的杨氏模量和泊松比, 定义了脆度并计算其分布规律. Sun等人[11]结合脆度与基于地震反演得到的裂缝分布, 优化选择了适于布井的区域. Metzner[12]发现岩石剪切刚度和体积密度的关系, 可以很好地反映所研究区块的最终采收率, 从而表征可压性优劣. 此外, 地震解释[13]或测井数据分析[14,15]得到的地层岩性与矿物成分剖面, 也可用于表征地层脆度. Guo等人[16]通过各种实验手段评价了页岩储层可压性.

2.3　各向异性

与传统岩石相比, 由于黏土矿物定向排列, 温度和压力条件下有机质成熟度引起的孔隙结构差异性, 成藏过程中高构造应力挤压作用, 导致页岩各向异性特征显著. 波速、弹性模量和泊松比在垂直其层理的方向上要低于平行于层理方向上的值[17–21]. 邓继新等人[20]研究了页岩声速各向异性及其影响因素, 指出平行于层理定向排列的黏土矿物和微裂隙是使样品显示出强弹性各向异性的主要原因. Sarout等人[22,23]在实验室中检测了页岩的弹性波速各向异性, 发现页岩的定向排列的黏土矿物成分与各向异性具有较好的相关性. Homand等人[24]采用动态和静态方法描述了板岩的弹性模量等力学参数. 该类岩石具有明确的非连续的作用于矿物生长线理的平面各向异性特征. 目前, 关于各向异性页岩地层岩石力学、声学性质的研究仍有很大空间, 有待更进一步的研究.

2.4　动态断裂韧性

岩石的断裂韧性是进行水力压裂分析及数值模拟的关键参数之一. 压裂包括I型、II型以及I-II复合型三类问题. I型断裂韧性控制水力裂缝平面延伸, 而II型断裂韧性控制水力裂缝转向弯曲; 控制水力裂缝延伸的机制一般认为是I-II复合型断裂问题. 水力压裂体现为井底压力的迅速增加, 受压岩体实际承受冲击载荷的作用. 采用动态冲击加载试验测得的动态断裂韧性, 能更准确地描述实际储层岩体的裂缝起裂. 李海波等人[25,26]分析了不同剪切速率下岩石节理的强度特性, 并讨论了动载荷作用下的岩体破坏问题, 基于岩石力学理论, Chen和Zhang[27], Al-Shayea等人[28]建立了砂岩断裂韧性测量方法, 金衍等人[29,30]建立了测井解释模型, 解决了深部砂岩地层断裂韧性单一深度测试到深度方向连续分布的难题. 满珂和周宏伟[31]、Zhang等人[32]研究了不同加载速率对应岩石的断裂韧性, 分析了动态断裂韧性与拉伸强度的关系. 但是, 目前尚未发表基于孔隙弹性动力学理论的动态断裂韧性预测理论模型.

2.5　孔隙压力与地应力

孔隙压力与地应力状态是控制劣质储层水力裂缝扩展的两个关键因素, 在很高程度上决定了压裂的成

败. 孔隙压力取决于油、气、水三相在地层孔隙中的能量传输, 同时还受到孔隙流体物质传输例如化学渗透的影响. Mody和Hale[33]利用半透膜渗透压的概念建立了化学势产生的等效孔隙压力模型, Yu等人[34]将化学影响考虑到压力穿透中并考虑了温度对泥页岩稳定的影响, 推导了耦合离子浓度变化的压力传递方程, 根据孔隙压力和热应力来求得总的应力分布, 余夫等人[35]解决了致密碳酸盐岩储层孔隙压力异常高压的预测难题, 将小波变换应用于测井资料并解释了异常高压地层的波速特征. 目前地应力的测试方法主要有水压致裂法、Kaiser声发射效应法、差应变法和多极子测井法等, 每种方法都有各自特有的局限性[36,37]. 这些测试手段假设的地层均质或岩心完整, 而劣质储层强非均质性、强各向异性的特点降低了测试结果的有效性.

3 裂缝系统与渗流问题

3.1 裂缝的起裂与延伸

与传统均质砂岩储层相比, 页岩储层层理及天然裂缝发育、各向异性特征显著, 裂缝的起裂及扩展形态复杂[38]. Shen和Zhao[39]通过考虑流体切应力效应, 建立了水力压裂在边界处完整的应力分布耦合模型, 分析了对称切应力对水力压裂裂缝扩展的影响, 给出了耦合全应力分量条件下水力裂缝扩展、转向及分叉的理论判据. 真三轴试验研究[38,40]表明页岩压裂裂缝不总垂直于最小地应力, 而是呈多方向共同扩展的组合体, Warpinski 等人[41]结合现场微地震监测得到了4种裂缝形态: 单一裂缝、复杂多裂缝、天然裂缝张开的复杂裂缝、复杂的网状裂缝. 压裂缝呈缝网延伸是页岩储层改造缝关键, 研究表明压裂后的缝网几何形态和范围主要受地质及工程因素共同影响[42]. 目前, 页岩的勘探开发对象逐步向深层进军, 随着深度的增加, 页岩气的地质条件发生显著变化[43,44], 其中高温高应力特征引起页岩塑性特征增强, 导致水力裂缝破裂及延伸更加困难, 裂缝的复杂程度及改造体积低, 极大制约了深层页岩气的商业开发. 为此, 建立高温高应力条件下的页岩非线性本构, 实现对裂缝周围应力场的准确描述, 对建立深层页岩的破裂及延伸模型及缝网压裂的分段分簇优化设计具有重要意义.

3.2 物理模拟与数值模拟

在物理模拟方面, Beugelsdijk等人[45]和Zhou等人[46]通过高温加热处理天然岩石模拟随机裂缝网络, 并通过室内试验证实了压后裂缝网络的存在. Fan和Zhang[47], Liu等人[48]研究了水力裂缝在具有不同天然裂缝产状的人造试样中的起裂及扩展规律. Hou等人[38]和Tan等人[40]采用页岩露头开展了压裂物理模拟实验, 研究了地质及施工参数对裂缝扩展形态的影响. 为了实时监测水力裂缝的扩展路径, 侯冰等人[49]和Chitrala等人[50]通过室内试验结合声发射研究了压裂不同阶段过程中的声学响应特征; Guo等人[51]和张然等人[52]结合CT扫描分析了裂缝性地层中天然裂缝的剪切破坏和张开的条件.

在数值模拟方面, 缝网扩展的模拟方法主要涉及扩展有限元、离散元、边界元等方法. Fu等人[53]基于扩展有限元方法, 考虑了天然裂缝与水力裂缝的应力干扰和离散裂缝网络中的流体动力学, 模拟天然裂缝性地层中的水力裂缝扩展过程. Damjanac和Cundall[54]采用离散元方法模拟了三维空间中水力裂缝在三维空间中的扩展过程. Kumar和Ghassemi[55]采用三维位移不连续法, 建立流固耦合条件下水力裂缝分段压裂裂缝扩展模型. Li等人[56]针对缝间应力干扰造成的段内各裂缝非均匀延伸问题, 采用有限元方法建立了综合考虑应力干扰、流固耦合、多裂缝流量分配的分段多簇压裂裂缝动态延伸数值模型.

室内试验研究表明层理对水力裂缝的垂向扩展具有显著的影响, 水力裂缝在垂向上往往也具有复杂的裂缝几何形态[38,40,51]. 页岩体积压裂水力裂缝扩展是一个全三维扩展过程, 传统的压裂模型(PKN, KGD等)将三维裂缝简化为缝高恒定的二维裂缝, 仅研究水力裂缝在水平面内的延伸行为, 忽略了水力裂缝的垂向扩展行为, 运用于层理性页岩储层具有较大的局限性和预测偏差. 因此, 亟需建立全三维裂缝扩展模型, 将影响水平向和纵向扩展的多种因素综合考虑, 以获得最大有效裂缝改造体积和产能为目标进行压裂施工方案设计.

3.3 人工裂缝与天然裂缝

页岩储层压后的复杂裂缝形态是由水力裂缝与页岩中天然裂缝、层理等不连续结构面相互干扰形成

的, 因此有必要明确这些不连续面对水力裂缝延伸路径的影响规律, 建立天然裂缝与人工裂缝的相交作用准则. Lamont和Jessen[57]及Warpinski和Teufel[58]最早开展了天然裂缝对水力裂缝扩展形态影响的室内试验, 分析了水力裂缝逼近天然裂缝的相交角(逼近角)、水平应力差两个参数对水力裂缝延伸影响. Zhou等人[59]定量研究了水平应力差、逼近角、天然裂缝面摩擦系数对水力裂缝破坏机制的影响, 得到了裂缝剪切破坏边界和张开破坏边界. 程万等人[60]考虑了天然裂缝走向, 通过理论分析和室内试验研究了三维空间中水力裂缝穿透扩展行为. Olson等人[61]采用平面玻璃模拟天然裂缝的方法研究天然裂缝网络与水力裂缝的相互干扰. Warpinski和Teufel[58], Renshaw和Pollard[62]及Gu和Weng[63]建立不同假设条件下水力裂缝与天然裂缝的交叉准则, Zhao等人[64]及Chuprakov和Prioul[65]在此基础上考虑天然裂缝面受力状态的变化, 分析了水力裂缝与天然裂缝相交过程的力学行为.

3.4 压裂液的返排

与常规储层相比, 页岩气储层压后返排率普遍偏低, 且与产量呈负相关[66]. 国内外学者在此领域开展大量的研究, 具体表现为三个方面.

(1) 渗吸作用. 研究发现页岩渗吸存在多种驱动力[67–73]. Dehghanpour等人[67]研究发现页岩中黏土水化可提供额外渗吸动力, 黏土膨胀产生微裂缝, 促进渗吸作用; Xu和Dehghanpour[68]发现页岩水湿的孔隙通道可通过渗透率为渗吸提供附加的驱动力; Roshan等人[69]指出表面-渗透水化和毛细管力共同控制水的渗吸, 页岩通过吸水膨胀产生微裂缝.

(2) 次级裂缝闭合滞留作用. Fan等人[70]研究表明压后次级裂缝会发生闭合, 导致压裂液滞留, 降低返排率.

(3) 不稳定驱替与重力分异. Parmar等人[71]通过室内试验系统研究了重力、表面张力和润湿性对支撑裂缝中气驱排水的影响, 研究发现气体指进会降低波及体积, 进而导致低返排率.

Agrawal和Sharma[72]采用三维数值模拟研究了重力对压裂液返排的影响, 研究发现低气流速或者低压差能够显著加剧压裂液在裂缝中的滞留. 页岩气储层裂缝网络是压裂液返排和页岩气产出的通道, 也是压裂液流失和页岩气产出的发生场所, 对返排特征具有关键性影响. 目前研究注重主裂缝的积液返排研究, 对体积压裂的返排特征认识具有局限性, 因此, 建立从缝网结构上理解和分析返排特征等问题.

3.5 裂缝长期有效性

页岩储层基质渗透率极低, 裂缝因其高导流性, 是页岩气藏流体由基质流向井筒的主要通道[73,74]. 人工裂缝与天然裂缝耦合的离散裂缝壁面损伤变形是影响页岩气长效流动机制的关键因素. 随着储层开采, 裂缝系统内压力发生变化, 引起支撑剂破碎、镶嵌压实、裂缝变形闭合, 裂缝导流能力下降, 严重制约页岩储层流体资源的进一步开采.

Engelder和Scholz[75]及Buchsteiner等人[76]曾指出裂缝界面岩石变形引起的裂缝渗透率降低是由于地层压力降低造成的有效应力增加而引起, 并证实了裂缝变形对多孔介质渗流的显著影响. 目前关于缝网岩石应力敏感模型研究, 多简化裂缝形态均匀、单一[77], 通过探寻某一种固定显式函数形式获得裂缝渗透率与有效应力(或者孔隙压力)的相关关系[78], 缺乏对显式离散裂缝网络的界面力学特性和变形机理的研究. 郭建春等人[79]基于API标准导流室, 自行研制了一套支撑剂嵌入程度测试分析系统, 考虑地层碎屑对裂缝导流能力的影响, 对支撑剂嵌入后的岩心进行了微观分析. 但目前关于裂缝导流能力的模型未考虑裂缝界面围岩变形、生产制度对结构体稳定性的长期作用规律. 因此, 理论模型需要重新建立.

4 力学与化学多场耦合页岩井筒破坏

4.1 页岩地层多尺度井壁稳定机理

与传统地层, 页岩富含黏土矿物、多尺度裂缝共存和长水平段钻进的需求, 页岩地层的井壁稳定研究又区别于常规储层, 总体可概括为4个方面.

(1) 水岩作用下页岩强度弱化的宏观力学响应的实验研究. Yew等人[80]和Chenevert等人[81]实验研究了页岩吸水后力学性质的响应特征, 分析了页岩密度、屈服强度、吸水膨胀与吸水量和离子类型与浓度之间的关系. Chen等人[82,83]建立了泥页岩物理力学参数与含水量之间的非线性关系, 在线弹性力学本构的基础采用有限差分求解了井周围岩水化应力.

(2) 考虑到页岩地层微裂隙充分发育的特征, 传统

基于各向同性介质和线弹性假设建立的井壁稳定模型偏保守, 所以国内外进行了一系列考虑力-化-热等多场耦合的多孔介质井壁稳定模型研究. 刘铭等人[84]基于热孔隙弹性理论, 建立了横观各向同性页岩井壁稳定力学模型, 揭示了裂缝产状、摩察系数、温度和钻井工况的井壁失稳控制机制. Ghassemi等人[85]以及Zhou和Ghassemi[86]针对膨胀性页岩, 建立了力-化-热耦合的线性与非线性井壁稳定有限元模型, 研究表明温度增加和盐度降低将显著增大孔隙压力、径向应力和总应力, 对井壁稳定影响显著.

(3) 借助先进的微纳米表征技术观察水岩作用中页岩中微裂隙萌生、贯通和扩展, 及流体对岩石的溶解和溶蚀现象, 分析水岩作用的微观结构损伤与弱化机制, 如图1所示. 马天寿等人[87,88]针对页岩水化问题, 基于CT扫描技术的页岩水化细观损伤特性定量评价方法, 开展了不同水化阶段页岩岩样CT扫描实验, 并分析了页岩水化细观损伤特性.

(4) 借助分子模拟技术进行黏土水化作用导致的岩石弱化的微观动力学机制研究. De Pablo等人[89], Zhang等人[90], Zheng等人[91]对高温高压条件下的Na, K, Ca-MMT进行了MC模拟, 分析了相应温压状态下水化稳定状态. Carrier等人[92]将蒙脱石考虑为横观各向同性介质, 利用MD方法分析了水化过程中弹性性质对温度和含水量的敏感性.

4.2 页岩气渗吸、润湿性

页岩气储层长水平段钻井常发生钻井液超量损失, 对页岩力学性质、微观破裂、井壁失稳和岩石破碎等具有重要影响[93–95]. 与常规储层漏失机理不同, 除了液柱压力引起的压差渗流外, 毛细管力和化学渗透压引起的自发渗吸是钻井液损失的重要动力和组成部分. 同时欠饱和、高盐度和微纳米孔缝发育的特点, 使页岩的自发渗吸作用显著强于常规储层, 所以开展页岩储层的自吸相关研究具有重要作用.

在传统致密砂岩的研究中, 已经发现岩石的自吸效应与岩石的润湿性具有显著的相关性. 但页岩储层油水双亲, 甚至亲油性更强[96]. 常规自吸实验却发现页岩的吸水能力显著强于吸油能力, 且页岩的自吸能力和自吸速率都表现出明显的各向异性[97], 所以对页岩吸液能力评价和温压条件下的井筒工作液进入储层孔隙的微观动力学效应研究有待深入. Dehghanpour等人[94–98]研究了页岩中黏土矿物与有机质含量和润湿性的相关性, 通过对比块状和粉末状页岩的吸水与吸油能力, 认为页岩中不同润湿性孔隙具有不同的分布特征和连通性, 亲水性孔隙的连通性好于亲油性孔隙. Ghanbari和Dehghanpour[99]研究了润湿性与页岩自吸特性的关系, 并结合SEM和EDS发现自吸会诱导裂缝产生, 同时围压对沿层理方向自吸量的影响远大于垂直于层理面. Makhanov[100]和Zolfaghari等人[101]研究了富有机质页岩自吸量与矿物含量、孔隙度和自然伽马值的关系.

4.3 套管损坏机理

统计表明, 大量的套管损坏现象出现在压裂期间. 体积压裂施工过程中, 受到挤压、剪切和弯曲等载荷作用, 套管容易出现变形、破裂和错断等破坏[102,103].

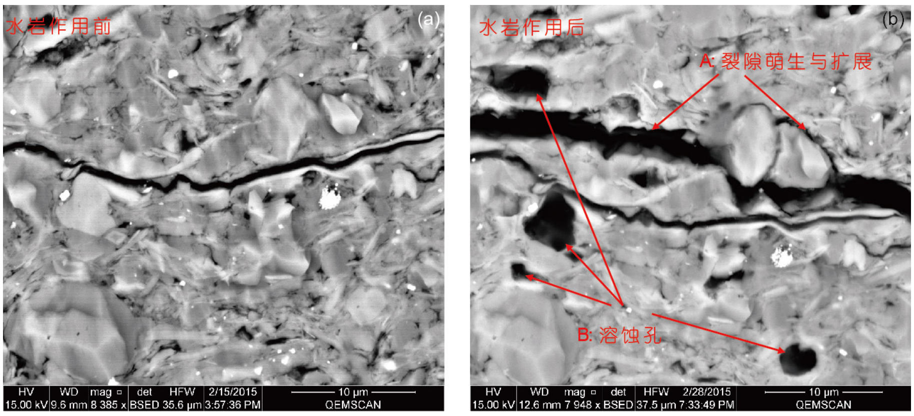

图 1 (网络版彩图)水岩作用后, 页岩中微裂隙的萌生与扩展(A区域)和矿物的溶蚀(B区域)现象
Figure 1 (Color online) Microcracks initiation and propagation (A) and mineral dissolution (B) after water-rock interaction.

国内外学者对页岩气井压裂过程中的套管损坏机理进行了研究. Chipperfield等人[104]和Hossain等人[105]认为体积压裂过程中的套管失效是由水平段套管周围地层的剪切、滑移等复杂的力学行为以及地应力场的变化引发的. 陈朝伟等人[106]分析了长宁-威远示范区压裂过程中套管损坏现象, 认为压裂液进入天然裂缝, 天然裂缝被激活产生滑动, 造成了套管变形. 田中兰等人[107]建立了多因素耦合套管应力计算评价模型, 对页岩层滑移机理及与套管剪切变形的关系进行了分析. 练章华等人[108]和于浩等人[109]建立了分段压裂过程中套管失效的三维有限元模型, 发现体积压裂引起的应力重新分布使局部区域应力降低, 可能出现“应力亏空”的现象, 是导致水平井套管失效的主要原因. 夏阳等人[110]分析了地层-水泥环-套管组合体的动态损坏机制, 认为致密地层更易导致水泥环脱落.

5　孔隙弹性力学

5.1　拟静态问题

掌握页岩储层孔隙压力和有效应力的基本特性是研究页岩气藏井壁稳定、压裂等问题的基础. 多孔弹性理论给出的应力解可以看作达到“平衡解”之前流固耦合的一个动态演化过程, 多孔弹性力学解可在一定时间内分析流体对井壁稳定性的影响. 图2所示为孔隙弹性力学理论下孔隙压力在井周的演变规律, 水平方向为最小地应力方向, 垂直方向为最大地应力方向. 在孔隙弹性力学中, 孔隙压力在最小地应力方向产生高压区, 造成孔隙压力在短期内局部升高, 使井筒更易失稳, 且局部高压随时间向井眼内部耗散, 孔隙弹性效应逐渐减弱.

在孔隙弹性力学中, 孔隙压力对有效应力的影响往往较为明显, 图3和4展示了不同渗透率岩石井周有效应力(径向、环向)的分布规律. 对于渗透率越小的地层, 在最小地应力方位的差应力越大, 这预示着对于页岩这样的低渗透率储层, 在钻井过程中更容易发生井壁延迟失稳, 需要采用更高的钻井液密度预防井壁垮塌[111–113].

5.2　动力学问题

井眼形成瞬间可以看作均匀地应力场中的应力扰动问题, 而应力扰动的传播会形成弹性波. 而应力波动常会引起井壁围岩的瞬时破坏, 此时井壁围岩内位移、应力、应变不仅是空间位置坐标函数, 还是时间的函数, 这样的力学称为弹性动力学. 弹性动力学在地震波动力学和地震勘探中已有了十分成熟的应用, 但其在石油工程方面的应用在国内外甚少研究, 并且常规的弹性动力学没有考虑流体的作用, 并不完全适用于分析饱含流体的多孔弹性体的应力瞬时扰动问题. Biot[114–116]以Terzaghi理论为基础, 提出了描述饱和流体的多孔介质理论模型, 加入适当的惯性项, 给出了饱和多孔介质的波动方程, 基于孔隙弹性力学研究了弹性波在多孔弹性体中的传播问题, 并求得了无旋波和等容波在介质中的传播速度, 但Biot并没有给出位移和应力随时间的变化.

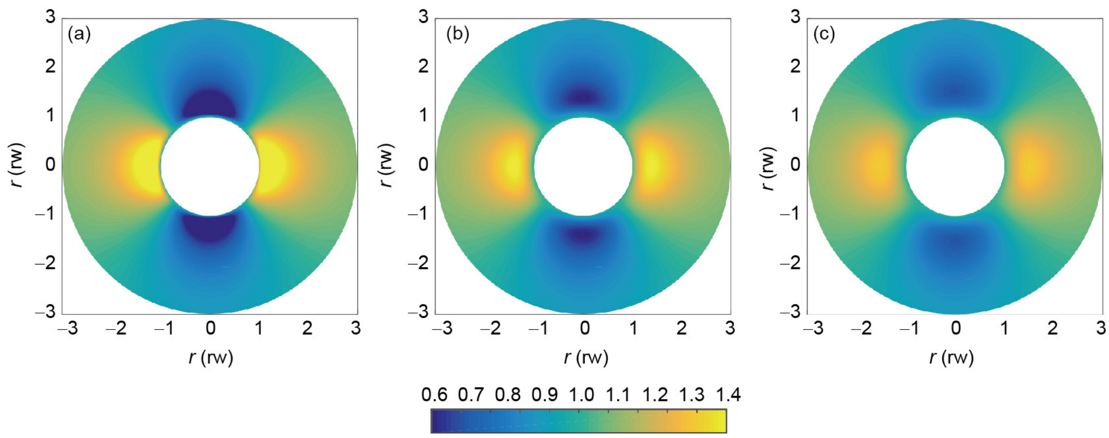

图 2　(网络版彩图)井周孔隙压力随时间变化图. (a) t=0.1 h; (b) t=1 h; (c) t=10 h

Figure 2　(Color online) Pore pressure distribution around a wellbore as a function of time. (a) t=0.1 h; (b) t=1 h; (c) t=10 h.

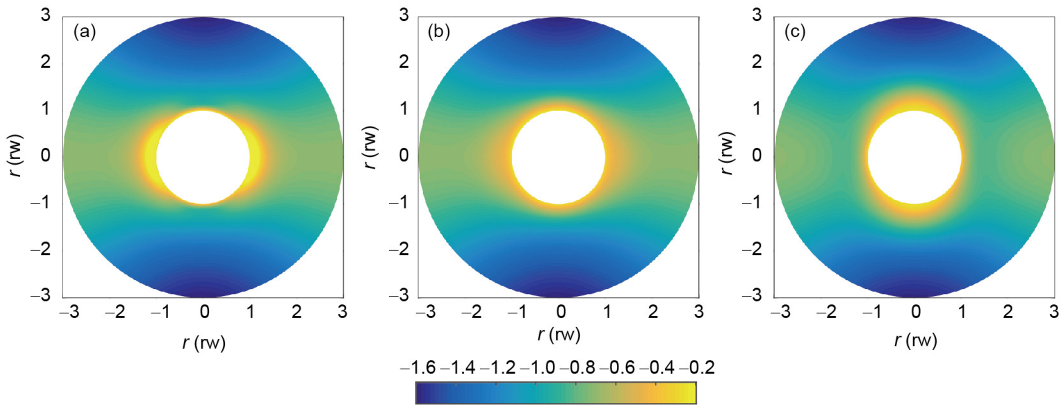

图 3 (网络版彩图)不同渗透率井周有效径向应力分布规律. (a) k=0.1 mD; (b) k=1 mD; (c) k=10 mD
Figure 3 (Color online) Effective radial stress distribution around a wellbore as a function of permeability. (a) k=0.1 mD; (b) k=1 mD; (c) k=10 mD.

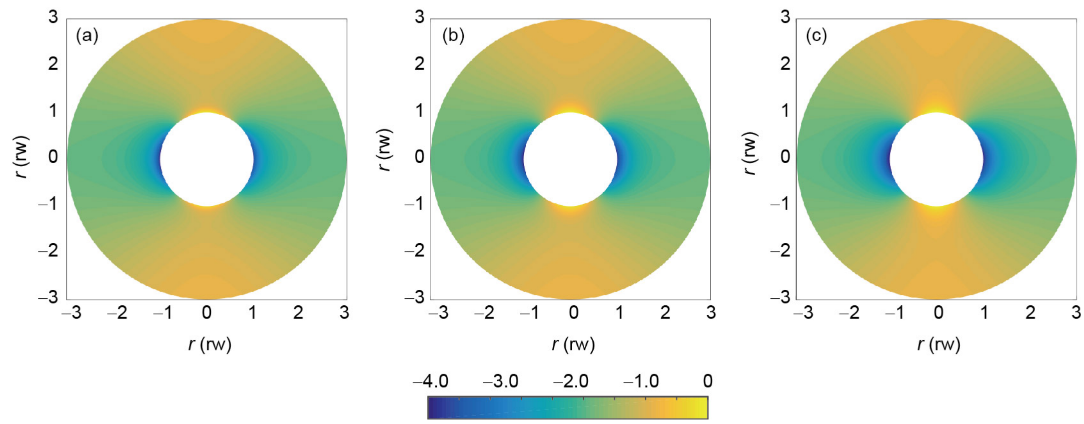

图 4 (网络版彩图)不同渗透率井周有效环向应力分布规律. (a) k=0.1 mD; (b) k=1 mD; (c) k=10 mD
Figure 4 (Color online) Effective circumferential stress distribution around a wellbore as a function of permeability. (a) k=0.1 mD; (b) k=1 mD; (c) k=10 mD.

多孔弹性动力学的基本假设是小变形和均匀初始应力场, 这对于井眼形成时的地层情况是符合的, 图5和6分别展示了静力学与动力学理论下井周拉伸与剪切破坏区域, 在存在应力波扰动的情况下, 井周破坏区域增大, 井周更容易形成微裂隙区域. 因此, 采用动力学理论分析井筒的瞬时失稳是页岩气井安全高效钻井的一个重要方向.

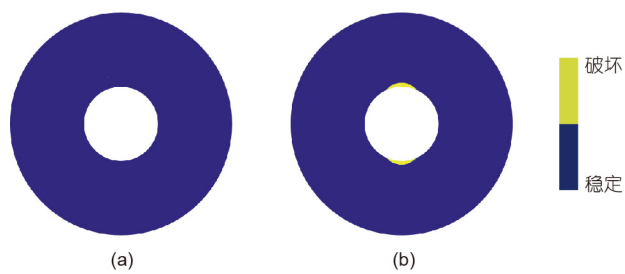

图 5 (网络版彩图)井周拉伸破坏区域. (a) 静力学; (b) 动力学
Figure 5 (Color online) Tensile breakout around a wellbore based on the theory of (a) statics and (b) dynamics.

6 结语

虽然我国页岩气开发取得了阶段性成果, 但是钻完井周期长、压裂改造效果差和开发成本高等问题普遍存在, 其主要原因: (1) 中美页岩气资源地质特征及地表条件等方面的差异, 国外现有技术不能完全适应于我国的地质情况; (2) 我国没有掌握页岩气开发的基础理论. 页岩储层特征的复杂性是明显有别于砂岩、碳酸盐岩储层. 深部页岩具有低渗透、致密、强非均质性、强各向异性等特征, 这不仅决定其特有的物质性和结构性, 也决定了它与其他常规材料在研究

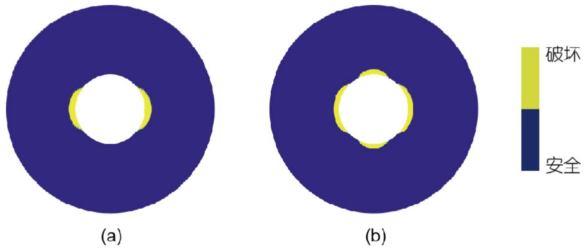

图 6 (网络版彩图)井周剪切破坏区域. (a) 静力学; (b) 动力学
Figure 6 (Color online) Shear breakout around a wellbore based on the theory of (a) statics and (b) dynamics.

方法上的重大差异. 现有岩石力学理论沿用连续介质理论与方法, 难以准确反映页岩非常规岩石力学特征, 许多重要科学问题尚未解决, 相关科学问题还需要深入探讨.

就物性特征而言, 受埋深、温度和压力变化, 深部页岩矿物组分存在差异, 就内部结构而言, 层理、节理及夹层发育, 具有高度的隐蔽性、不确定性和时空变异性. 因此, 如何识别不同尺度空间页岩结构特征成为需要研究的首要关键问题.

就赋存环境而言, 需要研究深部地层复杂的应力环境及高精度的测试方法, 揭示具有强烈构造活动特征的储层异常压力及地应力场形成机制, 建立考虑强烈构造活动和非线性边界条件的地层压力预测及地应力场反演理论; 同时重点考虑压裂改造中裂缝扩展对压裂空间井筒应力扰动规律分析, 建立典型深部页岩地层三维地应力场形成与压裂扰动条件下裂缝扩展模型.

对于深部页岩工程力学特征, 从研究复杂应力条件下深部裂缝岩体的宏细观变形破坏机理和强度特性, 建立非连续页岩岩体宏观力学特性的多尺度理论模型, 突破峰前的力学参数或者峰后的应力衰减程度表征脆性的局限性, 提出科学的脆性指数定义, 建立相应评价方法及分析预测模型, 形成非连续页岩脆度峰后评价理论体系.

对于断裂与流动问题, 研究页岩储层多尺度裂隙网络流动力学规律, 建立复杂裂隙网络三维流动力学模型, 揭示流动的长效机制, 优化高产的裂缝网络特征参数; 研究页岩储层岩石断裂的力学行为, 揭示页岩随机动力裂缝的起裂和延伸机理, 创建页岩油气压裂缝网的调控理论.

围绕页岩气开采涉及岩石力学相关的科学问题, 开展页岩油气流动、水平井钻完井一体化和缝网体长效压裂理论研究, 形成页岩气开发基础理论和原创技术, 为我国页岩气安全高效开采提供理论支撑.

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Shale gas development: Opportunities and challenges for rock mechanics

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Multistage hydraulic stimulations on long-lateral horizontal wells are critical technologies for improving shale gas production in China. With deeper exploration and development in depth, however, more challenges spring up. For example, high risks in drilling and completion, low-efficient stimulation, and rapid production decline, etc. The topics are related with failure and seepage modeling in shale gas reservoirs, for which the nature of the problems is highly focused on rock mechanics. More breakthroughs are excepted in laboratory tests, fracture networks characterization and seepage modeling, multi-field coupling and poroelasticity theories. Although China has achieved initial victory in shale gas development, more challenges remains to be disposed by deepening theories of rock mechanics and industrial innovations. Meanwhile, clean and cost-effective recovery of shale gas is the key role throughout the life-cycle of development. In this paper, we review geomechanics assessments, fracture mechanics, seepage and fluid-solid coupling theories used in shale gas reservoirs. We cover the topics of laboratory tests, wellbore safety and effective development technologies, with discussing the research direction and hotspot in the future.

shale gas, rock mechanics, wellbore stability, reservoir stimulation

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