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页岩气层水-岩作用机理、特征及意义

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摘要:页岩气效益开发依赖水平井分段水力压裂技术,然而水基钻井液、碱性油基钻井液、滑溜水压裂液、前置酸液和氧化性破胶液与页岩发生水-岩作用,潜在影响着钻井过程井壁稳定、压裂改造效果、压后闷井及返排效果。通过系统综述国内外页岩气层水-岩作用机理、水-岩作用下页岩组构响应特征,讨论了水-岩作用对页岩气开发的意义。综述认为,页岩富含水敏性组分黏土矿物等、酸敏性组分碳酸盐矿物、碱敏性组分石英等和氧敏性组分有机质和黄铁矿;页岩矿物组分水解程度极低,但黏土矿物水化膨胀、促缝现象突出;页岩孔隙和裂缝的分布均与化学不稳定组分石英、碳酸盐矿物、有机质和黏土矿物密切相关,化学溶蚀包括酸化溶蚀、碱液侵蚀和氧化溶蚀;水-岩作用下页岩组分溶蚀,诱发孔缝溶扩并劣化岩石力学性质。研究指出,推动工作液配方优化,攻关应用氧化性酸液和氧化性压裂液,有利于提高压裂造缝效果和促进吸附气产出,提高气层采收率;基于闷井压降曲线拐点确定最长闷井时间,构建考虑缝网导流能力保护的控压生产制度,有利于指导气井生产全过程合理控压,延长稳产期,提高单井产量。

关键词:页岩气层;水力压裂;工作液;水-岩作用;氧化;闷井;控压生产

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Mechanism, characteristic, and significance of water-rock interaction in shale gas reservoirs

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Abstract: Horizontal well multi-stage hydraulic fracturing technology makes the development of shale gas reservoirs efficient. However, water-rock interaction between shale rock and the work fluids like water-base drilling fluid, alkaline oil-base drilling fluid, slick-water fracturing fluid, pre-acid fluid, and oxidizing rubber breaking fluid may potentially affect wellbore stability, fracturing stimulation effect, shut-in performance, and flowback efficiency during the drilling process. This paper discusses the signifi-

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cance of water-rock interaction on shale gas development by systematically summarizing the mechanism of water-rock interaction and the response characteristics of shale pore structure under water-rock interaction in shale gas reservoirs in China and abroad. Shale is found rich in water-sensitive components such as clay minerals, acid-sensitive components such as carbonate minerals, alkali-sensitive components such as quartz, and oxidative-sensitive components such as organic matter and pyrite. The hydrolysis of shale components is very poor, while hydration swells and associated fracture generation due to clay minerals are prominent. The distribution of pores and fractures in shale is closely related to the chemically unstable components of quartz, carbonate minerals, organic matter, and clay minerals. Chemical dissolutions include acidizing, alkali, and oxidative dissolutions. The dissolution of shale components under water-rock action induces the dissolution and enlargement of pores and fractures, which also impairs the mechanical properties of rock. It is pointed out that optimizing working fluid, like the application of oxidative-acid and oxidative fracturing fluid, is conducive to improving the fracturing stimulation effect, promoting adsorption gas production, and improving shale gas recovery. Meanwhile, determining the maximum shut-in time based on the inflection point of the pressure drop curve and constructing the pressure control production system considering the protection of the diversion capacity of the fracture network can guide the reasonable pressure control in the whole process of gas well production, extend the stable production period, and increase the production of a single well.

Key words: shale gas reservoirs; hydraulic fracturing; working fluids; water-rock interaction; oxidation; shut-in; pressure control production

富有机质页岩储层蕴含丰富的天然气资源,甲烷气体主要以游离态和吸附态赋存于有机质孔隙、黏土矿物晶间孔隙或粒间孔隙^[1]。页岩气产出通常需经历解吸-扩散-渗流多尺度传输过程,但因纳米孔隙内吸附气解吸-扩散过程缓慢、游离气扩散-渗流阻力大,产出效率极低^[2]。以“甜点段”为目标的水平井分段水力压裂改造技术,通过“人造高渗区,重构渗流场”使得页岩气效益开发^[3-4]。

在页岩气层效益开发全过程中,随着各类工作液包括水基钻井液、碱性油基钻井液、滑溜水压裂液、前置酸液和氧化性破胶液的注入,页岩与这些工作液会发生一系列物理化学反应,导致岩石孔隙结构和岩石力学性质发生改变,即称作水-岩作用。在施工正压差、岩石孔缝毛细管力和渗透压驱动下,工作液渗吸分布使得页岩气层水-岩作用普遍存在,潜在影响着钻井过程井壁稳定、压裂改造效果、压后闷井及返排效果。在页岩气地质-工程一体化开发的背景下,水-岩作用对实现“钻好井、压好井、管好井”的目标构成潜在挑战。

正确深入认识页岩气层水-岩作用机理、特征,有利于指导页岩气井工作液配方优化,推动排采制度优化。目前,针对页岩气层水-岩作用机理、特征的研究已有广泛报道,基于水-岩作用的压后闷井制度优化成为研究热点。为了系统全面地认识页岩气层水-岩作用机理、特征,充分挖掘水-岩作用对页岩气效益开发的启示,笔者通过综述国内外页岩气井常见水-岩作用机理以及水-岩作用下页岩组构响应特征,结合页岩气开发的地质和工程特征,探讨水-岩作用对页岩气开发的意义。

1 页岩气层水-岩作用机理

根据矿物类型的分类原则,页岩矿物组分分为3大类:第①类是黏土矿物;第②类是碳酸盐矿物(包括方解石、白云石);第③类是石英、黄铁矿、长石和磷酸盐矿物^[5]。黏土矿物遇水易膨胀,碳酸盐矿物遇酸易溶蚀,石英及黏土矿物遇碱会发生侵蚀,还原环境沉积产物黄铁矿,有机质易在富氧条件下发生氧化溶蚀。

1.1 中性水溶液

中性水溶液对页岩矿物组分的溶解效率通过水解常数表征:水解常数越小,矿物越难水解(表1)^[6-7]。ALI等实验发现,在65℃条件下页岩粒屑样(粒径约为1 μm)经蒸馏水浸泡21 d后(固液比为1 g:5 mL),各矿物组分水解速率极低、矿物溶解效果不明显(表2)^[8]。

页岩富含由伊利石、伊/蒙间层矿物、绿泥石和高岭石组成的黏土矿物,其晶体结构和物理化学性质决定了页岩强水化能力。水分子和水化阳离子在黏土矿物层或其晶层表面吸附、聚集形成双电层,增大层间排斥力并扩大层间距,造成黏土矿物水化膨胀^[9]。黏土矿物水化膨胀包括表面水化、离子水化和渗透水化3种机理:表面水化是指黏土矿物在表面水化能驱动下对水分子的吸收作用;离子水化是指黏土矿物所含硅酸盐晶片上的补偿性阳离子周围形成的水化壳;渗透水化则起始于前两者之后,由扩散双电层排斥力和渗透压共同作用导致^[10]。所有黏土矿物都会发生表面水化,作用距离

表1 页岩矿物组分的水解机理与水解常数^[7]
Table1 Hydrolysis mechanism and hydrolysis constant of mineral components in shale^[7]

矿物组分	水解反应式	水解常数/(mol/L)
方解石	$\text{CaCO}_3(s) \rightleftharpoons \text{Ca}^{2+}_{(aq)} + \text{CO}_3^{2-}_{(aq)}$	3.8×10^{-9}
白云石	$\text{CaMg}(\text{CO}_3)_2(s) \rightleftharpoons \text{Ca}^{2+}_{(aq)} + 2\text{CO}_3^{2-}_{(aq)} + \text{Mg}^{2+}_{(aq)}$	10^{-17}
石英	$\text{SiO}_2(s) \rightarrow \text{HSiO}_3^-(aq) + \text{H}^+$	$10^{-9.9} \sim 10^{-11.7}$
伊利石	$(\text{K}, \text{H}_3\text{O}, \text{Na})(\text{Al}, \text{Mg}, \text{Fe})_2(\text{Si}, \text{Al})_4(\text{Si}, \text{Al})_4\text{O}_{10}[(\text{OH})_2, (\text{H}_2\text{O})] \rightleftharpoons \text{K}^+ + \text{Na}^+ + \text{Mg}^{2+} + 2 \sim 68\text{Al}(\text{OH})^- + \text{H}_4\text{SiO}_4^+ + 4(\text{OH})^-$	$10^{-45.8} \sim 10^{-73}$
高岭石	$\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4 \rightleftharpoons 2\text{Al}^{3+} + 2\text{H}_4\text{SiO}_4 + \text{H}_2\text{O}$	$10^{-37} \sim 10^{-40}$
钾长石	$3\text{KAlSi}_3\text{O}_8 \rightleftharpoons \text{KAl}_2(\text{AlSiO}_3)_2(\text{OH})_2 + 6\text{SiO}_2 + 2\text{K}^+$	$1.1 \times 10^{-20.04}$
斜长石	$5\text{CaAl}_2\text{Si}_2\text{O}_8 + 2\text{H}_2\text{O} \rightleftharpoons 2\text{Ca}_2\text{Al}_3\text{Si}_3\text{O}_{12}(\text{OH}) + \text{CaAl}_4\text{Si}_2\text{O}_{10}(\text{OH})_2 + 2\text{SiO}_2$	$1.1 \times 10^{15} \sim 2.5 \times 10^{15}$
黄铁矿	$\text{FeS}_2(s) + \text{H}_2\text{O}(l) \rightarrow 4\text{Fe}^{2+}_{(aq)} + 7\text{S}^{2-} + \text{SO}_4^{2-}_{(aq)} + 8\text{H}^+$	$10^{-15.2} \sim 10^{-17.6}$

表2 北美页岩水解前后的矿物组成对比^[8]
Table2 Comparison of mineral components before and after hydrolysis of shale samples from North America^[8] %

页岩产地	岩样类型	矿物组成及含量													
		方解石	白云石	石英	钾长石	斜长石	黄铁矿	磷灰石	沸石	石膏	蒙脱石	绿泥石	高岭石	伊利石	伊/蒙间层
Barnett	水解前	0	0	29	0	0	0	10	0	0.5	5	5	0	33	15
	水解后	0	0	29	0	0	0	9	0	0	4	3	0	29	21
Marcellus	水解前	32	5	30	0	0	5	1	0	0.2	0	0	0	19	5
	水解后	32	5	30	0	0	5	0	0	0	0	0	0	19	4
Eagle Ford	水解前	63	4	22	0	0	0	1	0	4	0	0	5	0	0
	水解后	65	3	21	0	0	0	0	0	0	0	0	5	0	0
Green River	水解前	0.4	74	5	4	0	0	0.6	5	0.4	0	0	0	4	4
	水解后	0	76	5	4	0	0	0	5	0	0	0	0	3	4

约为1 nm;渗透水化作用距离大于10 nm,且体积膨胀大、膨胀压小,平衡所需时间长^[11]。

1.2 碱液

相比水基钻井液,油基钻井液抗污染能力强、抑制性强且有利于保持井壁稳定,目前已广泛应用于页岩气井。为保证油基钻井液的流变性和各种处理剂的活性,通常使用烧碱或石灰调节钻井液pH值,油基钻井液pH值一般大于9^[12-13]。

页岩因黏土矿物含量高、矿屑颗粒微小,易发生碱液侵蚀^[12-13]。在碱性环境中,石英、长石和黏土矿物的溶蚀速率随着碱液pH值的升高而增加^[14]。在pH值为2.0~8.5时,石英溶蚀率保持不变;随着pH值的增大,溶蚀率急剧增大,同时温度升高也会提高溶蚀率^[15]。长石通常情况下能与一定浓度的氢氧化钠(NaOH)溶液反应。碱液会侵蚀高岭石、蒙脱石和伊利石等黏土矿物,其中高岭石被侵蚀后会生成非晶硅、三水铝石、钠长石和方沸石^[12]。反应方程式比较复杂,甚至多步反应相互关联。页岩矿物组分碱液侵蚀强弱序列为:蒙脱石>高岭石>伊利石>斜长石>石英>正长石^[16]。页岩与碱液发生反

应,反应生成物组分以硅酸盐矿物为主,含少量的碳酸盐化合物和氢氧化物^[17]。KANG等实验发现,四川盆地龙马溪组页岩与碱液反应十分缓慢,碱液浓度、温度二者均与反应速率呈正相关,分别符合幂函数和指数函数关系^[18]。

1.3 酸液

作为储层增产改造的常用工作液,酸液可直接侵入页岩的微孔缝,引发多种复杂反应。碳酸盐矿物暴露于酸性环境时具有高度活性,盐酸与方解石反应迅速,而与白云石反应相对较慢。GONNENTHAL等通过开展60℃条件下单矿物与酸液(pH=4)反应实验发现,方解石的反应速率为 $10^{-5} \sim 10^{-3} \text{ mol}/(\text{m}^2 \cdot \text{s})$,白云石反应速率为 $10^{-7} \sim 10^{-5} \text{ mol}/(\text{m}^2 \cdot \text{s})$ ^[19]。当盐酸侵蚀绿泥石晶层时, Al^{3+} 、 Mg^{2+} 和 Fe^{2+} 离子的浸出会导致绿泥石的过度溶解^[20],同时 H^+ 离子还会导致绿泥石矿物表面的整体溶解^[21]。高岭石表面整个晶格中几乎没有同晶取代现象,因而具有非常高的酸化稳定性,一般仅与高浓度(约为21%~26%)的盐酸在高温下发生化学反应^[22]。页岩组分伊利石与盐酸反应,其整体结构

会被破坏,并从页岩表面被完全剥落^[23]。伊利石酸化反应产物是微粒运移的主要来源,会导致储层内孔喉堵塞和渗透率降低^[24]。此外,高温环境也有利于伊利石、绿泥石和钠长石的酸化溶蚀。BLACK等实验发现,60℃条件下钠长石在pH=4的酸液中反应速率大约为 10^{-10} mol/(m²·s);黏土矿物的反应速率为 10^{-14} ~ 10^{-10} mol/(m²·s),且高岭石和伊利石的反应速率高于绿泥石和蒙脱石^[25]。黄铁矿是硫化矿物家族中最常见的矿物之一,可以被盐酸有效地溶解。

1.4 氧化性流体

黑色页岩地层由于构造抬升暴露于地表后,随着氧化-还原电位的升高,有机质、黄铁矿赋存的化学平衡被破坏,极易在富氧地表水作用下发生氧化分解反应^[26]。有机质与黄铁矿氧化过程形成的酸性水,不仅造成碳酸盐矿物的溶蚀,还会导致长石、伊利石、绿泥石矿物中的金属阳离子溶出以及硅酸盐矿物水解。石英在酸性、氧化条件下均不易被分解。如表3所示,对比分析地表环境下黑色页岩组分的稳定性发现,有机质和黄铁矿是主要风化氧化对象。

过氧化氢(H₂O₂)、过硫酸铵(Na₂S₂O₈)和二氧化氯(ClO₂)等氧化剂已被广泛应用于油气钻井、完井、增产改造和提高采收率等环节^[28-30]。MIKUTTA等实验揭示了H₂O₂、Na₂S₂O₈和次氯酸钠(NaClO)溶液对土壤中有机的溶蚀能力^[31]。煤岩有机质氧化降解伴随着烯烃的生成和脱羧基反应,且随着氧化程度的增加,依次发生脱羧反应和开环反应^[32]。已有实验证实,NaClO/H₂O₂对页岩组分有机质、黄铁矿及碳酸盐矿物的溶蚀^[33-34]。在H₂O₂分子氧化黄铁矿过程中,S₂O₂²⁻和S₂O₃²⁻等硫代硫酸盐优先生成,然后被进一步氧化为硫酸盐或分解为单质硫和亚硫

酸氢盐^[35]。页岩氧化反应速率与H₂O₂溶液浓度呈幂函数关系,与温度呈指数函数关系;当H₂O₂溶液质量分数为2%~10%时,龙马溪组页岩氧化活化能为3.51~12.10 kJ/mol^[36]。

2 水-岩作用下页岩组构响应特征

根据页岩气井常见工作液的化学性质,水-岩作用可划分为2类:非化学溶蚀和化学溶蚀。非化学溶蚀主要指中性水溶液与页岩相互作用,虽然页岩矿物组分解程度极低,但黏土矿物水化膨胀致裂现象突出。化学溶蚀包括酸化溶蚀、碱液侵蚀和氧化溶蚀。页岩孔隙结构复杂,孔隙类型包括有机质孔、黏土矿物孔和脆性矿物晶间孔,且层理和微裂缝发育,这些孔隙和裂缝的分布均与化学不稳定组分石英、碳酸盐矿物、有机质和黏土矿物密切相关^[37]。

2.1 水化致裂

硬脆性泥页岩具有较显著的毛细管效应,同时岩石矿物颗粒间微孔隙吸水后产生较强的水化膨胀作用,协同促成微裂纹产生、扩展与连通。微裂纹不断发展成裂缝并贯通,使岩石最终发生宏观破坏^[38]。断裂力学理论认为,材料的破坏源于内部微裂缝的产生、扩展和贯通。页岩胶结致密但微裂缝发育,黏土矿物水化产生的膨胀应力易在裂缝尖端形成应力集中,随着膨胀应力不断变大,一旦超过裂缝尖端临界应力强度因子,微裂缝不断扩展导致页岩破裂、垮塌^[39-40]。水-岩作用不仅会诱使页岩表面非黏土矿物颗粒脱落,形成孔径跨度从几微米到几十微米的无机孔隙,还会导致有机质与无机矿物之间、无机矿物内部产生或衍生出微裂缝^[41]。LIANG等通过建立考虑水化和润湿性(毛细管效

表3 地表环境下页岩组分稳定性与风化机理^[27]
Table3 Stability and weathering mechanism of shale components in surface environment^[27]

组分类型	组分名称	风化稳定性	化学反应类型	风化中的主要化学反应
还原性组分	有机质(C)	不稳定	氧化	$C + H_2O + O_2 \rightarrow CO_3^{2-} + 2H^+$
	黄铁矿	不稳定	氧化	$FeS_2 + 3.5O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$ $Fe^{2+} + 0.25O_2 + H^+ \rightarrow Fe^{3+} + 0.5H_2O$
	菱铁矿	不稳定	溶解、氧化	$FeCO_3 + 2H^+ \rightarrow Fe^{2+} + CO_2 + H_2O$ $Fe^{2+} + 0.25O_2 + H^+ \rightarrow Fe^{3+} + 0.5H_2O$
碳酸盐矿物	方解石	不稳定	溶解	$CaCO_3 + 2H^+ \rightarrow Ca^{2+} + CO_2 + H_2O$
	白云石	不稳定	溶解	$CaMg(CO_3)_2 + 4H^+ \rightarrow Ca^{2+} + Mg^{2+} + 2CO_2 + 2H_2O$
硅酸盐矿物	长石	次稳定	水解	长石→高岭石
	黏土矿物	次稳定	水解	伊利石→蛭石、绿泥石→蛭石→高岭石+铁的氧化物或氢氧化物
其他	石英	稳定		

应)的页岩裂纹扩展模型,认为页岩水化对应力强度因子增量的影响较大,易造成页岩微裂缝扩展^[42]。杨斌通过建立毛细管力作用下的页岩裂缝尖端机械能释放率计算模型,定量阐述了毛细管力作用下裂缝发生亚临界扩展的力学机理,解释了室内常见的页岩吸水起裂现象^[43]。

在储层条件下,无机孔隙呈现为黏土矿物与非黏土矿物颗粒之间的微裂缝,易造成页岩水化损伤^[44]。水化损伤主要沿页理面或原生裂缝发育方向延伸,可分为3个阶段:大孔隙裂纹发展阶段、小孔隙产生伴随大孔隙裂纹加剧扩展阶段、小孔隙加剧扩展伴随大孔隙裂纹归并贯通至水化破坏阶段^[45]。微观尺度的水化损伤在黏土矿物表面水化、离子水化和渗透水化共同作用下逐渐演变为宏观破裂,反映为岩石局部力学强度的连续性损失。黏土矿物含量越高,发生水化损伤的可能性越大,页岩结构破坏越严重且破坏发生的时间越短^[46]。水化损伤会加剧页岩在应力作用下的宏观破裂。在较高各向同性压应力条件下,页岩水化不易产生裂缝,而是导致微裂缝趋于闭合;而在低各向同性压应力条件下,水化诱致裂缝优先沿页理萌生,并使已有裂缝重新开启或扩展^[47-48]。相比各向同性压应力,各向异性压应力有利于形成水化诱致裂缝,且应力各向异性越大,水化诱致裂缝的几何形状越大,形成的裂缝也越多^[49-50]。LIU等采用离散单元法(DEM)模拟,通过研究应力各向异性条件下非均质页岩中黏土矿物膨胀对裂缝生成和孔隙度变化的影响,证实应力各向异性促进了水-岩作用过程中裂缝的产生^[51]。

2.2 碱液侵蚀

碱液强烈侵蚀页岩表面矿物,产生大量侵蚀孔^[18],增加页岩内部纳米孔隙体积和比表面积,使岩石结构变疏松、岩石抗压强度大幅下降,进而导致岩体裂缝扩展和缝宽增大,增强页岩裂缝应力敏感性^[18]。康毅力等研究指出,钻井液侵入诱发的水化膨胀和碱液侵蚀是页岩化学损伤的主要形式,也是诱发脆性页岩破裂失稳的直接原因^[52]。由于氢氧根(OH⁻)浓度对非膨胀性页岩水化有很大的积极影响,碱液侵蚀还会促使页岩水化膨胀。当NaOH或KOH溶液趋于中性时,页岩水化膨胀较强;pH值为8~9时,水化分散降低;pH值大于9时,水化膨胀再次得到增强^[53]。富有机质页岩水化能力随溶液pH值增加而增强,碱液侵蚀作用、碱性水溶液侵入增强黏土矿物水化,加剧裂缝扩展延伸^[54]。

2.3 酸化溶蚀

美国Bakken地区页岩经酸液处理后产生了大量溶蚀孔,其中最大孔径高达120 μm,孔隙连通性得到显著提高^[55]。MORSY等利用CT扫描对比观察了北美不同地区页岩经酸液处理后的孔隙度变化,发现富碳酸盐矿物页岩(Eagle Ford页岩)酸化溶蚀后孔隙度提高幅度最大,富黏土矿物页岩(Barnett页岩)的孔隙度减小(表4)^[56]。

酸液处理后,页岩内部通常会出现3类微裂缝:应力诱导缝、酸化收缩缝和酸化溶蚀缝。对于富黏土矿物页岩,酸化溶蚀使高岭石和绿泥石/黑云母区边界处产生更为明显的应力诱导微裂缝,而绿泥石区以酸化收缩缝为主;对于富碳酸盐矿物页岩,酸化溶蚀缝分布在硬石膏区、方解石区、伊利石区和有机质区^[57]。受页岩中碳酸盐矿物的分布影响,酸化溶蚀会改变岩石内部微结构如微裂隙、微孔洞以及节理,影响页岩矿物颗粒胶结强度、岩体强度和变形及破坏特征^[58]。MORSY等在93 °C条件下开展Eagle Ford页岩与稀盐酸溶液反应实验,发现反应后的岩样弹性模量降低了25%~82%^[59]。酸损伤后页岩硬度降低、微观结构变化均受反应矿物分布的影响^[55]。酸化溶蚀导致页岩力学强度的劣化,降低岩石破裂压力,有利于强化水力压裂改造效果^[60]。

2.4 氧化溶蚀

地表页岩风化的主要对象为有机质和黄铁矿,氧化反应过程产生的酸性水又导致碳酸盐矿物的溶蚀。在酸性水侵蚀下,矿物组分溶解、次生矿物

表4 北美页岩酸液处理后质量损失和孔隙度变化^[56]
Table4 Mass loss and porosity change after acid treatment of shale samples from North American^[56] %

页岩产地	盐酸质量分数	溶蚀量	初始孔隙度	酸化孔隙度	孔隙度变化率
Marcellus	0.8	2.06	1.89	2.00	5.82
	1.4	2.32	1.56	1.41	-9.12
	3.0	2.71	2.11	1.29	-38.86
Barnett	0.8	4.51	3.56	2.12	-40.45
	1.4	5.03	5.89	2.59	-56.03
	3.0	9.79	2.44	10.47	329.10
Mancos	0.8	7.73	2.67	3.29	23.22
	1.4	9.79	1.09	2.59	137.61
	3.0	11.86	0.78	2.71	247.44
Eagle Ford	0.8	8.12	1.89	2.71	43.39
	1.4	22.68	0.33	2.00	506.06
	3.0	49.87	1.78	27.29	1 433.15

生成及离子交换吸附作用,促使矿物成分发生转变和矿物颗粒间的连接方式发生改变,岩石内部产生大量微孔隙^[61]。

KUILA等选取东欧志留纪页岩、Haynesville页岩、北美古生代页岩、Marcellus页岩和波罗的海盆地页岩岩样,基于低压气体吸附、X射线衍射(XRD)、岩石热解和氮气吸附等方法,对经NaClO溶液处理后的页岩孔隙结构进行了表征,发现热成熟度高的富有机质页岩中有机质的溶蚀,使得孔径小于5 nm的孔隙体积明显减小,而孔径大于10 nm的孔隙体积明显增加^[62]。ZHU等采用相同的手段对经H₂O₂溶液处理后的中国鄂尔多斯盆地延长组页岩进行了孔隙度、有机质和矿物学特征分析,发现页岩TOC降低与孔隙体积增加呈正相关^[63]。CHEN等实验发现,龙马溪组露头页岩经H₂O₂溶液充分反应后,纳米孔隙平均孔径从4.9 nm增至24.5 nm,纳米孔隙体积(孔径<193.5 nm)从0.025 cm³/g增至0.041 cm³/g,整体孔隙体积从0.015 cm³/g增至0.079 cm³/g^[33]。HULL等观察页岩经氧化液浸泡前后的原位SEM,发现页岩表面的黄铁矿与有机质氧化溶蚀,原位生成溶蚀孔缝^[64]。氧化溶蚀不仅加速微裂缝亚临界扩展,提高页岩水化致裂效率,还造成页岩氧化损伤,加剧其在轴向应力作用下产生宏观破裂^[65-66];页岩裂缝柱样经蒸馏水浸泡后渗透率提高0.42~6.15倍,而经氧化液浸泡后渗透率提高5.53~65.45倍,且裂缝应力敏感性略有减弱^[67]。

3 水-岩作用对页岩气开发的意义

基于地质-工程一体化的开发理念,川南页岩气开发已经形成“定好井、钻好井、压好井、管好井”的四好做法。井壁失稳是钻好井的最大障碍之一,提高缝网的复杂程度是压好井的重要指标,合理的排采制度设计是压后管好井的重要抓手。围绕水-岩作用诱发井壁失稳的机理与防控,已有大量研究报告^[17,52,54,68-69]。为此,主要针对强化压裂改造和闷井稳产效果,瞄准工作液配方优化和页岩气井排采制度优化,探讨水-岩作用对页岩气开发的潜在意义。

3.1 工作液配方优化

聚焦页岩气井压裂改造过程用到的前置酸液和滑溜水压裂液,探讨能强化前置酸液降破功能的氧化性酸液和促进吸附气解吸的氧化性压裂液。

3.1.1 氧化性酸液

为增强水力压裂改造效果,现场施工通常会预

先向页岩储层泵入适量酸液,通过溶蚀碳酸盐矿物或其他岩石胶结物,降低岩石的破裂压力^[60]。储层岩石破裂压力主要受岩石矿物组成、含量及分布控制。据裸眼完井条件下产生垂直裂缝或水平裂缝的岩石破裂压力计算公式分别为:

$$P_{bv} = \frac{3\sigma_H - \sigma_h + \sigma_f - 2\eta P_o}{1 + \phi_c - 2\eta} \quad (1)$$

$$P_{bh} = \frac{P_{ob} + \sigma_f - 2\eta P_o}{\phi_c - 2\eta} \quad (2)$$

其中:

$$\eta = \frac{\phi(1 - 2\nu)}{2(1 - \nu)} \quad (3)$$

式中: P_{bv} 为垂直裂缝破裂压力,MPa; σ_H 为最大水平主应力,MPa; σ_h 为最小水平主应力,MPa; σ_f 为岩石单向抗拉应力强度,MPa; P_o 为孔隙内流体压力,MPa; ϕ_c 为岩石接触点孔隙度,%; P_{bh} 为水平裂缝破裂压力,MPa; P_{ob} 为上覆压力,MPa; ϕ 为岩石孔隙度,%; ν 为泊松比。

由式(1)~(2)可知,对于某一特定储层,岩石破裂压力与接触点孔隙度、泊松比和单向抗拉应力强度密切相关^[70]。宏观尺度上,岩石矿物组分的化学溶蚀会削弱岩石胶结强度,从而使岩石的内聚力降低和内摩擦角减小;微观尺度上,宏观裂缝的产生通常源于岩石内部大量微裂缝在应力作用下逐渐扩展、汇集和贯通,并在积累到一定程度后形成宏观破裂。

类比酸化溶蚀的降破机理,根据JY1HF页岩气井储层基本物性参数(表5),基于页岩氧化溶蚀过程孔径的变化,利用式(1)计算表征了氧化溶蚀过程岩石破裂压力变化(表6),揭示了氧化溶蚀对页岩储层岩石的降破效果。考虑H₂O₂等酸性氧化剂能与稀盐酸等酸性液体共存,酸性氧化液(或酸液与氧化液的混合液)对页岩的化学溶蚀将比单一酸液具有更强的化学损伤降破效果。

3.1.2 氧化性压裂液

统计分析了四川盆地某页岩气区块300余口老井的生产规律,这些井均采用10~13 mm油嘴放压生产,井均EUR(预测的20 a累积产气量)为1.13×10⁸ m³,井口压力递减快,无稳产期,产量表现出快速递减、缓慢递减两段式特征,依次对应套管生产阶段和油管生产阶段。在套管生产阶段,初始井口压力为26.6 MPa,日均压降为0.07 MPa/d,日产气量为10.1×10⁴ m³/d,年递减率为67%,采出28%的EUR;在油管生产阶段,初始井口压力为6.6 MPa,日均压降为0.01 MPa/d,日产气量为5.2×10⁴ m³/d,

表5 JY1HF页岩气井储层基本物性参数^[71]
Table5 Basic parameters of reservoir physical properties of shale gas Well JY1HF^[71]

井深/m	垂向应力/MPa	泊松比	抗张强度/MPa	最大水平主应力/MPa	最小水平主应力/MPa	孔隙弹性常数	孔隙压力/MPa
2 450	61.50	0.25	3.50	63.5	47.4	0.9	35.7

表6 页岩氧化溶蚀过程岩石破裂压力计算
(接触点孔隙度来源于文献[33])

Table6 Calculation of rock rupture pressure during shale oxidation solution (Contact point porosity obtained from Reference[33])

岩样类型	接触点孔隙度/%	P_{bv} /MPa
原样	3.90	144
氧化处理5 h	10.14	135
氧化处理24 h	135	124

年递减率为35%，采出14%的EUR，剩余58%的EUR则需要通过工艺措施如增压、泡排、柱塞等来获得。

从生产制度的执行来看，该区块气井生产初期(前2年)执行定产降压制度，后期转为定压降产制度。定压降产阶段井口压力从3.22 MPa逐年递减至2.32 MPa，日产气量从 $2.8 \times 10^4 \text{ m}^3/\text{d}$ 逐年递减至 $0.4 \times 10^4 \text{ m}^3/\text{d}$ (图1a)，累积产气量为 $5\,944 \times 10^4 \text{ m}^3$ (图1b)，占气井EUR的54%。分析认为，页岩气开采初期以裂缝网络中的游离气产出为主，且保持较高的日产气量；随着地层压力快速降低，吸附气开始急

剧解吸产出，对压裂缝网实现有利的补给供气，使得生产后期表现为递减率降低、持续长时间稳产特征^[72]。何希鹏等通过分析中国渝东南彭水-武隆地区常压页岩气井生产特征，证实吸附气更早解吸产出有助于相对减缓气井产量递减速率^[73]。

页岩中吸附气含量占比为20%~85%，主要赋存于纳米级有机质孔隙和无机孔隙，各类孔隙吸附能力高低呈如下规律：有机质孔隙>黏土矿物孔隙>石英孔隙^[74]。页岩甲烷吸附量与TOC呈线性正相关，TOC高的页岩具有更大的比表面积，可以为甲烷分子提供更多吸附位点^[75]；页岩中吸附气的赋存通常与孔径小于5 nm的纳米孔隙相关，有机质为吸附气提供更多纳米孔隙体积，氧化溶蚀对有机质分子结构的破坏以及对页岩微纳米孔隙结构的改善，有利于降低页岩中对甲烷的吸附量^[62]。同时，孔隙表面形成的水膜能改变甲烷吸附的相互作用特性，水分子通过毛细管凝聚占据孔隙空间，减小甲烷吸附的有效表面积^[76-77]，表现为页岩湿样对甲烷分子的吸附量相对降低^[74]。类比常规压裂液置换吸附气的行为，有机质氧化溶蚀会强化页岩水相吸附能力^[78]，因此氧化性压裂液有利于促使吸附气解吸，潜在提高页岩气层采收率。

此外，针对压后闷井期间缝内流体压力随着压裂液滤失而逐渐降低，杨斌通过开展页岩吸水促进裂缝扩展的数值模拟研究，认为在缝内流体压力降低到储层最小水平主应力之前，水-岩作用对增强闷井效果的贡献均存在^[43]。在此基础上，氧化性压裂液将在现有水化致裂的基础上，进一步增加闷井致裂效果，增加缝网密度。

3.2 页岩气井排采制度优化

页岩气井在水力压裂改造后，将依次历经闷井、返排和生产3个主要阶段，本节主要探讨考虑水-岩作用的闷井制度和控压生产制度的优化。

3.2.1 闷井制度优化

当前，页岩气井压后闷井制度的制定主要基于2方面考虑：支撑剂回流控制、水化致裂的压后持续改造和水化诱发的储层损害如水相圈闭损害。现场应用方面，支撑剂回流控制遵循页岩气井停泵后缝内流体压力降低到闭合压力以下，作为最低开井要求，即闷井时间的下限。室内实验方面，主要基

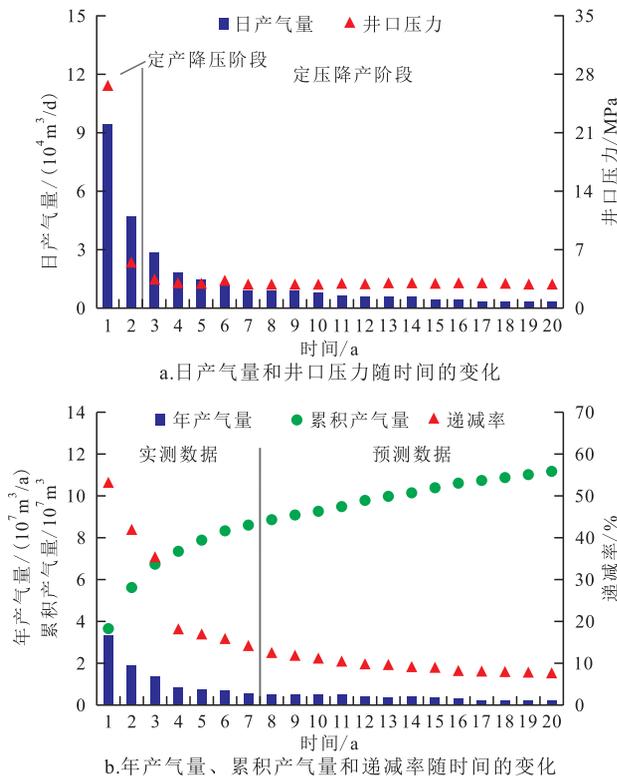


图1 四川盆地某页岩气区块气井生产规律表征
Fig.1 Production regularity characterization of wells in a shale gas block in Sichuan Basin

于水-岩作用下储层微改造和水相渗吸诱发储层损害的双重效应,进而确定闷井时间的上限。

闷井期间,压裂液沿着压裂缝网渗吸扩散,对应缝内流体压力的衰减。早期水相由压裂缝网向次级裂缝分布,表现为压降幅度大、压降速率快。在此过程中,水-岩作用致裂页岩会增加次级裂缝密度、提高水相赋存空间,有利于促进水相渗吸分布^[79],可维持较大的压降幅度、较高的压降速率;随着缝内流体压力持续降低,渗吸造缝能力逐渐减弱,水相沿裂缝面扩散进入孔隙占主导,导致水相分布效率降低,表现为压降幅度减小、压降速率放缓。这意味着整个过程会出现压降拐点即渗吸造缝效率达到峰值(图2)。

为了验证这一观点,通过选取四川盆地某页岩气区块同一区域内9口生产气井,统计闷井期间井口压力随时间的变化规律,并进一步对闷井压力与时间的对数关系求导,作出闷井压降速率变化规律示意图(图3),发现在相同时间段压降速率也出现拐点。分析认为,在拐点之前,水-岩作用致裂占主导,延长闷井的利大于弊;在拐点之后,水相滞留诱发的储层损害占主导,过度闷井的弊大于利。因此,拐点的确定有利于指导最长闷井时间的优化设计。

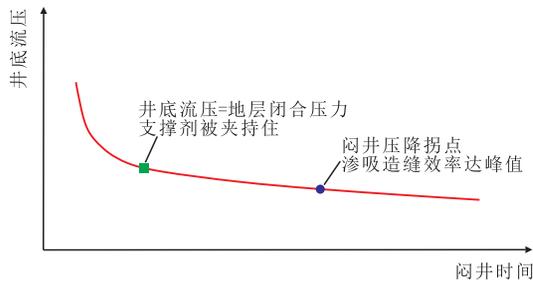


图2 页岩气井合理闷井时间判断图版

Fig.2 Judgment on reasonable shut-in time of shale gas well

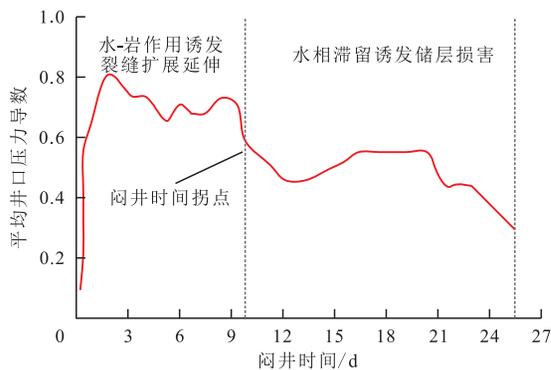


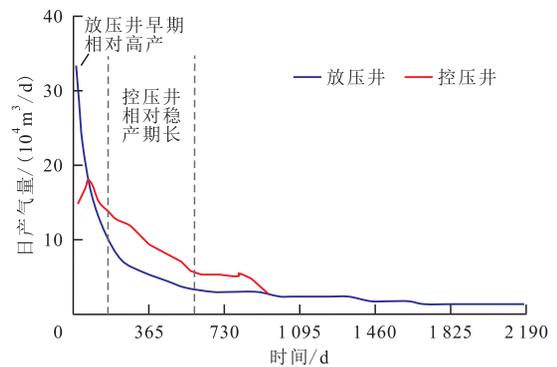
图3 四川盆地某页岩气区块平均井口压力导数与闷井时间的关系

Fig.3 Change of average wellbore pressure derivative with shut-in time for wells in a shale gas block in Sichuan Basin

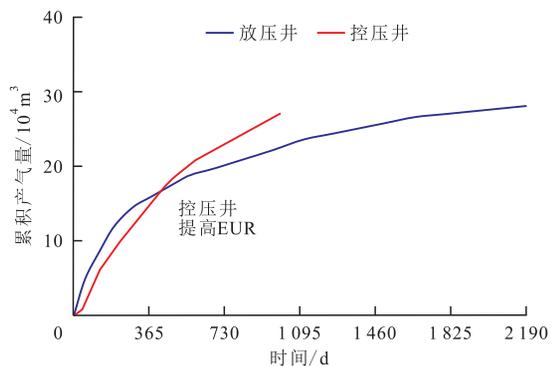
3.2.2 控压生产制度优化

在控压生产制度下,通过将气井生产压差逐渐增加到最大,以期延缓裂缝导流能力的衰减,气井产量呈逐渐增加至峰值后逐渐减小趋势^[80]。虽然页岩气井初期日产气量及累积产气量偏低,但为气井生产创造了一段相对高产的稳产期(图4a),从而获得相对更高的EUR(图4b)^[81]。北美 Hensivery 盆地页岩储层地层压力较高,与中国四川盆地页岩储层地层压力相当,裂缝应力敏感性强,该地区页岩气井实施控压生产制度后,单井EUR相比实施前平均提高了28%^[80]。

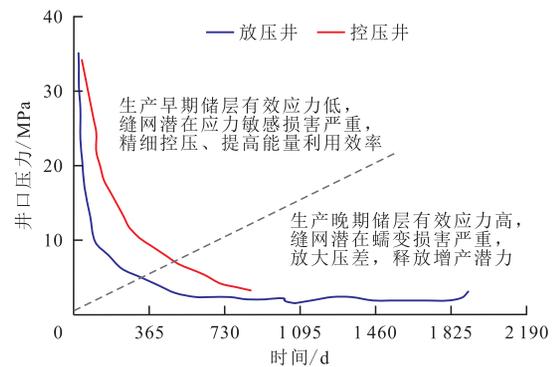
水力压裂产生的复杂缝网主要包括有支撑剂充填的支撑裂缝和无支撑剂充填的自支撑裂缝。



a. 日产气量随时间的变化



b. 累积产气量随时间的变化



c. 井口压力随时间的变化

图4 四川某页岩气区块典型放压井/控压井的生产动态对比

Fig.4 Production performance comparison of typical production pressure free/controlled wells of a shale gas block in Sichuan

相比支撑裂缝,自支撑裂缝应力敏感性极强,易闭合^[82]。在放大压差生产时,主裂缝短期内迅速泄压,压力敏感损害导致靠近主裂缝区储层渗透率急剧下降,快速形成储层损害区,过早阻挡外围气体进入主裂缝系统,严重影响气井日产气量和累积产气量^[83-85]。朱维耀等研究发现,应力敏感损害可导致微裂缝发育的气井日产气量降低73.5%,导致微裂缝不发育的气井日产气量降低39.7%^[86]。与此同时,页岩与滑溜水压裂液接触后诱发润滑作用、水化作用和侵蚀作用,会加剧裂缝渗透率的应力敏感损害^[66, 87-88]。

为保证地层能量的充分利用,提高产气效率,气井需要执行分阶段控压设计。如图4c所示,在气井生产早期,储层有效应力相对较低,若生产压差增大对提高产量的促进作用小于因应力敏感所引起的抑制作用,为了保护压裂缝网的渗流能力,需要针对缝网在水-岩作用下的应力敏感损害程度,进一步将生产压差控制在合理的范围,从而提高地层能量利用效率,延长气井稳产期;在气井生产晚期,储层有效应力相对较高,若生产压差增大对提高产量的促进作用大于因应力敏感所引起的抑制作用,同时考虑页岩水化蠕变加剧裂缝闭合的时间效应,需进一步提前放大压差,充分释放气井的增产潜力,从而保证EUR最大。

4 结论

在当前水力压裂技术不可替代和水-岩作用不可避免的情况下,“扬长避短、变害为利”的合理调控水-岩作用对页岩气井增产稳产的损益双重效应,有助于页岩气井实现“降本增效”开发。

页岩富含水敏性组分黏土矿物、酸敏性组分碳酸盐矿物、碱敏性组分石英和氧敏性组分有机质和黄铁矿,水-岩作用易改变岩石组构及力学性质。推动工作液配方优化,攻关应用氧化性酸液和氧化性压裂液,有利于潜在提高压裂造缝效果和促进吸附气产出,进而提高气藏采收率。

考虑水-岩作用的损益双重效应,基于页岩气井实际的闷井压降幅度、速率统计分析,寻找压降幅度与速率的拐点,确定水相渗吸造缝的时间峰值,有利于指导最长闷井时间的优化设计。考虑水-岩作用下裂缝应力敏感性和蠕变特征,构建考虑保护缝网导流能力的控压生产制度,有利于指导气井生产全过程合理控压,充分利用地层能量,延长稳产

期,最大化EUR。

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