引用本文:韩学婷,孟尚志,刘广景,等.煤层气新钻井对老井产能的影响及其控制因素——以沁水盆地柿庄南地区为例[J].石油实验地质,2025,47(1):195-203.DOI:10.11781/sysydz2025010195.

HAN Xueting,MENG Shangzhi,LIU Guangjing,et al.Impact of new coalbed methane wells on old well productivity and its controlling factors: a case study of Shizhuangnan block in Qinshui Basin[J].Petroleum Geology & Experiment,2025,47(1):195-203.DOI:10.11781/sysydz2025010195.

煤层气新钻井对老井产能的影响及其控制因素
——以沁水盆地柿庄南地区为例

韩学婷[1],孟尚志[1],刘广景[1],任镇宇[1],陶　树[2],门欣阳[2],韦子扬[2]

1.中联煤层气有限责任公司,北京　100015;
2.中国地质大学(北京) 能源学院,北京 100083

摘要:针对沁水盆地柿庄南地区产能释放不均衡等问题,通过水平井加密方式调整优化初始井网以提高储量动用程度,但钻井泥浆、压裂液窜流至邻井现象频发,导致老井产能受到不同程度的影响。以柿庄南地区煤层气开发实践为基础,分析了该区井间干扰发生的主要原因及其对产能的响应,从地质和工程角度提出应对方法或新钻井部署建议。新钻水平井分段压裂是影响老井产能的主要方式,钻井影响井占比较低、产能恢复率较差且集中发生于近井地带(最小井距小于 120 m)。压裂影响井最小井距普遍介于 120~300 m,在 550~900 m 埋深范围内均有分布。被影响井生产异常主要体现为液柱回升,最小井距小于 150 m 或构造煤发育的部分老井伴有黑水产出、卡泵停机等现象。卡泵停机或黑水产出井产能恢复效率较低,卡泵停机井人工实时解卡产量可大幅恢复,但解卡失败,检泵作业后产气量降幅明显。受新钻井压裂影响的老井分布在新钻井水平段射孔方向,地质层面主要受控于水平主应力各向异性,不同井距条件下存在水力裂缝沟通和压裂液前缘波及两种方式。柿庄南地区煤储层水平应力差为 5.5~13.5 MPa,压裂影响井平均水平主应力差普遍大于 10 MPa,高水平应力差条件下水力裂缝的强定向性致使老井流体场受到扰动。新钻井部署应与老井最小井距大于 300 m 且规避断层,高应力差地带可通过暂堵压裂或缩小簇间距、强化缝间应力干扰以弱化其对老井产能的影响。

关键词:煤层气;水平井;水平应力差;井网加密;柿庄南地区;沁水盆地

中图分类号:TE324　　**文献标识码**:A　　DOI:10.11781/sysydz2025010195

Impact of new coalbed methane wells on old well productivity and its controlling factors:
a case study of Shizhuangnan block in Qinshui Basin

HAN Xueting[1], MENG Shangzhi[1], LIU Guangjing[1], REN Zhenyu[1], TAO Shu[2], MEN Xinyang[2], WEI Ziyang[2]

1. *China United Coalbed Methane Corporation Ltd.*, *Beijing* 100015, *China*;
2. *School of Energy Resources*, *China University of Geosciences* (*Beijing*), *Beijing* 100083, *China*

Abstract: To address the issue of uneven productivity release in the Shizhuangnan block of the Qinshui Basin, the initial well pattern is optimized through horizontal well infill to enhance reservoir utilization. However, frequent occurrences of drilling mud and fracturing fluid migration to neighboring wells have resulted in varying degrees of effect to old well productivity. Based on the coalbed methane development in the Shizhuangnan block, the study analyzed the main causes for well-to-well interference and its impact on productivity. From the geological and engineering perspectives, countermeasures and suggestions on well deployment were proposed. The results revealed that staged fracturing of new horizontal wells is the primary cause impairing old well productivity. The proportion of wells affected by drilling is relatively low, with poor productivity recovery efficiency. The impact from fracturing is predominantly concentrated near the wellbore (minimum well spacing <120 m). The minimum well spacing for

收稿日期(Received):2024-10-16;**修订日期(Revised)**:2024-12-13;**出版日期(Published)**:2025-01-28。
作者简介:韩学婷(1989—),女,硕士,高级工程师,从事非常规气藏开发工作。E-mail:hanxt2@cnooc.com.cn。
通信作者:陶树(1981—),男,博士,教授,从事非常规油气地质与工程研究与教学工作。E-mail:taoshu@cugb.edu.cn。
基金项目:国家自然科学基金面上项目(42272200)资助。

fracturing-affecting wells generally ranges from 120 to 300 m, with impact observed at burial depth between 550 to 900 m. The abnormal production in affected wells is characterized by the height increase in liquid water column. Some old wells, with a minimum well spacing of less than 150 m or developed tectonic coal, experience black water production and pump shutdowns. Wells with these issues exhibit lower recovery efficiency. While the production can be significantly restored by manual real-time unclogging, failure in unclogging results in a substantial decrease in gas production. Old wells affected by new well fracturing are distributed in the perforation direction of the horizontal section of new wells. Geologically, the distribution is mainly controlled by the anisotropy of horizontal principal stress. There are two propagation mechanisms depending on well spacing: hydraulic fracture communication and fracturing fluid front propagation. The horizontal stress difference in the coal reservoir of the Shizhuangnan block ranges from 5.5 to 13.5 MPa, with the average horizontal stress difference in the fracturing-affected wells greater than 10 MPa. Under high horizontal stress differences, the strong orientation of hydraulic fractures disturbs the fluid field of the old wells. To mitigate the impact, the deployment of new wells should maintain a minimum well spacing of over 300 m to the old wells and avoid faults. In areas with high stress differences, temporary plugging and diverting fracturing, reducing spacing between clusters, and enhancing stress interference between fractures can be employed to mitigate the fracturing impact on old well productivity.

Key words: coalbed methane; horizontal well; horizontal stress difference; well network infill; Shizhuangnan block; Qinshui Basin

深部煤层气水平井体积压裂技术的应用极大提升了煤层气单井产能,也为中浅层煤层气的高效建产提供了新的思路[1-9]。近年来,针对储层物性、渗透率各向异性和储层改造效果等因素影响下,井间储量动用程度差异大、平面产能释放不均衡等问题,中联煤层气有限责任公司在沁水盆地柿庄南地区采用水平井加密的方式对初始直井/定向井井网进行调整优化,以期提高井组采收率和储量动用程度[10-12]。然而,随着加密井数量的增多,逐渐缩小的井间距使得裂缝可延伸扩展的空间越来越小,加密水平井钻完井过程中频繁出现老井与新井间的井间干扰(或压窜)。具体而言,井网调整过程中,新钻井泥浆、压裂液窜流至邻近老井现象多见,致使老井产能受到不同程度的伤害,如压力突增、产量陡降、产水大幅增加等老井排采异常均较为常见,大部分被干扰井产量急剧下降后难以再恢复到原有水平[13-15]。

当前,页岩气及常规油气关于井间压窜的研究成果较为丰富,但煤层气领域鲜有报道[16-20]。据此,本文以柿庄南地区煤层气开发实践为基础,分析了该区井间干扰发生的主要原因及其产能响应,从地质和工程角度提出了应对方法或新钻井部署建议,以期为我国煤层气新钻井部署引起的井间干扰问题提供预防和缓解思路。

1 区域地质概况及开发现状

柿庄南地区位于沁水盆地南部(图1),为一向西倾的单斜构造,北部发育2个规模较大的近南北方向的背斜和向斜,南部发育近东西轴向的檀山背斜、北甲向斜、上梁背斜,断层主要分布在寺头断层附近[21-23]。二叠系山西组3#和石炭系—二叠系太原组15#煤全区分布且发育稳定,3#煤层平均厚度为6.13 m,15#煤层平均厚度为4.18 m。煤层埋深呈"北深南浅"的特征,埋深小于800 m区域占56.9%,

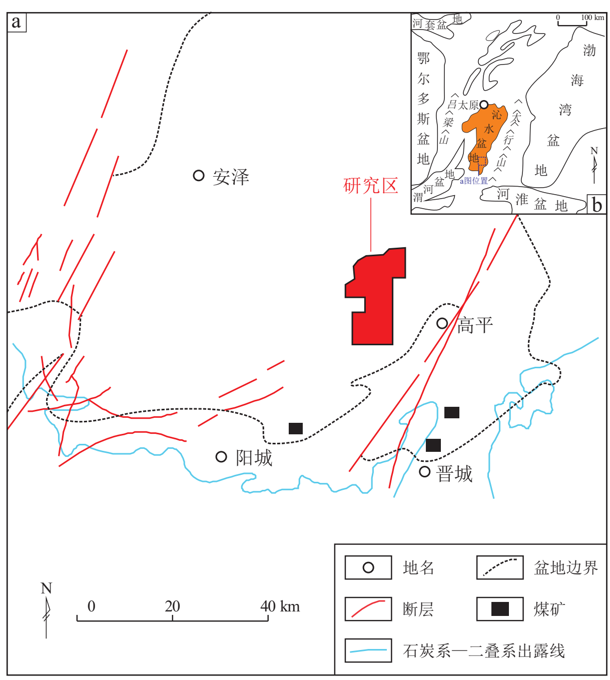


图1 沁水盆地柿庄南地区研究区地理位置

据参考文献[22-23]修改。

Fig.1 Geographical location of the study area in Shizhuangnan block, Qinshui Basin

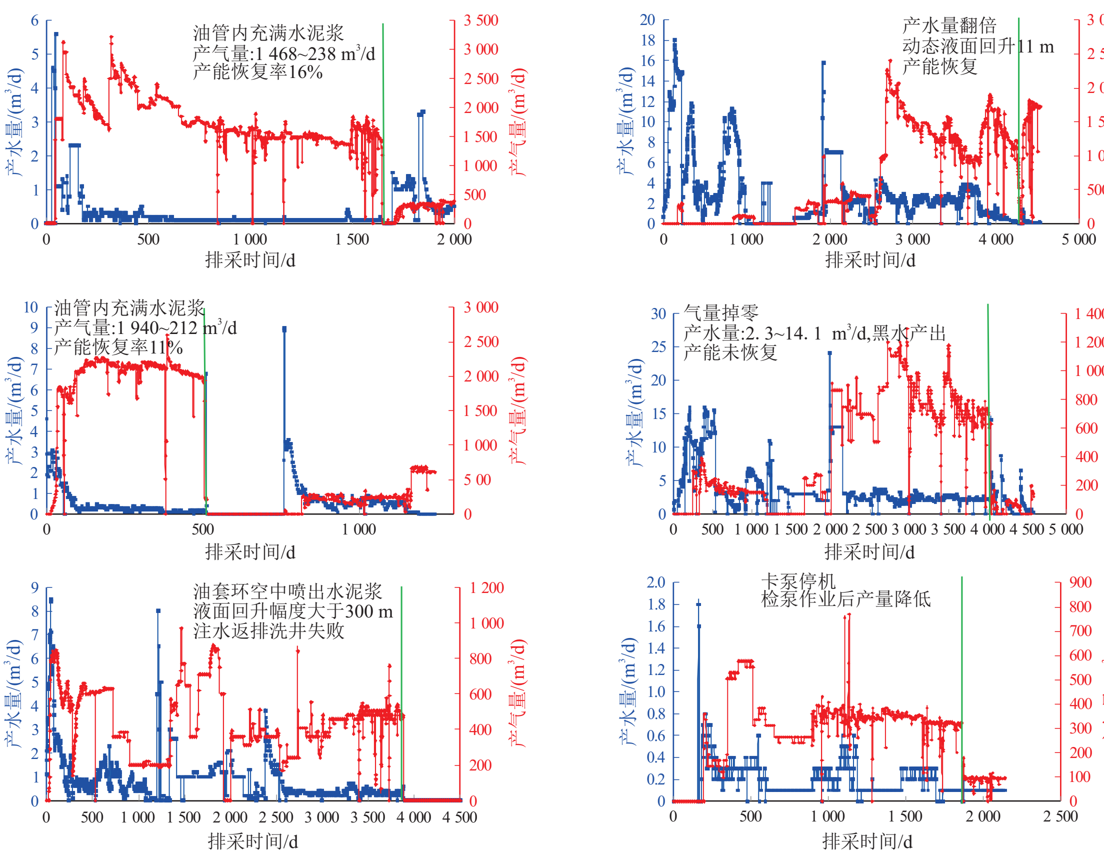
北部埋深平均约 750 m,南部埋深平均约 600 m;煤层直接顶板岩性以泥岩为主,水动力条件相对稳定[24]。

其中,3#煤层是当前开发主要目的层,投产煤层气井近 1 500 口(直井为主,井距为 200~300 m)。但是,区内煤层气藏具有低压、低渗、欠饱和的特点,构造煤相对较发育,加之前期煤层气井水力压裂规模小(液量为 300~500 m^3;排量为 6~8 m^3/min;砂量为 40~50 m^3)、裂缝扩展/支撑剂铺设运移范围受限,效果不佳。近年来,开发方式由直定井组向水平井勘探方式转变,通过增大泄压面积,在一定程度上提升了复杂煤储层生产效果,80 余口水平井年产贡献率达 41%[25]。

2　新钻井对老井产能的影响方式

截至 2024 年 4 月,柿庄南地区井网加密调整过程中累计已有 91 口老井产能受到新钻水平井的影响(水平段长 610~1 109 m,平均为 893 m;压裂 5~13 段;单段液量为 200~1 000 m^3,平均为 560 m^3;单段砂量为 20~80 m^3,平均为 40 m^3;排量为 6~8 m^3),含直井 63 口、定向井 20 口、水平井 8 口,被影响井区域尺度分布无明显规律,各个井区均存在,且受影响的老井排采周期普遍较长(大于 1 500 d)。其中,受钻井影响的井占比相对较低,绝大部分井排采异常发生在新井压裂过程中,5 口井在水平井钻井和压裂阶段均受到不同程度的影响。

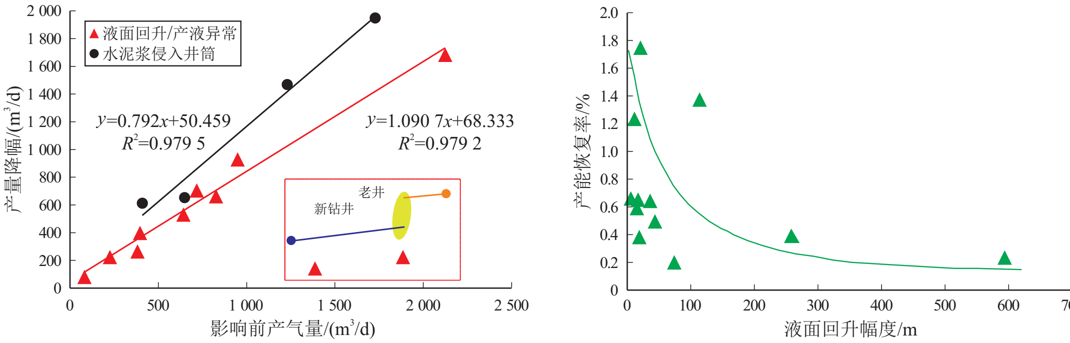
受钻井影响的井主要体现为钻井液侵入,老井油管内充满水泥浆、液柱回升、气量下降或直接掉零。遭受水泥浆侵入的老井注水返排洗井失败率高,成功修井后产能恢复率普遍较低(小于 20%,图 2a)。新钻井对老井的井间相对位置是决定产能恢复效率的关键,新钻井轨迹末段与老井邻近时,液面微弱抬升引起的产能下降可大幅恢复。同时,气井初始产能效果越好,被影响后产量降幅越大(图 3a)。受压裂影响的井主要体现为液柱回升、气量陡降、产水骤增、煤粉产出、卡泵停机等。进一步而言,压裂影响井主要存在 3 种表现方式:其一,仅液面回升,无煤粉产出;其二,液面回升同时伴有少量煤粉产出;其三,液面回升且伴有大量黑水产出、卡泵停机现象(图 2b)。从产能恢复效果来看,液面回升幅度越大,产量恢复率越低(图 3b);从排采周期来看,相同液面回升幅度下,部分生产



a.加密井钻井过程中被影响井产能变化　　b.加密井压裂过程中被影响井产能变化

图 2　沁水盆地柿庄南地区典型被影响井产能特征

Fig.2　Productivity characteristics of typical affected wells in Shizhuangnan block, Qinshui Basin



a.钻井影响前后产气量　　b.压裂影响井液面回升与产能恢复的关系

图 3　沁水盆地柿庄南地区加密井对老井影响方式及其对产能恢复率的影响

Fig.3　Impact mechanisms of infill wells on old wells and their effect on productivity recovery rate in Shizhuangnan block, Qinshui Basin

时间较长的老井产能恢复率相对更高;无煤粉产出且液面回升幅度较小的煤层气井平均产能恢复率超过 80%,煤粉大量产出(黑水)或卡泵停机井人工实时解卡产量可大幅恢复,但解卡失败或随后的检泵作业会致使产量下滑明显,相对于被影响前产量降幅超过 80%。

3　新老钻井井间干扰控制因素

井网密度和最小井距是导致新钻井与老井形成井间干扰的核心要素。据统计,柿庄南地区新钻井井眼轨迹与被影响老井最小井距介于 20~380 m 之间,钻井影响井的最小井距普遍小于 120 m(平均 99.3 m),绝大多数压裂影响井的最小井距超过 120 m(76%)。柿庄南地区早期部署的直井或定向井井网密度较大且排采周期较长,老井周围的地层压力下降幅度较大或压力衰竭。当井距较近且新钻井路径存在高渗通道(大于 0.1×10^{-3} μm²)或碎粒煤较为发育(占比大于 40%)时,邻近新井钻井过程中钻井液滤失严重,极易发生泥浆侵入;钻井引起的液面回升井周边原位渗透率普遍较低(小于 0.1×10^{-3} μm²)且构造改造不强烈,以原生和碎裂结构煤为主(占比大于 80%),老井排采异常主要表现为孔压恢复、液柱回升或产气停滞(表 1)。该地区构造煤分布与区域断裂系统密切相关,不同规模断层附近的煤层易发生剪切、破坏和强烈变形,且应力相对释放致使煤层渗透率偏高,断层的存在可能也为钻井液的侵入提供了通道。受新钻井压裂影响的老井主要分布在水平段两侧射孔方向,不同井距对老井排采异常表现方式影响显著,卡泵停机或产黑水井平均最小井距小于 150 m,含少量煤粉或仅液面回升的井平均最小井距约 190 m(图 4)。

地应力场对钻井影响井的分布不甚明显,但对压裂影响井的区域分布具有极强的控制作用。研究区煤层气井注入压降试井测试数据有限(17 层次),利用考虑岩石力学性质和构造应变的地应力反演模型计算水平最大($\sigma_{H,max}$)、最小主应力

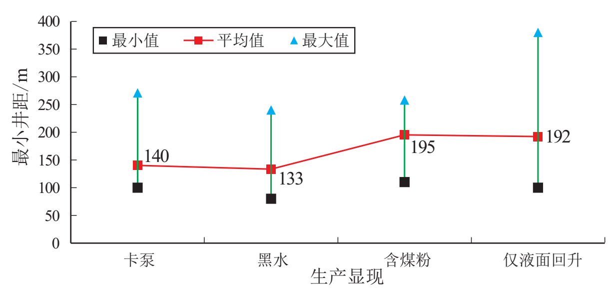


图 4　沁水盆地柿庄南地区压裂影响井不同类型排采异常最小井距分布

Fig.4　Distribution of minimum well spacing for different types of abnormal drainage and production in fracturing-affected wells of Shizhuangnan block, Qinshui Basin

表 1　沁水盆地柿庄南地区钻井过程中水泥浆侵入井和液面回升井周边地层参数

Table 1　Parameters of strata surrounding wells with cement slurry intrusion and liquid level rise in Shizhuangnan block, Qinshui Basin

井号	最小井距/m	影响方式	渗透率/10^{-3} μm²	孔隙度/%	碎粒煤占比/%
A	73	水泥浆侵入	0.708 4	0.073 5	50.00
B	67	水泥浆侵入	0.417 4	0.117 9	43.40
C	109	水泥浆侵入	0.169 1	0.214 7	70.21
D	119	液面回升	0.088 9	0.015 8	16.80
E	108	液面回升	0.060 0	0.031 4	17.52
F	112	液面回升	0.023 9	0.055 6	5.77

$(\sigma_{h,\min})$[26-27]:

$$\sigma_{H,\max}=\frac{\mu_s}{1-\mu_s}(\sigma_v-\alpha P_0)+\alpha P_0+\frac{E_s}{1-\mu_s^2}\xi_H+\frac{E_s\mu_s}{1-\mu_s^2}\xi_h \quad (1)$$

$$\sigma_{h,\min}=\frac{\mu_s}{1-\mu_s}(\sigma_v-\alpha P_0)+\alpha P_0+\frac{E_s}{1-\mu_s^2}\xi_h+\frac{E_s\mu_s}{1-\mu_s^2}\xi_H \quad (2)$$

式中:μ_s为静态泊松比;σ_v为垂直应力,单位 Pa;α为 Biot 系数,可由经验公式 $\alpha=1-(1-\Phi)^{\frac{3}{(1-\Phi)}}$确定,其中 Φ 为孔隙度,单位%;P_0为孔隙压力,单位 Pa;E_s为静态杨氏模量,单位 GPa;ξ_h为最小主应力应变,ξ_H为最大主应力应变,可通过将水力压裂测得的地应力数据带入方程求解获取,参照储层压力梯度定义,以地表构造应变为 0 作为基准求取构造应变梯度,并据此建立构造曲率与应变梯度的相关性方程以预测区域分布(图 5)。

综合测井实测及地球物理反演结果,在柿庄南地区 400~1 200 m 埋深段范畴,煤储层地应力场以走滑断层应力场为主,其次为正断层应力场,二者在各个埋深段连续分布;逆断层应力场占比较低且集中分布于浅部(800 m 以浅)。埋深仍是控制地应力大小的关键,煤储层最大(8.4~33.1 MPa)、最小(5.4~21.2 MPa)水平主应力均随埋深增大而增高,但局部微幅构造及断层扰动效应致使数据点分布存在一定的离散性(图 6)。地应力高值区主要分布于埋深较大的区域及负向构造带(图 7)。值得注意的是,北部寺头断层附近沟槽区受断层影响存在一定程度的应力释放,未表现出明显的水平应力集中效应。水平主应力各向异性是影响水力裂缝定向性和缝长的关键,该区煤储层水平主应力差介于 5.5~13.5 MPa,受压裂影响井主要分布在埋深 550~900 m 且水平主应力差大于 10 MPa 的地带(图 7e)。

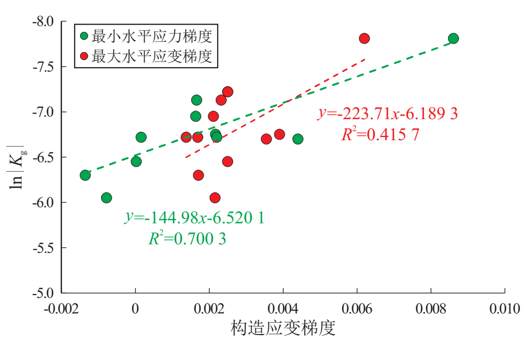


图 5　沁水盆地柿庄南地区构造应变梯度与高斯曲率(K_g)的相关关系

Fig.5　Correlation between tectonic strain gradient and Gaussian curvature (K_g) in Shizhuangnan block, Qinshui Basin

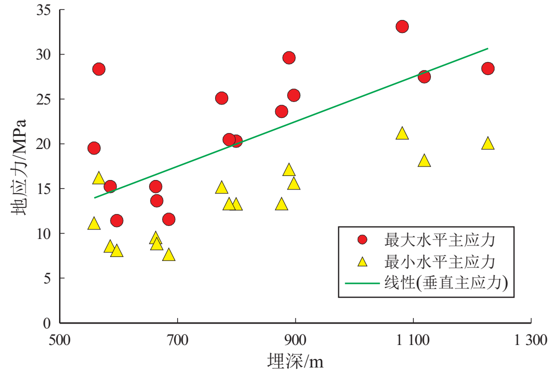


图 6　沁水盆地柿庄南地区煤层试井实测地应力参数垂向变化规律

Fig.6　Vertical variation pattern of in-situ stress parameters measured during coalbed methane well testing in Shizhuangnan block, Qinshui Basin

进一步而言,原位条件下煤层处于垂向应力和 2 个水平主应力的三向应力状态下,低水平应力差条件下水力压裂裂缝易沿着天然裂缝和割理扩展,形成更为复杂的缝网裂缝形态;随着水平应力差增大,地应力对水力压裂裂缝扩展的控制作用增强,可以有效降低起裂压力、缩短破裂时间,形成方向显著、形态单一且延伸较远的水力主缝[28-30]。通常,水平应力差存在一个临界值,大于该值时水力裂缝才有可能穿透天然裂缝而不被其兼并捕获,反之则无法穿过[31-32]。根据沁水盆地南部地区直井水力压裂裂缝形态的地震监测解释结果,煤储层水力裂缝形态整体表现为单条主缝与多条分支短裂缝的组合,水力缝长随水平应力差增大而增高,特别是当水平应力差大于 10 MPa 时快速增高。换言之,沁水盆地高阶煤层水力裂缝穿透天然裂缝的临界水平应力差大致位于 10 MPa 附近,这与 CHEN 等[33]的认识基本一致(图 8)。从这一点来看,高水平应力差下的裂缝强定向性是导致新钻井与邻近老井压窜的关键,新钻井水平段两侧射孔方向的邻近老井通常处于水力主缝的拓展方位,老井受到新钻井水力裂缝沟通、压裂液侵入影响,流体系统平衡受到干扰,产能骤降而后逐渐恢复,压窜后产能恢复效率及流体产出动态受关井时间、井筒液位变化、压裂液侵入量、煤粉扰动情况等多因素影响,机理较为复杂,尚待进一步探索深化。

4　新钻井井间干扰规避思路

综上所述,井距是控制新钻井对老井影响的关键要素。当新钻井与老井最小井距小于 120 m 时,新井钻进过程中易发生钻井液侵入老井井控范畴进而诱导液面回升、产液异常等现象;当构造煤较

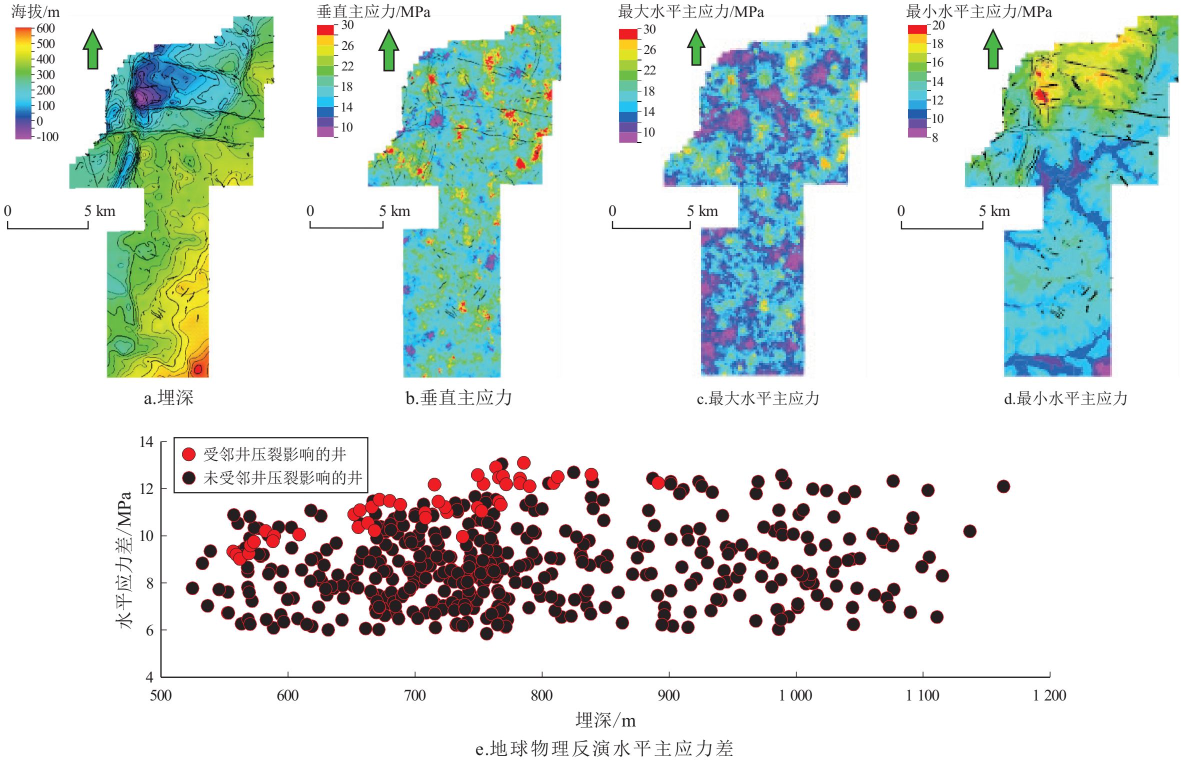


图 7 沁水盆地柿庄南地区 3 号煤埋深及地球物理反演最大、最小、垂直主应力大小平面分布

Fig.7 Planar distribution of burial depth of No. 3 coal seam and maximum, minimum, and vertical principal stress from geophysical inversion in Shizhuangnan block, Qinshui Basin

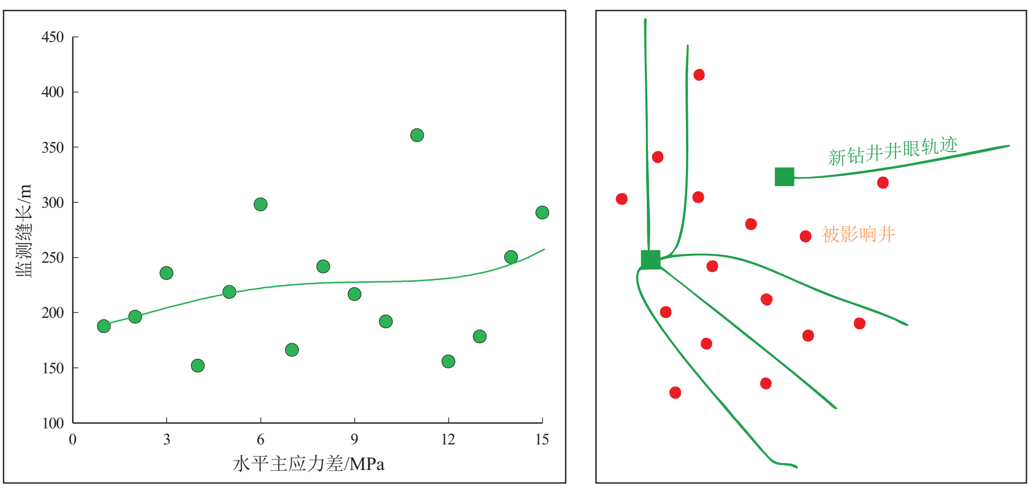


图 8 沁水盆地柿庄南地区水平应力差与水力缝长的关系(a)及新钻井轨迹与被影响井的相对位置(b)

Fig.8 Relationship between horizontal stress difference and hydraulic fracture length(a), and relative positions of new drilling trajectories and affected wells (b) in Shizhuangnan block, Qinshui Basin

发育且存在高渗通道时,钻井水泥浆侵入老井井筒对产能造成不可逆的伤害。压裂对老井的影响主要受控于井间距离及水平应力差,当新钻井与老井最小井距超出钻井影响范畴时,新钻井水力裂缝在局部高应力区(大于 10 MPa)的强定向性会沟通邻近老井致使老井流体系统受到破坏,进而诱导液面回升、煤粉产出、卡泵停机等系列生产异常(图 9)。为减少井间干扰,需要根据地质条件和资源分布合理规划井距,就当前水平井压裂规模及井间干扰统计分析结果而言,柿庄南地区新钻井与老井应控制最小井距大于 300 m 且尽可能在较低应力差的地带部署新井,同时保证井眼轨迹远离断层或构造煤发育区。

从工程角度,控制裂缝几何形态、参数及其延展方向是减小井间干扰的核心,可通过以下 2 个技术路径加以实现:(1)暂堵转向压裂技术可以通过

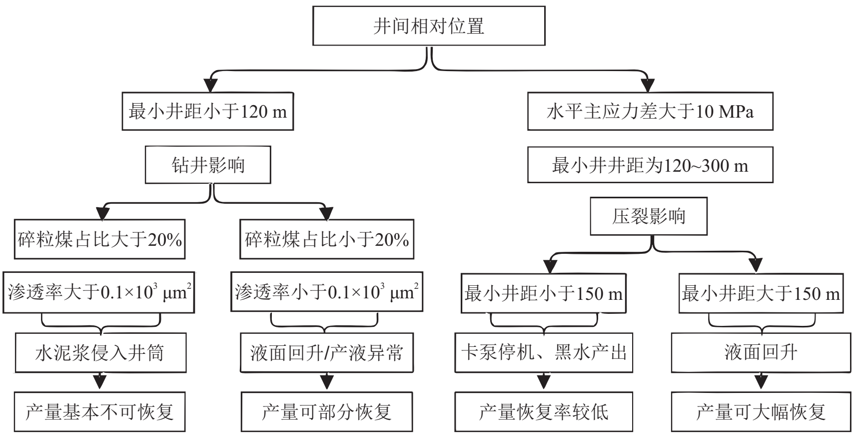


图 9　沁水盆地柿庄南地区新钻井与老井井间干扰影响因素及生产显现

Fig.9　Factors influencing well-to-well interference between new and old wells in Shizhuangnan block of Qinshui Basin and their production performance

老缝的暂堵实现导流体系的转向重构。近年来,煤层气井暂堵转向压裂增产试验在沁水盆地南部、鄂尔多斯盆地东部等地区进行了有益探索并已初见成效(例如,沁水盆地郑庄地区郑 X 井绒囊暂堵压裂后裂缝转向 55°),初步落实了该技术在该区的应用前景[34]。但是,当前压窜井多位于高应力差地带,水力裂缝的强定向性可能会致使裂缝仅在暂堵剂作用范围内发生转向,裂缝的转向程度和转向距离受到限制,压裂施工措施及参数需根据井间位置、裂缝转向能力合理配置。(2)缩小簇间距,提高应力阴影效应。应力阴影效应在水平井多簇水力压裂中普遍存在,受控于多簇裂缝的缝间干扰行为,水力裂缝之间的同步拓展以及被沟通的天然裂缝与水力裂缝的相互作用都将改变其辐射范围内的局部应力场,导致压裂裂缝拓展规律改变。簇间距的增大会致使缝间干扰作用减弱,有利于单缝的生长[35-37]。因此,井网调整过程中可适当缩小簇间距,强化缝间阴影效应,限制单缝长度扩展,增加近井储层改造体积,进而规避其与老井的裂缝沟通或压窜行为。

5　结论

(1)沁水盆地柿庄南地区井网加密调整过程新钻水平井对老井产能影响显著,钻井影响的井占比相对较低,绝大部分井排采异常发生在新井压裂过程中。被影响井钻井液侵入、水力裂缝沟通会引起液面回升、煤粉产出、产量落零、产水骤增、卡泵停机等系列生产异常,钻井泥浆侵入或煤粉扰动效应显著的气井产能恢复效率普遍较低,液面回升井回升幅度越低,产能恢复效果越好。

(2)井间相对位置和水平应力差是控制新钻井对老井井间干扰的关键。钻井影响井最小井距普遍小于 120 m,相对高渗或构造煤发育区是造成水泥浆侵入的主要原因;压裂影响井最小井距主要为 120~300 m 且发育于高水平主应力各向异性地带,高水平应力差(大于 10 MPa)下裂缝的强定向性致使主缝拓展方向的老井流体场受到波及,进而诱导老井周边流体系统平衡受到干扰。

(3)为减少井间干扰,需要根据地质条件和资源分布合理规划井距。柿庄南地区新钻井与老井应控制最小井距大于 300 m,高地应力差地区可通过暂堵转向压裂技术和缩小簇间距控制水力裂缝几何形态、参数及其延展方向以减小压窜的风险。

利益冲突声明/Conflict of Interests

作者陶树是本刊青年编委会成员,未参与本文的同行评审或决策。

Author TAO Shu is a Young Editorial Board Member of this journal, and he did not take part in the peer review or decision-making of this article.

作者贡献/Authors' Contributions

韩学婷参与论文写作和修改、实验数据分析;孟尚志、刘广景、任镇宇参与实验设计;陶树参与实验设计、论文写作及修改;门欣阳、韦子扬完成实验操作、参与论文写作及修改。所有作者均阅读并同意最终稿件的提交。

HAN Xueting participated in paper writing and editing, as well as experimental data analysis. MENG Shangzhi, LIU Guangjing, and REN Zhenyu participated in experimental design. TAO Shu participated in experimental design, paper writing, and revision. MEN Xinyang and WEI Ziyang completed experimental operation, participated in the writing and revision of the paper. All authors have read the final version of the paper and consented to its submission.

参考文献:

[1] 徐凤银,侯伟,熊先钺,等.中国煤层气产业现状与发展战略[J].石油勘探与开发,2023,50(4):669-682.
XU Fengyin, HOU Wei, XIONG Xianyue, et al. The status and

development strategy of coalbed methane industry in China[J]. Petroleum Exploration and Development, 2023, 50(4): 669-682.

[2] 秦勇.中国深部煤层气地质研究进展[J].石油学报,2023,44(11):1791-1811.
QIN Yong. Progress on geological research of deep coalbed methane in China[J]. Acta Petrolei Sinica, 2023, 44(11): 1791-1811.

[3] 陈世达,汤达祯,侯伟,等.深部煤层气地质条件特殊性与储层工程响应[J].石油学报,2023,44(11):1993-2006.
CHEN Shida, TANG Dazhen, HOU Wei, et al. Geological particularity and reservoir engineering response of deep coalbed methane[J]. Acta Petrolei Sinica, 2023, 44(11): 1993-2006.

[4] 冯义,任凯,刘俊田,等.深层煤层气水平井安全钻井技术[J].钻采工艺,2024,47(3):33-41.
FENG Yi, REN Kai, LIU Juntian, et al. Safe drilling technology for deep CBM horizontal wells[J]. Drilling and Production Technology, 2024, 47(3): 33-41.

[5] 桑树勋,韩思杰,周效志,等.华东地区深部煤层气资源与勘探开发前景初探[J].油气藏评价与开发, 2023, 13(4): 403-415.
SANG Shuxun, HAN Sijie, ZHOU Xiaozhi, et al. Deep coalbed methane resource and its exploration and development prospect in East China [J]. Petroleum Reservoir Evaluation and Development, 2023, 13(4): 403-415.

[6] 孔祥伟,谢昕,王存武,等.基于灰色关联方法的深层煤层气井压后产能影响地质工程因素评价[J].油气藏评价与开发,2023,13(4): 433-440.
KONG Xiangwei, XIE Xin, WANG Cunwu, et al. Evaluation of geological engineering factors for productivity of deep CBM well after fracturing based on grey correlation method[J]. Petroleum Reservoir Evaluation and Development, 2023, 13(4): 433-440.

[7] 李小刚,秦杨,刘紫微,等.微波强化煤层气井压裂开采的物性规律[J].特种油气藏,2024,31(3):70-77.
LI Xiaogang, QIN Yang, LIU Ziwei, et al. Physical property law of coalbed methane well fracturing development enhanced by microwave[J]. Special Oil & Gas Reservoirs, 2024, 31(3): 70-77.

[8] 孔祥伟,谢昕,王存武.基于综合可压指数的煤层气水平井压裂分段参数优化[J].油气藏评价与开发, 2024, 14(6): 925-932.
KONG Xiangwei, XIE Xin, WANG Cunwu. Optimization of segmented fracturing parameters for coalbed methane horizontal wells based on comprehensive fracability index [J]. Petroleum Reservoir Evaluation and Development, 2024, 14(6): 925-932.

[9] 李可心,张聪,李俊,等.沁水盆地南部煤层气水平井射孔优化[J].新疆石油地质,2024,45(5):581-589.
LI Kexin, ZHANG Cong, LI Jun, et al. Optimization of perforation in CBM horizontal wells in southern Qinshui basin[J]. Xinjiang Petroleum Geology, 2024, 45(5): 581-589.

[10] 段宝江,孙雨亭,刘成桢,等.柿庄南煤层气低效井区水平井加密技术研究及应用[J].江汉大学学报(自然科学版),2023,51(2):90-96.
DUAN Baojiang, SUN Yuting, LIU Chengzhen, et al. Research and application of horizontal well infilling technology in low-efficiency well area of Shizhuang south coalbed methane field[J]. Journal of Jianghan University (Natural Science Edition), 2023, 51(2): 90-96.

[11] 张万春,郭布民,孔鹏,等.柿庄南煤层气重复压裂裂缝形态反演及效果分析评价[J].非常规油气,2022,9(1):119-128.
ZHANG Wanchun, GUO Bumin, KONG Peng, et al. Fracture morphology inversion and effect evaluation of CBM refracturing in southern Shizhuang block [J]. Unconventional Oil & Gas, 2022, 9(1): 119-128.

[12] 李勇,王延斌,倪小明,等.煤层气低效井成因判识及治理体系构建研究[J].煤炭科学技术,2020,48(2):185-193.
LI Yong, WANG Yanbin, NI Xiaoming, et al. Study on identification and control system construction of low efficiency coalbed methane wells[J]. Coal Science and Technology, 2020, 48(2): 185-193.

[13] 陈明,孙俊义,王立伟,等.大宁—吉县区块深层煤层气井间压窜主控因素分析及防治对策研究[J/OL].煤炭科学技术, 1-8[2024-09-16]. http://kns.cnki.net/kcms/detail/11.2402.TD.20240902.1652.020.html.
CHEN Ming, SUN Junyi, WANG Liwei, et al. Analysis of the main controlling factors of intra-well frac hit between deep coalbed methane in Daning-Jixian block and research on countermeasures to prevent and control it[J/OL]. Coal Science and Technology, 1-8[2024-09-16]. http://kns.cnki.net/kcms/detail/11.2402.TD.20240902.1652.020.html.

[14] 王喆.延川南煤层气田压窜井影响因素分析和措施[J].中国石油和化工标准与质量,2022,42(16):9-11.
WANG Zhe. Analysis and measures of pressure intra-well frac hit in south CBM field [J]. China Petroleum and Chemical Standard and Quality, 2022, 42(16): 9-11.

[15] 姚秀田,苏鑫坤,郑昕,等.特高含水期油藏井网调整开发效果三维物理模拟实验研究[J].油气地质与采收率,2023,30(1):139-145.
YAO Xiutian, SU Xinkun, ZHENG Xin, et al. 3D physical simulation experiments of development effects after well pattern adjustment in extra-high water cut reservoirs[J]. Petroleum Geology and Recovery Efficiency, 2023, 30(1): 139-145.

[16] 王挺,汪杰,江厚顺,等.页岩水平井水力压裂裂缝扩展及防窜三维地质模拟[J]. 新疆石油地质,2023,44(6):720-728.
WANG Ting, WANG Jie, JIANG Houshun, et al. 3D geological simulation of hydraulic fracture propagation and frac-hit prevention in horizontal shale gas wells[J]. Xinjiang Petroleum Geology, 2023, 44(6): 720-728.

[17] 胡永章,唐煊赫,朱海燕,等.威荣深层页岩储层水力压裂多井压窜现象及机理[J].断块油气田,2024,31(5):851-857.
HU Yongzhang, TANG Xuanhe, ZHU Haiyan, et al. Phenomenon and mechanism of multi-well frac hits hydraulic fracturing in Weirong deep shale reservoir[J]. Fault-Block Oil & Gas Field, 2024, 31(5): 851-857.

[18] 何乐,袁灿明,龚蔚.页岩气井间压窜影响因素分析和防窜对策[J].油气藏评价与开发,2020,10(5):63-69.
HE Le, YUAN Canming, GONG Wei. Influencing factors and preventing measures of intra-well frac hit in shale gas[J]. Reservoir Evaluation and Development, 2020, 10(5): 63-69.

[19] 罗志锋,李建斌,张楠林,等.小井距压裂防窜机理研究与应

用[J].断块油气田,2023,30(4):593-600.
LUO Zhifeng,LI Jianbin,ZHANG Nanlin,et al.Research and application of anti-channeling mechanism in small well spacing fracturing[J].Fault-Block Oil & Gas Field,2023,30(4):593-600.
[20] 郑马嘉,欧志鹏,伍亚,等.深层页岩气井压窜特征与产能维护对策:以四川盆地泸 203 井区北部为例[J].天然气工业,2024,44(8):95-106.
ZHENG Majia,OU Zhipeng,WU Ya,et al.Frac-hit characteristics and productivity maintenance strategies of deep shale gas wells:a case study of northern Lu 203 well block in the Sichuan Basin[J]. Natural Gas Industry,2024,44(8):95-106.
[21] 周优.柿庄南区块煤系地层精细描述与三维地质建模[D].北京:中国地质大学(北京),2021.
ZHOU You.Fine description and 3D geological modeling of coal measures in southern Shizhuang block[D].Beijing:China University of Geosciences (Beijing),2021.
[22] 伊永祥.沁水盆地柿庄南区块煤层气井生产特征及排采控制研究[D].北京:中国地质大学(北京),2020.
YI Yongxiang.Research on the production characteristics and drainage control of CBM wells in the Shizhuangnan block of Qinshui Basin[D]. Beijing:China University of Geosciences (Beijing),2020.
[23] 杨延辉, 张鹏豹, 刘忠, 等.沁水盆地南部深层高阶煤层气成藏特征[J].中国石油勘探, 2024,29(5):107-119.
Yang Yanhui, Zhang Pengbao, Liu Zhong, et al. Gas accumulation characteristics of high-rank coal in deep formations in the southern Qinshui Basin[J]. China Petroleum Exploration, 2024,29(5):107-119.
[24] 孙强,孙建平,张健,等.沁水盆地南部柿庄南区块煤层气地质特征[J].中国煤炭地质,2010,22(6):9-12.
SUN Qiang,SUN Jianping,ZHANG Jian,et al.CBM geological characteristics in Shizhuang south block,southern Qinshui Basin[J].Coal Geology of China,2010,22(6):9-12.
[25] 徐最,陆小霞,李晨,等.开发中期煤层气田上市储量评估方法:以柿庄南区块为例[J].中国煤层气,2023,20(3):36-40.
XU Zui,LU Xiaoxia,LI Chen,et al.Evaluation method of listed reserves for coalbed methane fields in the middle development stage:based on the Shizhuang south block as an example[J].China Coalbed Methane,2023,20(3):36-40.
[26] LV A,AGHIGHI M A,MASOUMI H,et al.The effective stress coefficient of coal:a theoretical and experimental investigation[J].Rock Mechanics and Rock Engineering,2021,54(8):3891-3907.
[27] TAKADA A.The influence of regional stress and magmatic input on styles of monogenetic and polygenetic volcanism[J].Journal of Geophysical Research:Solid Earth,1994,99(B7):13563-13573.
[28] 孟召平,雷钧焕,王宇恒.基于 Griffith 强度理论的煤储层水力压裂有利区评价[J].煤炭学报,2020,45(1):268-275.
MENG Zhaoping,LEI Junhuan,WANG Yuheng.Evaluation of favorable areas for hydraulic fracturing of coal reservoir based on Griffith strength theory[J].Journal of China Coal Society,2020,45(1):268-275.
[29] HUANG Saipeng,LIU Dameng,YAO Yanbin,et al.Natural fractures initiation and fracture type prediction in coal reservoir under different in-situ stresses during hydraulic fracturing[J].Journal of Natural Gas Science and Engineering,2017,43:69-80.
[30] 孙逊,张士诚,马新仿,等.基于高能 CT 扫描的煤岩水力压裂裂缝扩展研究[J].河南理工大学学报(自然科学版),2020,39(1):18-25.
SUN Xun,ZHANG Shicheng,MA Xinfang,et al.Study on fractures propagation mechanism in coal hydraulic fracturing based on high-energy CT scanning technique[J].Journal of Henan Polytechnic University (Natural Science),2020,39(1):18-25.
[31] 何俊铧,陈立超,胡奇,等.不同原生裂缝壁面特征对煤储层压裂造缝影响的对比分析[J].煤炭学报,2014,39(9):1868-1872.
HE Junhua,CHEN Lichao,HU Qi,et al.Comparative analysis for the impact of different natural fracture surface characteristics on CBM fracturing[J].Journal of China Coal Society,2014,39(9):1868-1872.
[32] 张士诚,郭天魁,周彤,等.天然页岩压裂裂缝扩展机理试验[J].石油学报,2014,35(3):496-503.
ZHANG Shicheng,GUO Tiankui,ZHOU Tong,et al.Fracture propagation mechanism experiment of hydraulic fracturing in natural shale[J].Acta Petrolei Sinica,2014,35(3):496-503.
[33] CHEN Shida,ZHANG Yafei,TANG Dazhen,et al.Present-day stress regime,permeability,and fracture stimulations of coal reservoirs in the Qinshui Basin,northern China[J].AAPG Bulletin,2024,108(8):1509-1536.
[34] 郑力会,崔金榜,聂帅帅,等.郑 X 井重复压裂非产水煤层绒囊流体暂堵转向试验[J].钻井液与完井液,2016,33(5):103-108.
ZHENG Lihui,CUI Jinbang,NIE Shuaishuai,et al.Temporary plugging diverting test with fuzzy ball fluids in non-water producing coal beds in re-fracturing well Zheng-X[J].Drilling Fluid & Completion Fluid,2016,33(5):103-108.
[35] LIU Xiaoqiang,RASOULI V,GUO Tiankui,et al.Numerical simulation of stress shadow in multiple cluster hydraulic fracturing in horizontal wells based on lattice modelling[J].Engineering Fracture Mechanics,2020,238:107278.
[36] SIDDHAMSHETTY P,WU Kan,KWON J S I.Optimization of simultaneously propagating multiple fractures in hydraulic fracturing to achieve uniform growth using data-based model reduction[J].Chemical Engineering Research and Design,2018,136:675-686.
[37] MCKENNA J P,BLAZ M S,GREALY M H,et al.Using fracture stress shadows to drive stage spacing[C]//Proceedings of the Unconventional Resources Technology Conference.Austin,Texas,USA:American Association of Petroleum Geologists,2017.

(编辑　黄　娟)