引用格式：孙四清，杨帆，郑玉岐，等. 煤矿区煤层气开发技术应用现状及展望[J]. 油气藏评价与开发，2025，15(6)：972-982.
SUN Siqing, YANG Fan, ZHENG Yuqi, et al. Current applications and prospects of coalbed methane development technologies in coal mining areas [J]. Petroleum Reservoir Evaluation and Development, 2025, 15(6): 972-982.
DOI：10.13809/j.cnki.cn32-1825/te.2025.06.003

煤矿区煤层气开发技术应用现状及展望

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摘要：“十二五”以来，为保障煤层气资源开发和煤矿安全高效生产，根据煤矿采掘工程部署、开采扰动和煤层地质条件，经过生产实践探索，形成了适用于中国煤矿区煤层气开发的“四区联动”抽采模式，即煤矿规划区、准备区、生产区及采空区的煤层气协同开发，已取得较好应用效果。主要表现在以下几个方面：①开发形成了适合于规划区的地面垂直井压裂、顺煤层水平井分段压裂及碎软煤层顶板水平井地面分段压裂抽采技术。甘肃窑街海石湾矿垂直井单井产气量达到2 607 m^3/d；山西晋城寺河矿顺煤层分段压裂单井产气量突破9 100 m^3/d；安徽淮北芦岭矿碎软煤层顶板水平井单井产气量达到10 760 m^3/d。②研发了适合于准备区的煤矿井下定向长钻孔分段压裂抽采技术。陕西彬长大佛寺矿硬煤顺煤层长钻孔分段压裂钻孔长度达到600 m，单孔瓦斯抽采纯量达到3 600 m^3/d；山西阳泉新景矿碎软煤层顶板分段压裂钻孔长度达到609 m，单孔瓦斯抽采纯量达到2 811 m^3/d。③探索形成了适合于生产区的碎软煤层井下穿层钻孔高压加砂水力压裂和顺煤层气动定向钻进高效抽采技术。安徽淮南潘三矿穿层钻孔加砂水力压裂钻孔瓦斯抽采纯量是普通清水压裂的2.38倍；山西阳泉二矿气动定向钻进深度最大达到607 m，单孔瓦斯抽采纯量达到971.6 m^3/d。④提出了适合于煤矿采空区的地面垂直井和L型水平井瓦斯抽采模式。安徽淮南潘一矿垂直井抽采量最高超过50 000 m^3/d；山西晋城寺河矿L型水平井抽采量最高达30 000 m^3/d。随着煤矿区煤层气开发效果进一步提升的需要，提出了煤矿区煤岩层大规模体积压裂、煤矿井地联合分段水力压裂、煤矿区深部煤层气开发等技术攻关方向，推动煤矿区煤层气开发技术发展，以更好保障煤炭资源安全开采和煤层气资源高效开发。

关键词：煤矿区；煤层气；四区联动；分段压裂；碎软煤层
中图分类号：TE37 **文献标识码：**A

Current applications and prospects of coalbed methane development technologies in coal mining areas

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Abstract: Coalbed methane (CBM) is a hazardous gas that leads to gas explosions, coal and gas outbursts, and contributes to atmospheric greenhouse effects in coal mines. At the same time, CBM is a clean and efficient energy source. Developing CBM in coal mining areas offers significant benefits for enhanced safety, energy production, and environmental protection. In China, the estimated CBM resource is 32.86 × 10^{12} m^3 at depths shallower than 2 000 meters and 40.71 × 10^{12} m^3 at depths beyond 2 000 meters. Since the “12th Five-Year Plan”, an extraction model of “four-zone coordination” has been developed through practical exploration to ensure both CBM resource development and the safe, efficient operation of coal mines. This model is tailored to mining engineering deployment, mining-induced disturbances, and coal seam geological conditions. It involves coordinated CBM development in planning, preparation, production, and goaf areas, demonstrating significant effectiveness in practice. The key outcomes include: (1) Three technologies have been developed for use in planning areas, namely, surface vertical well fracturing, staged fracturing in coal-seam horizontal well, and staged fracturing and extraction. In the Haishiwan Mine of Yaojie, Gansu, vertical well interlayer temporary plugging and diverting fracturing technology is used in the target coal seam, and the CBM well production reaches 2 607 m^3/day. In Sihe mine of the Jincheng Mining Area, Shanxi, bottom-sealed coiled tubing pulling hydraulic jet and annulus sand fracturing technology is used in coal seam 15. The length of the horizontal well is 820.53 m

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收稿日期：2024-10-17。
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基金项目：国家科技重大专项“地面钻井煤层密闭取心气含量测试技术及装置”（2016ZX05045-002-002）；国家自然科学青年基金项目“钻孔绳索取芯煤层气损失量估算方法研究”（41202122）。

with 8 fracturing sections. The maximum well production is 9 100 m^3/day, and the stable gas production is 7 000-8 000 m^3/day. U-shaped horizontal well staged fracturing is used in the roof of fragmented and soft coal seam 8 of Luling Mine in the Huaibei Mining Area, Anhui Province. The horizontal well length is 585.96 m with 7 fracturing sections. The maximum well production is 10 760 m^3/day, and the total production is 7.5 million m^3. (2) Directional long borehole staged fracturing and extraction technology in underground coal mines have been developed in preparation areas. In the Dafosi Mine of Binchang, Shaanxi Province, long borehole staged fracturing is used in coal seam 4. The horizontal well length is 600 m with 8 fracturing sections. The maximum pure gas production is 3 600 m^3/day, and the average is 1 000-2 500 m^3/day. Pure gas production per 100 meters is 4.9-11.0 times that of unfractured boreholes in the same area. In the Xinjing Mine of the Yangquan Mining Area, Shanxi Province, the roof of fragmented and soft coal seam 3 is sand fractured in stages. The drilling length reaches 609 m with 10 fracturing sections. The maximum pure gas production is 2 811 m^3/day, and the pure gas production per 100 meters is 5.6-15.4 times that of unfractured boreholes in the same area. (3) For fragmented and soft coal seams, technologies such as high-pressure sand hydraulic fracturing and pneumatic directional drilling have been developed in production areas. In the Pansan Mining Area, Anhui Province, sand hydraulic fracturing technology is used in coal seam 13-1. The pure gas production per 100 meters of sand-fractured borehole is 2.38 times that of conventional water fracturing. In the No.2 Mine of Yangquan, Shanxi Province, to address the difficulties of drilling in fragmented and soft coal seams and the tendency of borehole collapse upon encountering water, pneumatic directional drilling drainage technology is used in coal seam 8. The drilling depth is 607 m, and the pure gas production is 971.6 m^3/day. (4) A ground vertical well and L- shaped horizontal well gas extraction model is developed for goaf areas in coal mines. In the Panyi Mine of the Huainan Mining Area, Anhui Province, due to the depressurization mining of coal seam 11-2, ground vertical wells are used to drain gas from coal seam No.13-1, and gas production reaches 50 000 m^3/day. In the Sihe Mine, Jincheng Mining Area, Shanxi Province, the L-shaped horizontal well is used in the roof coal seam 3, and the pure gas production is 30 000 m^3/day. Innovative technologies such as large-scale staged fracturing both at the surface and underground and deep CBM development have been proposed to promote technological advancement in coal mining areas and ensure the safe mining and efficient development of CBM resources.

Keywords: coal mining area; coalbed methane (CBM); four-zone coordination; staged fracturing; fragmented and soft coal seam

煤层气既是一种引起煤矿瓦斯爆炸、煤与瓦斯突出和大气温室效应的灾害性气体,也是一种清洁能源,开发煤矿区煤层气具有安全、环保等多重效益。中国能源结构相对富煤、贫油、少气,2023年石油、天然气对外依存度分别为73%、42%[1-2]。中国煤层气资源储量丰富,据预测,埋深2 000 m以浅煤层气资源量为32.86×10^{12} m^3[3],埋深2 000 m以深煤层气资源量为40.71×10^{12} m^3[4]。中国煤层地质条件复杂,煤储层非均质性强,煤体结构复杂,主要以碎裂、碎粒和糜棱结构为主[5-6]。煤层整体渗透性较低,其中渗透率低于1.0×10^{-3} μm^2的煤层大约占到70%,较国外相同煤阶煤层渗透率低1～2个数量级,中国煤层气开发难度较大[7-9]。借助国家科技重大专项连续资助,中国煤矿区煤层气抽采量逐年稳步提升,2020年中国煤层气抽采量达到185.64×10^8 m^3,其中煤矿井下抽采量为127.97×10^8 m^3,地面抽采量为57.67×10^8 m^3[10-11],截至2023年,中国地面煤层气年抽采量增加到117.7×10^8 m^3[12]。基于中国煤层地质条件和煤矿采掘工程部署,经多年实践探索,晋城、淮南、淮北、阳泉、彬长等矿区已形成了煤矿区煤层气“四区联动”开发模式[13-14],并构建了适用于不同地质条件下的多种煤层气开发技术体系。基于上述研究背景,系统阐述了当前煤矿区煤层气开发模式,从煤矿生产时空接续角度,深入剖析了煤矿不同生产阶段及不同地质条件下的煤层气开发技术,并针对煤矿区煤层气开发提出下一步发展方向及研发重点。

1　煤矿区煤层气开发四区及特点

煤矿区生产是一个长期规划的资源开发过程,根据井田内各区域煤炭开采服务年限和开发先后顺序,可将开采煤层划分为生产规划区、开拓准备区、生产区以及煤炭开采后形成的采空区。煤矿规划区是指煤炭资源在未来5～10 a甚至更长时间才能开采的区域,煤层基本未受煤矿采掘扰动影响,煤层气地质、水文地质条件保存较好,该区域适合定向井压裂、水平井分段压裂等技术进行地面煤层气开发。准备区是指煤矿在3～5 a内进行回采区域,开拓巷道已经形成,煤层受到一定采掘扰动作用,煤层中大量水已基本疏干,煤层渗透性有所下降,在该区域往往利用井下开拓巷道布置千米定向长钻孔和分段压裂长钻孔进行井下大区域煤层气高效抽采。生产区是指正在进行煤炭开采的采(盘)区,已布置大量回采巷道,煤岩层受到强烈采掘扰动,在该区域一般利用回采巷道布置顺煤层钻孔、底抽巷布置穿层钻孔进行井下煤层气局部抽采。采空区主要指工作面煤层开采后在其后方形成的采动立体空间,该区域覆岩发生大范围移动,在垂直方向自下而上依次发育形成垮落带、裂隙带以及弯曲下沉带,在水平方向自工作面煤壁向后依次形成煤壁支撑区、离层区及重新压实区,其中裂隙带和离层区内赋存大量游离态煤层气。随着工作面的推移,三带、三区位置不断前移,空间内赋存煤层气也随之运移。采空区内煤层气一般采用地面直井、L型水平井或井下高位定向长钻孔进行煤层气负压抽采。

在传统煤矿区煤层气开发模式中，地面煤层气开发更注重资源收益转换，而井下煤层气抽采更注重降低煤层瓦斯压力，保障煤矿安全生产。在过往煤矿生产中忽略了煤炭开采与煤层气开发之间的相互影响，造成地面煤层气开发与煤矿井下安全生产、瓦斯治理脱节，甚至产生负面效应，给煤矿生产造成安全隐患[15-17]。在煤矿安全、高效开采背景下，要求在保障煤矿安全生产基础上促进煤与煤层气资源协调开发，尽可能从地面降低煤层中的含气量和压力，同时井下进行煤层气补充抽采。在此基础上，考虑煤矿生产时空顺序关系，依据煤矿开采中四区特点，采用不同形式的煤层气开发技术，建立煤矿区煤层气“四区联动”开发技术体系（图1）。通过规划区地面预抽、准备区井下区域预抽、生产区采中局部抽采以及采空区采后补充抽采，促进煤矿区煤层气多区域、全方位、全流程开发，同时有效减少煤矿瓦斯灾害，保障煤矿安全生产，实现“资源+安全”双效益[10,13,18]。

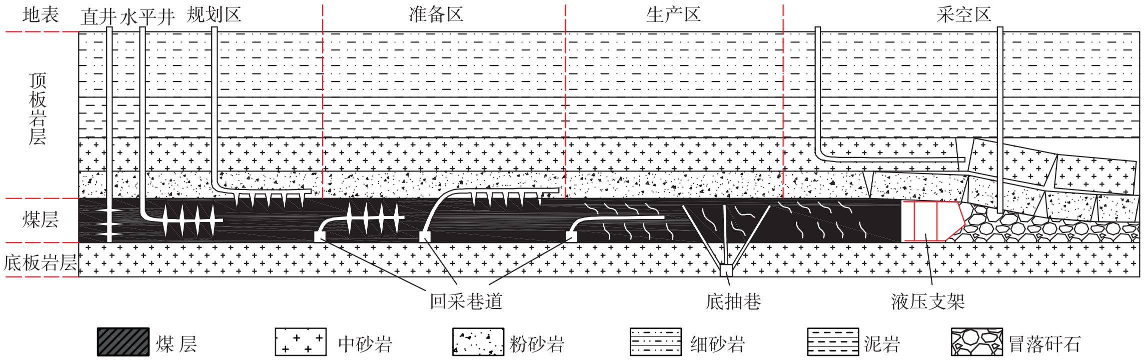


图1　煤矿区煤层气“四区联动”开发技术体系

Fig.1　Technical system for “four-zone coordinated” development of coalbed methane in coal mining areas

2　煤矿区煤层气开发技术及应用

2.1　规划区煤层气开发

煤矿规划区煤层基本不受开采扰动作用，煤层气主要以吸附气的形式存在，游离气较少。由于规划区煤层处于原始状态，井下未形成相应的采掘巷道，主要通过从地面施工垂直井或水平井对煤储层进行水力压裂，实现煤层气开发。针对规划区煤储层特点，目前已形成的煤层气开发技术主要有地面垂直井压裂技术、顺煤层水平井分段压裂技术及碎软煤层顶板水平井地面分段压裂技术。

2.1.1　地面垂直井压裂技术

地面垂直井压裂是通过从地面施工垂直井筒至煤层，利用高压流体直接压裂煤层，提高储层渗透率，进而通过排水降压促进煤层气解吸。该技术要求构造条件相对简单，目标煤层厚度大且稳定，埋深一般介于300～1 200 m，层数介于1～3层，煤体结构以碎裂结构—原生结构为主，煤层含气量及渗透率相对较高[19]。根据压裂介质不同，已形成活性水压裂、CO_2伴注、N_2伴注、N_2泡沫压裂等多项压裂技术。针对多煤层煤层气开发，已形成多煤层合层投球分压技术、垂直井层间暂堵转向压裂技术等。据不完全统计，中国主要煤炭企业在陕、晋、皖、豫、黔、甘等地煤矿施工7 100余口煤层气垂直井，并取得良好效果[20]。

陕西焦坪矿区煤层厚度介于4～12 m，含气量介于1～3 m^3/t，渗透率为3×10^{-3} μm^2，煤体结构坚硬，属于低煤阶、高渗透率硬煤层[21]。通过地面垂直井压裂技术进行煤层气开发，单井最高产气量达到1 929 m^3/d，累计产气量突破223×10^4 m^3，取得较好产气效果。甘肃窑街矿区海石湾煤矿煤层主要以肥煤为主，有少量气肥煤，煤层平均厚度为26.8 m，含气量介于8.33～8.79 m^3/t，渗透率为0.033×10^{-3} μm^2，煤体结构坚硬，属于低煤阶、低渗透率硬煤层[22]。从地面施工垂直井，采用层间暂堵转向压裂技术进行煤层气开发，单井最高产气量达2 607 m^3/d，稳定产气量为1 000 m^3/d以上。

2.1.2　顺煤层水平井分段压裂技术

地面垂直井压裂过程中，井筒与煤层接触面积较小，煤层气开发效率受限。为此，发展形成了顺煤层水平井分段压裂技术，即从地面向煤层中施工水平井直接进行分段水力压裂，达到改造煤层的目的（图2）。相比传统地面垂直井压裂，水平井分段压裂技术水平段井筒布置在煤层内，控气面积更大，煤层气开发效率相对更高。该技术在硬煤层压裂应用时，需要在钻井完成后进行固井操作，配合射孔-桥塞联作分段压裂工艺进行煤层气开发。而在软硬复合煤层压裂应用时，钻井下套管后可不进行固井操作，使用油管喷射+环空水力压裂的方式进行煤层气开发，环空中注入的高压液体在射流液体黏滞作用下被卷入煤层，可实现在低于煤层破裂压力条件下将煤层压开，并且套管外防窜流效果较好[23]。

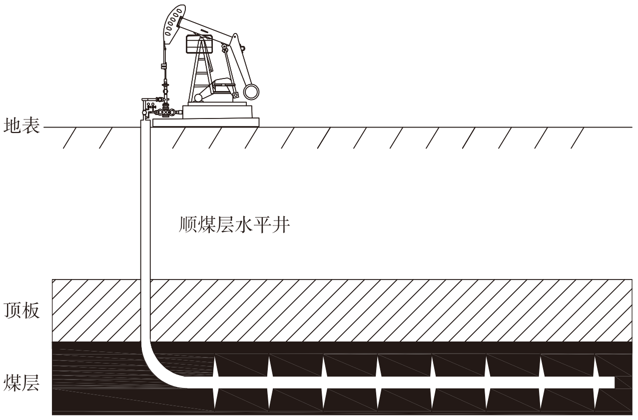


图2 顺煤层水平井分段压裂示意图

Fig.2 Schematic diagram of staged fracturing in coal-seam horizontal well

山西晋城矿区寺河煤矿15号煤层平均埋深为458 m，平均厚度为2.67 m，渗透率为$1.95\times10^{-3}\ \mu m^2$，平均含气量为24.10 m^3/t[24]。采用带底封油管拖动水力喷射与环空加砂压裂工艺进行煤层气开发，水平段长820.53 m，分8段进行射孔压裂，段间加密补射孔8段。该井是中国首次施工下套管不固井的水平井，煤层经过加砂压裂后，最高产气量突破9 100 m^3/d，稳定产气量为7 000～8 000 m^3/d。

2.1.3 碎软煤层顶板水平井地面分段压裂技术

碎软煤层具有煤体坚固性系数低、弹性模量低、泊松比高等特点，煤层气开发面临以下难题：钻井成孔困难，容易发生塌孔、埋钻事故；下套管困难、水泥固结质量差；在煤层中直接压裂时，容易导致裂缝前缘钝化，压裂缝延伸长度受限[25-27]。针对碎软煤层中煤层气开发难题，提出碎软煤层顶板水平井地面分段压裂技术。通过将水平井的水平段布置在煤层顶板岩层中，实施定向射孔分段压裂，进而沟通煤层与井筒，以增加煤层渗透率，提高煤层气产量（图3）。在进行碎软煤层顶板压裂时，裂缝的穿层扩展主要受控于地应力的分布特征，当地层垂直应力大于最小水平主应力时，有利于形成垂直压裂缝，这是裂缝穿层扩展的前提条件，而煤层最小水平主应力小于顶板岩层最小水平主应力是裂缝在煤层中水平方向不断扩展延伸的重要动力[28-30]。

安徽淮北矿区芦岭煤矿8号煤层平均埋深为729.15 m，平均厚度为10.09 m，含气量介于7～8 m^3/t，渗透率为$0.033\times10^{-3}\ \mu m^2$，煤体破碎松软，属于典型碎软低渗煤层[31]。采用U型顶板水平井进行煤层气开发，水平段长585.96 m，分7段进行水力压裂。前期采用4口垂直井进行压裂排采，平均产气量为1 446 m^3/d，后期同区域采用煤层顶板水平井分段压裂开发技术，单井产气量达到10 760 m^3/d，累计产气量超过750×10^4 m^3。对该井抽采5 a后进行含气量和地层压力数值模拟，结果显示：煤层气井压裂缝控制范围内含气量降低到5 m^3/t以下，部分区域含气量已降低至4 m^3/t以下，可见经过地面水平井抽采后，水平井控制范围内含气量降低约50%（图4a）；煤层气井周围地层压力约2.5 MPa，而煤层原始地层压力超过6.5 MPa，经过水平井抽采后，地层压力至少降低61.5%（图4b）。

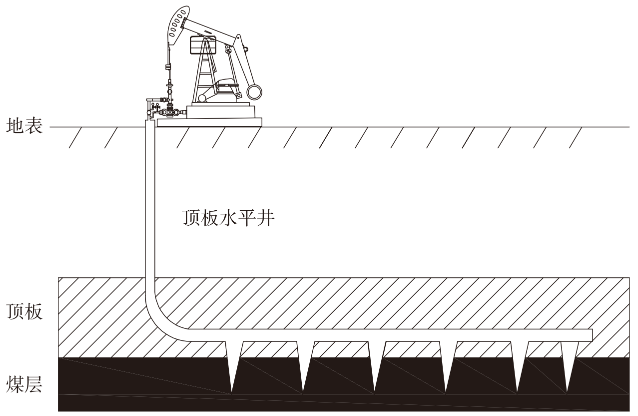
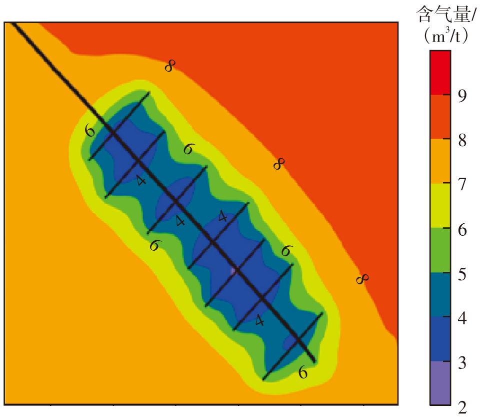
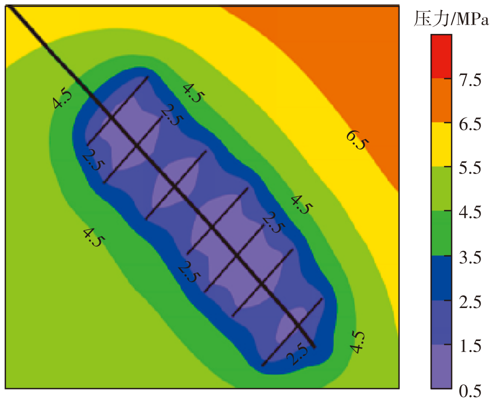


图3 碎软煤层顶板水平井地面分段压裂示意图

Fig.3 Schematic diagram of surface staged fracturing for horizontal wells in roof of fragmented and soft coal seams



a. 含气量变化情况



b. 地层压力变化情况

图4 煤层气井抽采5 a后含气量及地层压力变化情况

Fig.4 Variations in gas content and formation pressure after 5 years of coalbed methane well extraction

2.2 准备区煤层气开发

准备区煤层气开发主要是对煤层的采前预抽,该区域周围已经形成部分开拓巷道,可用作后期煤层气开发场地。准备区的煤层气开发主要采用煤矿井下定向长钻孔水力压裂技术,实现对工作面超前区域煤层气抽采。煤矿井下水力压裂技术又分为整体水力压裂和分段水力压裂:整体水力压裂技术包括硬煤顺煤层定向长钻孔整体水力压裂[32]和碎软煤顺煤层定向长钻孔整体水力压裂[33];分段水力压裂技术包括硬煤顺煤层定向长钻孔分段水力压裂、碎软煤层顶板定向长钻孔分段水力压裂及碎软煤层顶(底)板梳状定向长钻孔分段水力压裂[34]。分段水力压裂相比整体水力压裂更有利于裂缝的扩展,实现煤层大区域增透,目前作为准备区煤层气开发的主要手段被广泛应用。

2.2.1 硬煤顺煤层定向长钻孔分段水力压裂技术

硬煤层自身坚固性系数大,在钻井过程中容易成孔,有利于后期进行压裂和煤层气抽采。基于硬煤层特点,形成硬煤顺煤层定向长钻孔分段水力压裂技术,即沿着工作面倾向或走向在煤层中施工定向长钻孔,然后通过分段水力压裂技术对煤层进行卸压增透,提高煤层气抽采效率。

陕西彬长矿区大佛寺煤矿4号煤层埋深介于520~596 m,平均厚度为11.6 m,瓦斯压力介于0.65~0.70 MPa,瓦斯含量介于5.5~6.0 m^3/t,煤体坚固性系数介于1.0~2.0,属于典型硬煤层[34]。采用顺煤层定向长钻孔分段水力压裂技术进行煤层气抽采,共施工3个压裂钻孔,每个压裂钻孔长500~600 m,孔径为96 mm,分8段进行压裂,钻孔注入液体量900~1 200 m^3。压裂影响直径80 m,压裂钻孔瓦斯抽采纯量最高为3 600 m^3/d,平均1 000~2 500 m^3/d,百米瓦斯抽采纯量是同区域未压裂钻孔的4.9~11.0倍。

2.2.2 碎软煤层顶板定向长钻孔分段水力压裂技术

对于煤体结构碎软的煤层,传统顺煤层定向长钻孔分段水力压裂技术适用性较差,在煤层中钻进定向长钻孔时容易发生塌孔事故,并且压裂缝在碎软煤层中扩展长度有限,导致煤矿井下碎软煤层的煤层气开发效率低。借鉴地面碎软煤层的煤层气开发经验,研发了适用于煤矿井下的碎软煤层顶板定向长钻孔分段水力压裂技术,即从井下巷道向上施工顶板定向长钻孔进行分段水力压裂,通过穿层裂缝对煤层进行增透,在提高钻孔成孔率的同时,提高煤层气抽采效率(图5)。

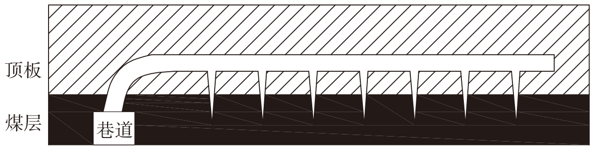


图5 碎软煤层顶板定向长钻孔分段压裂示意图

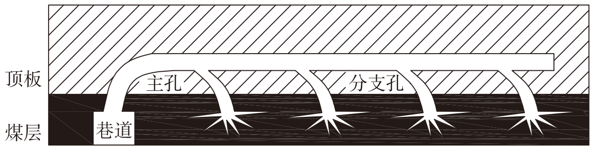
Fig.5 Schematic diagram of staged fracturing for directional long boreholes in roof of fragmented and soft coal seams

山西阳泉矿区新景煤矿3号煤层埋深介于458.9~558.2 m,厚度介于2.1~2.7 m,煤体结构类型以碎粒煤、糜棱煤和碎裂煤为主,煤体坚固性系数介于0.3~0.8,含气量为15.98 m^3/t[35]。共施工2个煤层顶板定向长钻孔对煤层进行水力压裂改造,钻孔长度均为609 m,孔径为120 mm,压裂支撑剂选用0.4~0.6 mm和0.6~0.8 mm的核桃壳砂,压裂采用BYW(S)-30/1000型加砂压裂泵组、89 mm型双封单卡分段压裂工具。压裂结果显示:最大压裂影响直径达到76 m,1号钻孔百天瓦斯抽采量为1 025.11 m^3/d,2号钻孔百天瓦斯抽采量为2 810.60 m^3/d,百米钻孔瓦斯抽采纯量是同区域顺煤层未压裂钻孔瓦斯抽采量的5.6~15.4倍。

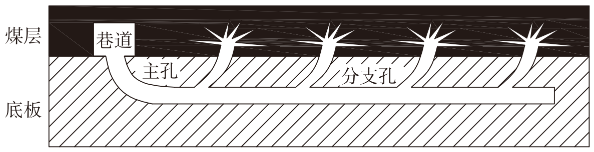
2.2.3 碎软煤层顶(底)板梳状定向长钻孔分段水力压裂技术

对于一些不具备裂缝穿层条件或穿层效果较差的碎软煤层,研发了碎软煤层顶(底)板梳状定向长钻孔分段水力压裂技术,即从煤矿井下巷道内向顶(底)板施工定向长钻孔作为主孔,沿主孔间隔一定距离施工分支孔进入煤层并适当延伸。在进行水力压裂时,分支孔可对裂缝扩展起到有效引导作用,有利于对碎软煤层更好进行增透(图6)。

陕西韩城矿区桑树坪二号井3号煤层平均厚度为5.97 m,煤体结构以碎粒煤和糜棱煤为主,煤体坚固性系数介于0.1~0.5,瓦斯含量介于6.75~9.80 m^3/t,煤层瓦斯



a. 顶板梳状定向长钻孔分段水力压裂



b. 底板梳状定向长钻孔分段水力压裂

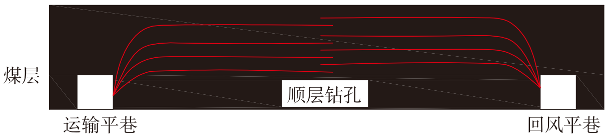
图6 碎软煤层顶(底)板梳状定向长钻孔分段水力压裂示意图

Fig.6 Schematic diagram of staged hydraulic fracturing for comb-shaped directional long boreholes in roof (or floor) of fragmented and soft coal seams

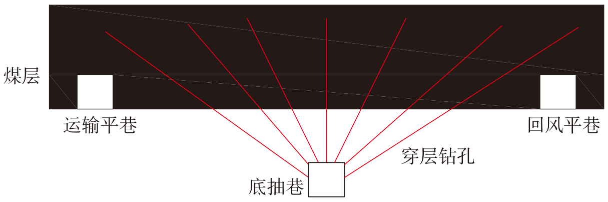
压力为2.5 MPa[36−37]。施工1个煤层顶板梳状定向长钻孔对煤层进行压裂，压裂钻孔主孔长588 m，开8个分支孔，钻孔直径98 mm，分4段进行压裂，累计注入液体量2 012 m^3。压裂结果显示：最大压裂影响直径达到79 m，钻孔连续抽采93 d，平均瓦斯含量为1 559 m^3/d，百米钻孔瓦斯抽采纯量是水力割缝钻孔瓦斯抽采纯量的1.2倍，是常规百米钻孔瓦斯抽采纯量的4倍。

2.3　生产区煤层气开发

生产区煤层气开发主要是对正在进行生产的采区或盘区工作面进行卸压瓦斯抽采，消除煤层内部瓦斯抽采“空白带”。生产区煤层相较于准备区受到工作面开采扰动更强烈，煤层卸压明显，煤层气开发方式根据煤层坚固性系数不同有所差异。对于硬煤层，一般在工作面回采巷道施工顺煤层定向长钻孔，或底板巷道施工穿层定向长钻孔直接进行煤层瓦斯抽采（图7）。对于碎软煤层，针对其易塌孔、透气性低、煤层瓦斯解吸困难等问题[38−39]，研发了碎软煤层井下穿层钻孔高压加砂水力压裂和顺煤层气动定向长钻孔高效抽采技术。



a. 顺煤层定向长钻孔抽采



b. 底板巷穿层钻孔抽采

图7　生产区煤层气开发技术模式

Fig.7　Technical model of coalbed methane development in production areas

2.3.1　井下高压加砂水力压裂技术

针对碎软煤层水力压裂过程中裂缝易闭合的问题，借鉴地面水力加砂压裂经验，研发了井下穿层钻孔高压水力压裂技术。高压水力加砂压裂，是指将石英砂或其他骨料提前放入到加砂装备，当高压水经过加砂装备，对骨料进行冲击扰动实现混砂，然后由高压水携带进入地层裂缝。该技术可实现多穿层钻孔连续加砂压裂，有效提高了现场施工效率。

安徽淮南矿区潘三煤矿13−1煤层平均厚度为4 m，煤层坚固性系数介于0.26～0.52，瓦斯含量为8.4 m^3/t，煤层瓦斯压力介于2.6～2.8 MPa，煤层透气性系数为0.022 m^2/(MPa·d)，属于碎软低渗高突煤层[40]。为消除煤层瓦斯突出危险性，从煤层底板巷道施工穿层钻孔进行高压水力加砂压裂，共施工5个压裂钻孔，最大加砂量达到150 kg，最大注水量达到316 m^3。抽采结果显示，加砂压裂后百米钻孔瓦斯抽采纯量是常规清水压裂的2.38倍。

2.3.2　气动定向长钻孔高效抽采技术

针对碎软煤层钻进过程中，钻孔受水流冲刷作用容易发生塌孔问题，研发了顺煤层气动定向长钻孔高效抽采技术。该技术采用压风驱动气动螺杆钻具定向钻进，利用单弯螺杆钻具实现井下碎软煤层中定向钻进成孔及筛管完孔[41−42]，有效提高了碎软煤层瓦斯治理效率。

山西阳泉矿区华阳某矿8号煤层平均厚度为11.6 m，煤层坚固性系数为0.48，瓦斯含量介于7.05～8.48 m^3/t，煤层瓦斯压力介于0.48～0.59 MPa，煤层透气性系数为0.003 1 m^2/(MPa·d)，属于碎软低渗煤层[43]。共施工10个顺煤层气动定向长钻孔进行工作面煤层瓦斯区域抽采，最大钻孔深度达到607 m，单孔日均抽采瓦斯纯量最大达到971.6 m^3.

2.4　采空区煤层气开发

在煤层开采后，上覆岩层垮落形成采空区，岩层自上而下形成弯曲下沉带、裂隙带和垮落带。其中，在裂隙带和垮落带内容易积聚瓦斯，影响煤矿安全生产。针对采空区内瓦斯治理，发展形成了地面采动井抽采技术，采动井根据井型可分为L型水平井和直井[44]（图8）。由于该区域内工作面上覆岩层卸压强烈，采动裂隙大量发育，区别于规划区、准备区和生产区的煤层气开发方式，该区域内的煤层气抽采一般不需要对煤层进行水力压裂，而是直接将采动井布置在裂隙发育区内，使瓦斯经由裂隙网络和井眼抽采至地面，从而降低采空区范围内的瓦斯含量[45−47]。

安徽淮南矿区潘一矿11−2煤层厚度介于1.2～2.2 m，13−1煤层厚度介于3.0～7.0 m，11−2煤位于13−1煤的下方，两层煤平均间距为64 m，两层煤均具有突出危险性，通过对下部厚度较小的11−2煤开采，实现对上部厚煤层卸压抽采的效果[48]。采用地面采动直井对上部13−1煤层进行煤层气抽采，单井最高日抽采瓦斯纯量超过5×10^4 m^3，共抽采360余天，累计抽采量为(120～360)×10^4 m^3。山西晋城矿区寺河矿3号煤层厚度为6.1 m，测定最大瓦斯含量为7.5 m^3/t，采用地面采动L型水平井进行煤层气抽采，瓦斯抽采体积分数保持在70%～90%，单井最高日抽采瓦斯纯量达到3×10^4 m^3，共抽采240余天，累计抽采量约300×10^4 m^3[49]。

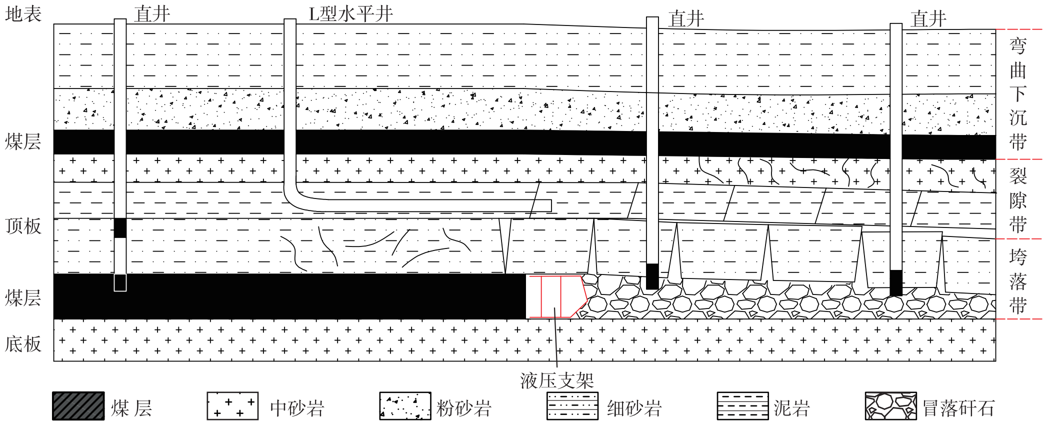


图8　采空区煤层气开发技术模式

Fig. 8　Technical model of coalbed methane development in mined-out areas

3　展望

3.1　发展大规模分段压裂技术

针对煤矿规划区煤层气开发，目前采用的地面井压裂技术排量有限，当煤层埋藏较深时，形成的水力压裂缝在高地应力作用下很快发生闭合，导致地面煤层气开发时采气量衰减过快。已有深部煤层气开发实践表明，增加煤层有效改造体积是提高煤层气产量的关键。在大宁—吉县区块煤层气开发过程中，丛式井平均单井压裂液量由1 600 m^{3}增至3 100 m^3，平均单井加砂量由30 m^{3}增至400 m^3，平均产气量由2 680 m^3/d增至1.4×10^4 m^3/d，提高了4.2倍；水平井平均单段压裂液量由1 000m^{3}增至近4 000 m^3，平均单段加砂量由55 m^{3}增至530 m^3，平均产气量由1×10^4 m^3/d增至10.2×10^4 m^3/d，提高了9.2倍[50]。借鉴深部煤层气开发经验，将极限饱和体积压裂技术引入煤矿区煤层气水平井分段压裂施工中，通过大排量、大砂量，对煤层均衡压裂，使水力压裂缝全域覆盖，从而实现“无空白带”煤层气区域高效抽采。针对煤矿区极限体积压裂技术的应用，未来主要攻关方向包括：小间距水平井防窜扰压裂技术、暂堵转向压裂技术及煤层气水平井产气/产液剖面监测技术等。在规划区发展大规模水力压裂时，要选择合理压裂层位和压裂排量，避免过度压裂对煤层后期回采可能造成的负面影响，包括工作面顶板支护、巷道围岩控制等问题。

3.2　发展井地联合分段水力压裂技术

当前，煤矿井下定向长钻孔分段水力压裂技术受井下巷道空间条件及水力压裂装备能力的制约，导致压裂规模有限，并且压裂施工与生产作业容易出现时空矛盾，这不仅影响煤矿生产效率，还会影响压裂施工效果。而地面水力压裂则可发挥场地优势，排量更大、压裂影响范围更广，同时可实现工厂化一体式压裂施工作业[51-53]。在此基础上，发展一种适合于煤矿区的新型井地联合分段水力压裂技术。在煤矿井下施工定向长钻孔群，将大排量、高压力的携砂压裂液通过地面贯通井和高压管汇泵注到煤矿井下钻场，再依次对多个定向长钻孔实施分段水力压裂（图9）。通过井巷联合、地面大排量泵注、井下压裂、并网抽采，更好实现煤矿区煤层气开发。该技术未来主要攻关方向包括：地面垂直井与井下压裂巷道精准对接技术、煤矿井下近水平大直径定向长钻孔下套管及固孔技术、井下多钻孔分段压裂裂缝扩展机理、井下水平定向长钻孔套管内分段射孔及压裂工艺技术等。在发展井地联合分段水力压裂技术时，要考虑矿井通风能力，有序、分区域对煤层进行压裂增透，避免大范围压裂煤层后造成煤矿井下瓦斯大量解吸，进而引发井下瓦斯超限，影响煤矿正常生产活动。

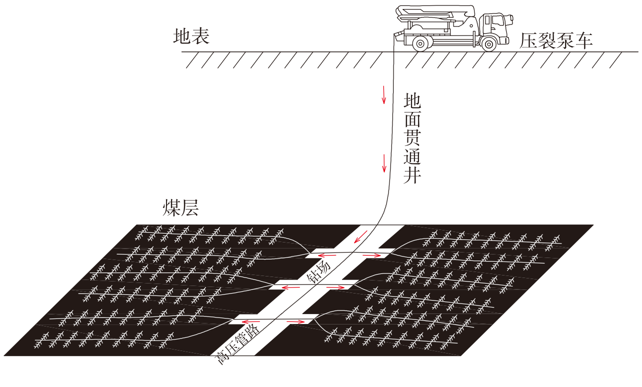


图9　煤矿区井地联合压裂技术示意图

Fig.9　Schematic diagram of combined underground and surface fracturing technology in coal mining areas

3.3　加强煤矿区深部煤层气开发

中国深部煤层气地质储量丰富，远大于埋深2 000 m以浅资源量，大宁—吉县区块、大牛地气田、延川南区块

等开发实践已证明深部煤层气开发潜力巨大[54–58]。随着中国煤矿开采强度不断增加，煤矿开采正以8～12 m/a的速度向深部延伸。进入深部开采后，煤层赋存地质条件更加复杂，面临高地应力、高地温、岩石破裂程度加剧及涌水量增加等系列问题，给深部资源开发带来严峻挑战[59]。加强煤矿区深部煤层气开发不仅可以提升煤矿区煤层气产量，同时有利于进一步掌握煤矿区深部煤炭资源赋存规律，为未来深部煤炭资源开采奠定基础。针对深部煤层气的开发，未来主要攻关方向包括：煤矿区深部煤层气甜点区优选技术、煤层气长水平井钻完井技术、煤岩层缝网压裂工艺技术及智能排采技术等。

4　结论

1）生产实践形成了以规划区、准备区、生产区和采空区为基础的“四区联动”煤矿区煤层气开发高效开发技术体系，建立了煤矿生产过程中高瓦斯突出煤层全覆盖、立体式煤层气抽采模式，保障了煤层气高效开发及煤矿安全生产。

2）根据煤矿采掘工程部署和煤层地质条件，形成了适应于煤矿不同区域的煤层气开发技术。煤矿规划区煤层主要采用地面垂直井压裂、水平井顺煤层分段压裂模式进行煤层预抽，碎软煤层一般采用顶板水平井分段压裂预抽；在煤矿准备区利用煤矿开拓巷道进行煤层气抽采，硬煤层一般采用顺煤层定向长钻孔井下分段压裂预抽，碎软煤层主要采用围岩定向长钻孔井下分段压裂预抽；在煤矿生产区利用回采巷道或底抽巷，采用顺煤层钻孔、穿层钻孔两种形式抽采；在煤矿采空区多采用地面L型水平井或直井对采动卸压区煤层气进行抽采。

3）煤矿区煤层气开发取得较好应用效果。甘肃窑街海石湾矿地面垂直井单井产气量最高达2 607 m^3/d；山西晋城寺河矿地面水平井单井产气量最高达9 100 m^3/d；安徽淮北芦岭矿碎软煤层单井产气量最高达10 760 m^3/d；陕西彬长大佛寺矿井下定向长钻孔分段水力压裂瓦斯抽采量最高可达3 600 m^3/d；安徽淮南潘一矿采空区地面直井煤层气单井日抽采量最高超过5×10^4 m^3/d；山西晋城寺河矿采空区地面水平井抽采量最高可达3×10^4 m^3/d。

4）结合中国煤矿区煤层气开发需求，分析了当前煤矿区煤层气开发过程中面临的主要问题，为增强煤矿区煤层气开发效果，煤矿区要进一步发展大规模分段压裂技术和井地联合分段压裂技术，同时加强对深部煤层气资源的开发。

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（编辑　柳超超）