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## 基于CT扫描的CO<sub>2</sub>相变致裂煤裂隙演化特征

刘高峰<sup>1,2,3</sup>, 关文博<sup>1</sup>, 张震<sup>1</sup>, 李宝林<sup>1</sup>, 刘欢<sup>1</sup>, 司念<sup>1</sup>

1. 河南理工大学资源环境学院, 河南焦作 454003;
2. 河南理工大学煤炭安全生产与清洁高效利用省部共建协同创新中心, 河南焦作 454003;
3. 河南理工大学中原经济区煤层(页岩)气河南省协同创新中心, 河南焦作 454003

**摘要:**为进一步揭示CO<sub>2</sub>相变致裂煤的裂隙改造机理,开展了CO<sub>2</sub>相变致裂煤体实验,基于CT扫描和三维裂隙重构,分析了CO<sub>2</sub>相变致裂前后的煤样内部裂隙结构参数,查明了CO<sub>2</sub>相变致裂煤的三维裂隙结构演化特征。结果表明,致裂后煤样的裂隙总数量减少,裂隙总体积和裂隙总表面积增加;CO<sub>2</sub>相变致裂产生了裂隙扩张转化效应,在致裂压力的扩张作用下,小尺度裂隙转化为更大尺度的裂隙;长度小于1 000 μm的裂隙数量减少、裂隙体积和表面积明显减小,长度大于1 000 μm的裂隙体积和表面积明显增大,且裂隙之间扩张贯通而引起其数量减少;CO<sub>2</sub>相变致裂大幅度改善了煤体三维裂隙的连通性,有利于气体的运移和产出。此研究为CO<sub>2</sub>相变致裂效果提供新的分析评价方法,也可为其他非常规天然气储层及其改造的裂隙演化特征研究提供参考和借鉴。

**关键词:**CO<sub>2</sub>相变致裂;CT扫描;煤储层;三维裂隙演化

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## Evolution characteristics on coal fractures induced with CO<sub>2</sub> phase transition fracturing based on CT scanning

LIU Gaofeng<sup>1,2,3</sup>, GUAN Wenbo<sup>1</sup>, ZHANG Zhen<sup>1</sup>, LI Baolin<sup>1</sup>, LIU Huan<sup>1</sup>, SI Nian<sup>1</sup>

1. School of Resources & Environment, Henan Polytechnic University, Jiaozuo Henan 454003, China;
2. Collaborative Innovation Center of Coal Work Safety and Clean High Efficiency Utilization, Henan Polytechnic University, Jiaozuo Henan 454003, China;
3. Collaborative Innovation Center of Coalbed Methane and Shale Gas for Central Plains Economic Region, Henan Polytechnic University, Jiaozuo Henan 454003, China

**Abstract:** This study conducted the CO<sub>2</sub>-PTF coal experiment to further reveal the fracturing transformation mechanism of CO<sub>2</sub> phase transition fracturing (CO<sub>2</sub>-PTF) coal. According to the CT scanning and 3D fracture reconstruction, we analyzed the fracture structure parameters of coal before and after CO<sub>2</sub>-PTF, and clarified the evolution characteristics of the three-dimensional fracture structure of coal induced by CO<sub>2</sub>-PTF. The research results indicated that after CO<sub>2</sub>-PTF, the total number of fractures in the coal sample decreased, while the total volume and surface area of fractures increased. The CO<sub>2</sub>-

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作者简介:刘高峰(1982—),男,河南沁阳人,博士,副教授,博士生导师,主要从事瓦斯地质与煤层气开发等方面的研究工作。Tel: 13639624360, E-mail: liugaofeng82@163.com

PTF generated fracture expansion and transformation effects where the small-scale fractures were expanded and transformed into larger scale fractures under the CO<sub>2</sub>-PTF pressure. The number, volume, and surface area of fractures of less than 1 000 μm in length were significantly reduced, while the volume and surface area of fractures of longer than 1 000 μm in length were significantly increased. The expansion and connection between fractures caused a decrease in their quantity. CO<sub>2</sub>-PTF improves the connectivity of the three-dimensional fracture in coal and is conducive to gas migration and production. This study offers new insights into and evaluation method for the effect of CO<sub>2</sub>-PTF, and could provide references for the research on fracture evolution characteristics in other unconventional natural gas reservoirs and their modifications.

**Key words:** CO<sub>2</sub> phase transition fracturing; CT scanning; coal reservoir; three dimensional fracture evolution

我国构造煤普遍发育,具有低渗透、难抽采和易发生煤与瓦斯突出等显著特征<sup>[1-2]</sup>。随着采掘深度的加大,受地质构造演化、煤层赋存环境以及瓦斯赋存条件等因素影响,煤与瓦斯突出问题将严重制约煤炭安全高效开采<sup>[3-6]</sup>。针对低渗难抽突出煤层,我国开发了多种煤矿井下增透抽采和消突技术,但不同技术适应于不同瓦斯地质条件的煤层和矿区。研发安全、有效、经济且适用性强的增透抽采和消突技术,是煤与瓦斯共采领域的主要研究内容和重大需求之一<sup>[7-8]</sup>。

CO<sub>2</sub>相变致裂技术源于1914年美国发明的CARDONX技术,是利用液态CO<sub>2</sub>加热膨胀所产生的高压气体膨胀能作用在煤体或岩体,进而使煤层或岩层破裂的非炸药物理爆破技术。能量分析表明,CO<sub>2</sub>经历由液态至超临界和气态的转变,1 kg的液态CO<sub>2</sub>相变后,相变能当量相当于397 g TNT炸药<sup>[9]</sup>。20世纪90年代,我国引入CO<sub>2</sub>相变致裂技术,21世纪初在高瓦斯矿井采煤工作面进行采煤试验,发现应用于瓦斯治理的潜在可行性。近年来开展的系统研究、设备研发和工程应用试验,主要应用于煤矿井下致裂煤层卸压增透抽采瓦斯<sup>[10]</sup>、煤巷消突快速掘进<sup>[11]</sup>、井筒揭煤等技术领域<sup>[12]</sup>。现场试验效果显示,CO<sub>2</sub>相变致裂煤层是一种新兴的增透消突方法,具有安全性能高、避免水力化措施的负面效应等独特的技术优势<sup>[13-14]</sup>。

煤是一种多尺度孔-裂隙介质,其孔-裂隙结构特征及其连通性,直接控制着煤层气(瓦斯)的解吸、扩散和渗流等运移产出能力<sup>[15-17]</sup>。因此,学者进行水力压裂<sup>[18]</sup>、爆生气体<sup>[19]</sup>、酸化<sup>[20]</sup>、冲击荷载<sup>[21]</sup>、溶剂萃取<sup>[22]</sup>、高压电脉冲<sup>[23]</sup>等多种储层改造研究,通过分析改造储层的孔-裂隙结构演化特征,去揭示储层改造机理,为改造参数的优化提供科学依据。最近,CO<sub>2</sub>相变致裂对煤储层孔-裂

隙结构的改造研究受到了关注,一系列研究致力于探索CO<sub>2</sub>相变致裂对煤储层孔-裂隙结构的影响。BAI等<sup>[24]</sup>研究表明,CO<sub>2</sub>相变致裂后,煤中孔径大于1 μm的孔容明显增加;XIA等<sup>[25]</sup>开展高压压汞测试,CO<sub>2</sub>相变致裂后大于1 000 nm的大孔孔容明显增大;LIU等<sup>[26]</sup>的压汞实验结果表明,距CO<sub>2</sub>相变致裂孔1.5 m范围内,煤样100~1 000 nm孔隙的孔容降低,孔径大于1 000 nm的孔容明显增大,渗透率明显提高;最近研究揭示了CO<sub>2</sub>相变致裂煤的孔隙改造效应,主要影响的孔隙尺度为孔径大于2 nm<sup>[27-28]</sup>;致裂后,煤对瓦斯的吸附能力减弱、解吸能力增强<sup>[29]</sup>。在裂隙研究方面,CAO等<sup>[30-31]</sup>现场监测发现,CO<sub>2</sub>相变致裂产生了长度达到1~3 m的放射状裂隙,进一步通过扫描电子显微镜观察,发现致裂后煤样产生了大量三翼型微裂隙和损伤坑;白鑫等<sup>[32]</sup>借助扫描电子显微镜观察致裂后的煤样,发现微裂隙开度集中在数十微米。

上述相关研究主要以定性或半定量分析CO<sub>2</sub>相变致裂煤的二维裂隙演化特征。但是,煤中裂隙分布具有明显三维特征<sup>[33]</sup>,裂隙的数量、长度、体积、表面积是反映煤裂隙三维特征的关键参数<sup>[34-36]</sup>,CO<sub>2</sub>相变致裂煤的三维裂隙结构演化特征尚未查明,阻碍了CO<sub>2</sub>相变致裂增透消突机理的全面揭示,制约了CO<sub>2</sub>相变致裂的效果评价和参数优化。因此,有效获取、分析CO<sub>2</sub>相变致裂煤的三维裂隙结构参数,查明三维裂隙结构演化特征,对进一步揭示CO<sub>2</sub>相变致裂煤层增透消突机理具有重要意义。CT扫描作为一种无损技术,结合三维重建可以有效对三维裂隙进行精细表征<sup>[37]</sup>,为分析CO<sub>2</sub>相变致裂煤的三维裂隙演化提供了技术支撑。通过开展CO<sub>2</sub>相变致裂煤体模拟实验,借助CT扫描和裂隙三维重构获取CO<sub>2</sub>相变

致裂前后煤样内部的三维裂隙结构参数,分析 CO<sub>2</sub> 相变致裂煤的裂隙结构演化特征,进一步揭示 CO<sub>2</sub> 相变致裂改造煤层的机理,同时为研究 CO<sub>2</sub> 相变致裂效果提供新的评价分析方法。

## 1 样品与测试

### 1.1 样品

实验样品采自河南平顶山八矿的己<sub>15</sub> 煤层,煤样块状构造,原生条带结构保存完好,内生裂隙发育。煤样工业分析结果见表 1。煤样采集后密封包装运至实验室,利用线性切割机加工 CO<sub>2</sub> 相变

致裂所需煤柱(直径 50 mm,高 75 mm)。

表 1 煤样工业分析

Table 1 Proximate analysis of coal %

空气干燥基水分	空气干燥基灰分	干燥无灰基挥发分	最大镜质体反射率
0.97	10.03	24.91	1.22

### 1.2 CO<sub>2</sub> 相变致裂实验

CO<sub>2</sub> 相变致裂煤体实验装置(图 1)主要包括:由液态 CO<sub>2</sub>、加热器、定压爆破片组成的 CO<sub>2</sub> 相变致裂器,致裂器外部套管,4 个煤样盒。

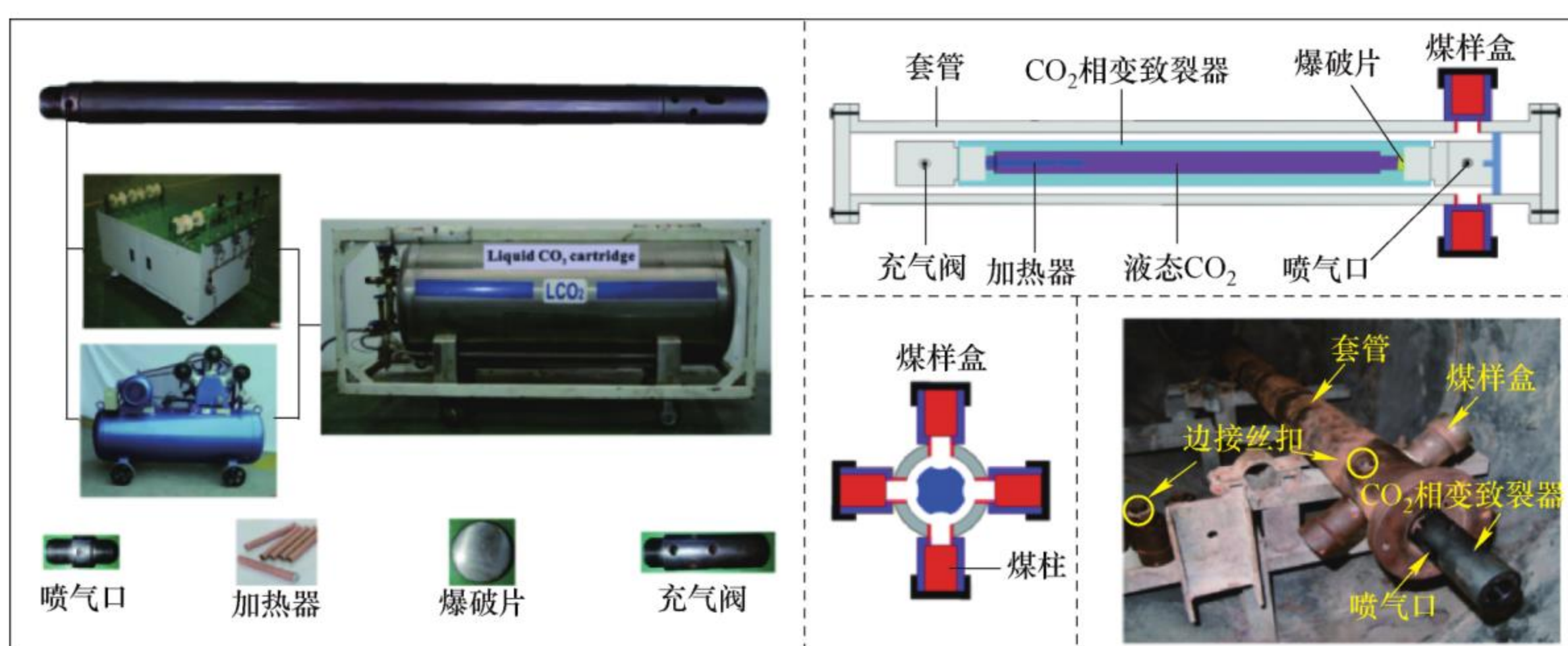


图 1 CO<sub>2</sub> 相变致裂实验装置

Fig. 1 Experimental device of CO<sub>2</sub> phase transition fracturing

CO<sub>2</sub> 相变致裂煤体的实验流程如下:

- (1) 组装致裂器并充装液态 CO<sub>2</sub>;
- (2) 将致裂器外部套管固定在安全实验仓支架上;
- (3) 将致裂器放入套管,调整致裂器喷气口使之正对外部煤样盒;
- (4) 连接致裂器导线,封闭外部套管,关闭安全实验仓,启动加热器,开展 120 MPa 压力下 CO<sub>2</sub> 相变致裂实验;

(5) 卸下煤样盒,取出煤样密封保存。

### 1.3 CT 扫描

采用 GE 公司的 CT 扫描装置,型号为 Phoenix V|tome|xm(图 2),主要参数:分辨率 30.4 μm,扫描电压 200 kV,扫描电流 170 μA,曝光时间 500 ms,每次扫描获得 1 611 × 1 611 像素的切片 2 467 张。

对 CT 扫描的切片进行消噪滤波、阈值分割、三维重构等处理后,即可获取煤样内部三维裂隙。

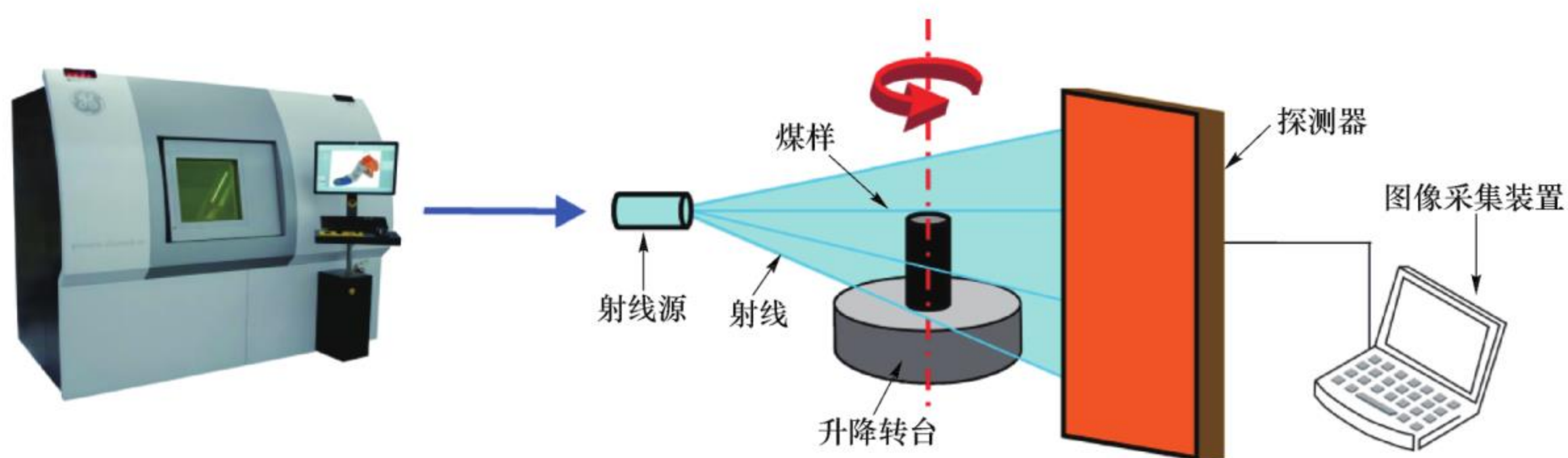


图 2 煤体 CT 扫描装置

Fig. 2 CT scanning device for coal

## 2 CT 图像分析

### 2.1 CT 扫描切片二维裂隙图像分析

基于CT扫描实验,选择CO<sub>2</sub>相变致裂前后6个不同角度的煤样纵切面(致裂后的6组纵切面位置与致裂前的6组纵切面位置一一对应),CO<sub>2</sub>相变致裂前后煤样纵切面裂隙的二值化过程如图3所示。可以看出,与以往借助扫描电镜相比,CT扫描的二维裂隙图像分析可以更直观、更全面地对

比分析致裂前后、不同角度纵切面的二维裂隙发育特征,煤样不同角度纵切面的二维裂隙分布差异性大,存在明显的非均质性。但是,由于二维裂隙仅是三维裂隙在二维平面上的局部反映,不同纵切面内的二维裂隙可能对应的是同一条三维裂隙,通过CT扫描二维裂隙图像只能分析局部裂隙的分布情况,无法对煤样内部整体的三维空间裂隙发育特征进行表征和分析,因此需要利用CT扫描切片图像对煤样的裂隙结构进行三维重建。

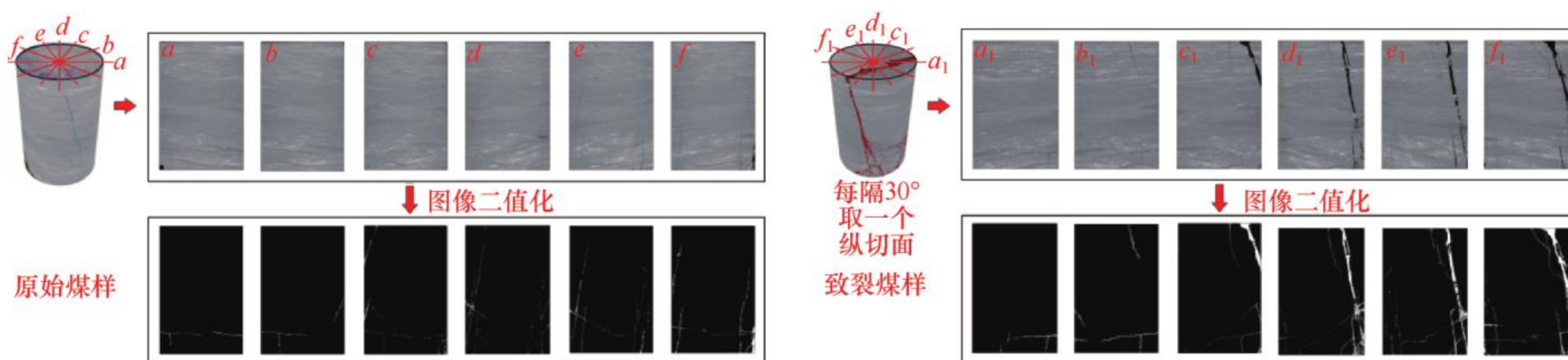


图3 CO<sub>2</sub>相变致裂煤的不同角度纵切面二值化

Fig. 3 Binarization of longitudinal sections with different angles in the coal sample with CO<sub>2</sub>-PTF

### 2.2 CT 扫描三维重构裂隙图像分析

将CT扫描的煤样裂隙二维切片沿煤样径向逐层导入三维可视化软件VG Studio Max中,利用该软件的重构模块对煤样裂隙进行三维重构<sup>[38]</sup>,将重构得到的裂隙进行颜色渲染,建立直观的三维裂隙结构。CO<sub>2</sub>相变致裂前后煤样三维裂隙如图4所示,由裂隙渲染的颜色反映出裂隙体积不断增大(蓝色到红色)。由图4(a)可知,致裂前

煤样内部裂隙体积主要在30~240 mm<sup>3</sup>之间,以小体积裂隙为主,裂隙之间连通性较差;由图4(b)可知,致裂后煤样内部裂隙体积在272.49~2724.90 mm<sup>3</sup>之间,煤样内部形成纵向贯通的大体积裂隙,反映在CO<sub>2</sub>相变致裂过程中,高压CO<sub>2</sub>气流超过煤体抗拉强度,煤体结构被破坏,促使煤体原有裂隙扩张并产生新裂隙,裂隙之间连通性增强。

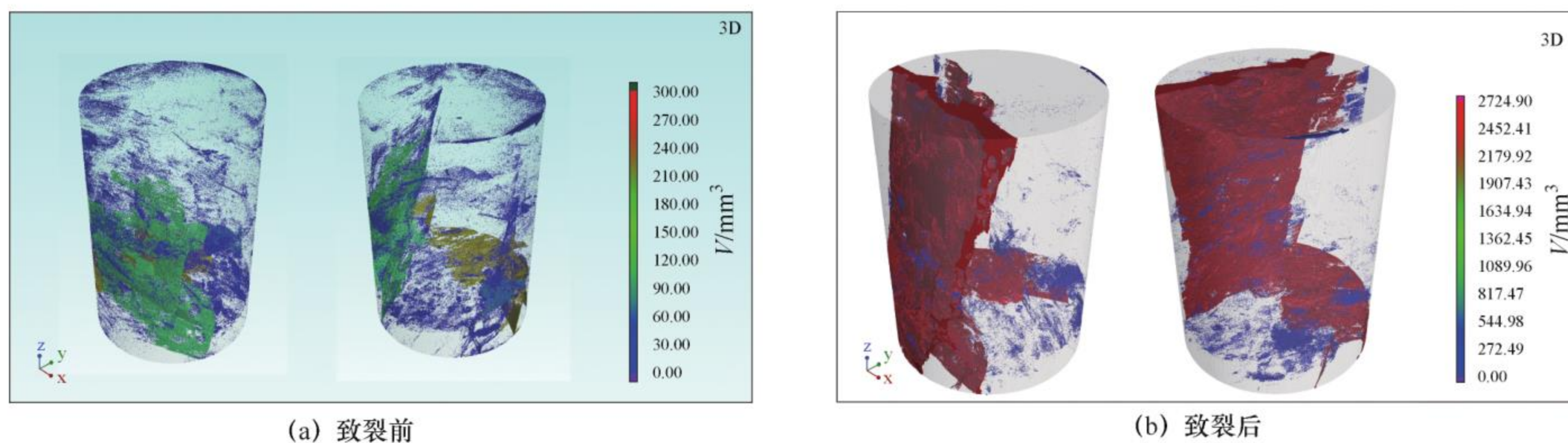


图4 CO<sub>2</sub>相变致裂同一煤样不同角度三维裂隙重构

Fig. 4 3D fracture reconstruction of the coal samples before and after CO<sub>2</sub>-PTF

## 3 CO<sub>2</sub>相变致裂煤的三维裂隙演化特征及机理

### 3.1 CO<sub>2</sub>相变致裂煤的三维裂隙演化特征

借助CT扫描三维重构方法,可以进一步定量

化分析CO<sub>2</sub>相变致裂前后的裂隙数量、体积和表面积,以及不同尺度下裂隙结构参数变化特征。相关研究表明,煤中裂隙表现出不同尺寸的三维结构特征,单一裂隙通常可以利用平板状裂隙模型进行量化<sup>[39]</sup>,裂隙长度、开度和高度3个关键参数通常

用于表征三维裂隙,裂隙体积是裂隙长度、开度和高度的综合反映<sup>[40-42]</sup>(图5)。因此,CT扫描三维

重构得到的裂隙体积综合反映了三维裂隙结构的长度、开度和高度特征。

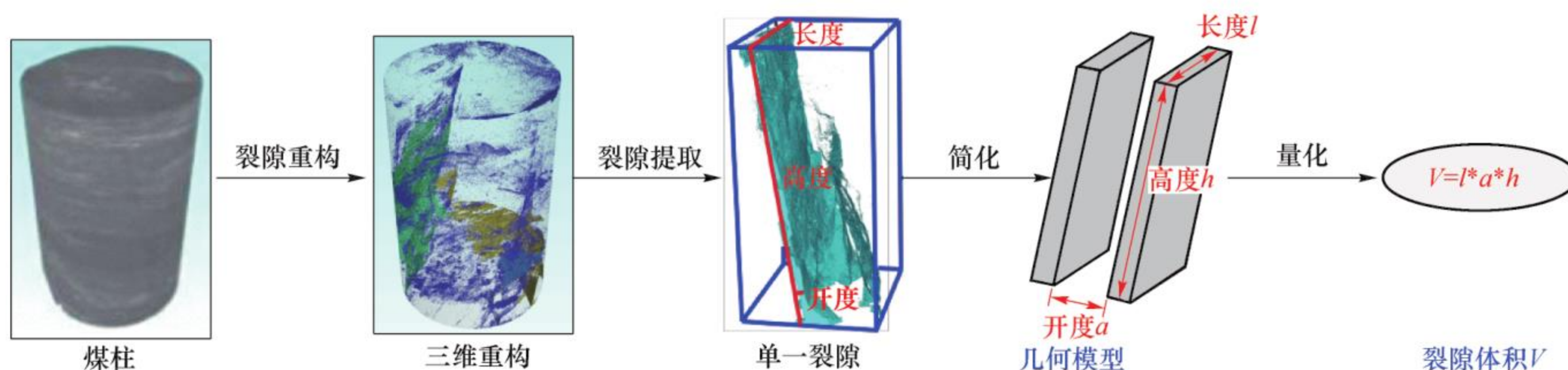


图5 三维裂隙结构特征

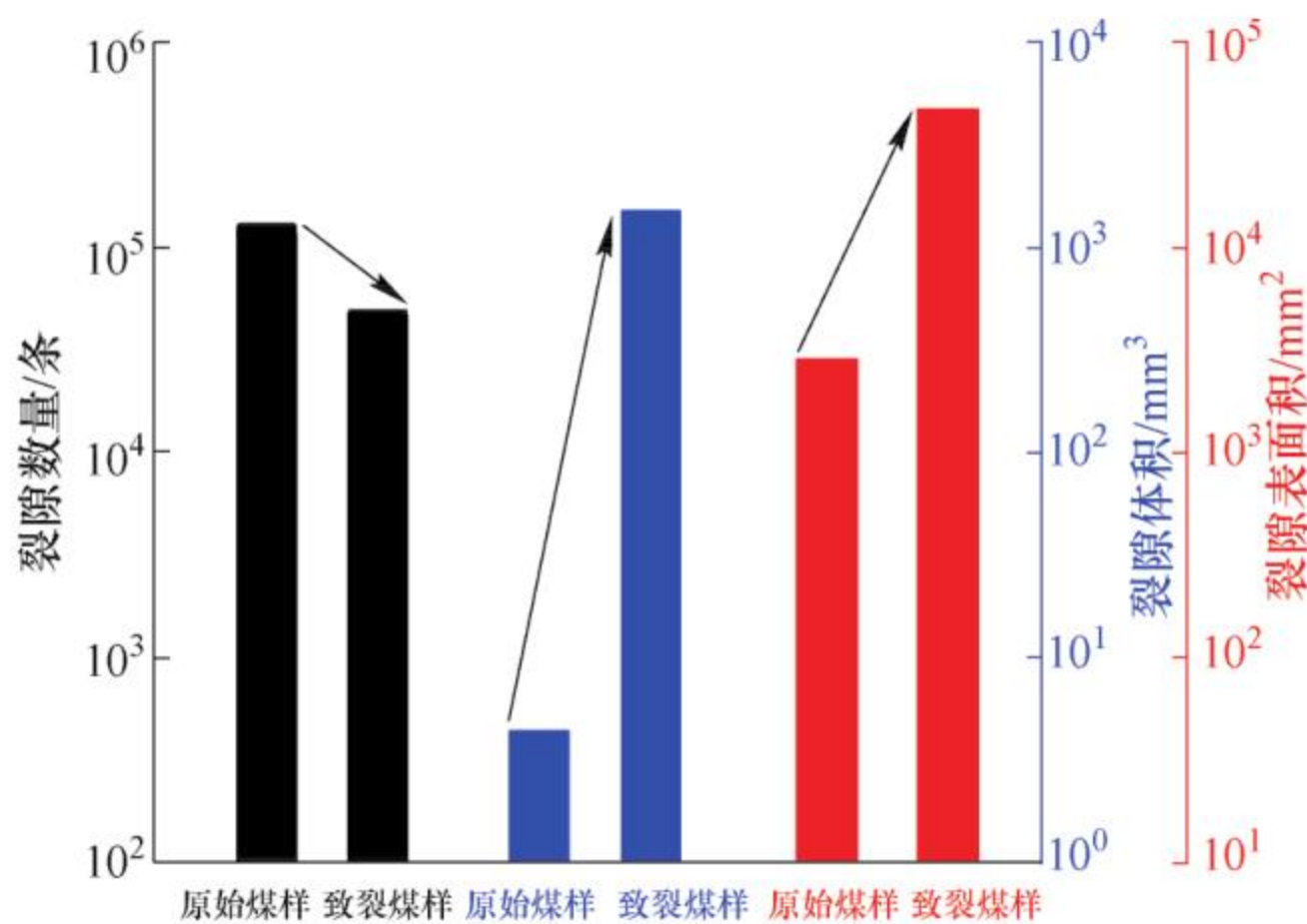
Fig. 5 3D fracture structure characteristics

CO<sub>2</sub>相变致裂前后,裂隙总数量、总体积以及总表面积见表2。与原始煤样相比,致裂后煤样的裂隙总数量由129 500条减少至49 313条,减少了61.92%;裂隙总体积由564.72 mm<sup>3</sup>增大至2 782.58 mm<sup>3</sup>,增大了392.73%;裂隙总表面积由24 630.50 mm<sup>2</sup>增加至36 838.00 mm<sup>2</sup>,增加了49.56%。CO<sub>2</sub>相变致裂前后裂隙数量、体积、表面积在不同裂隙长度范围的变化趋势,如图6所示。

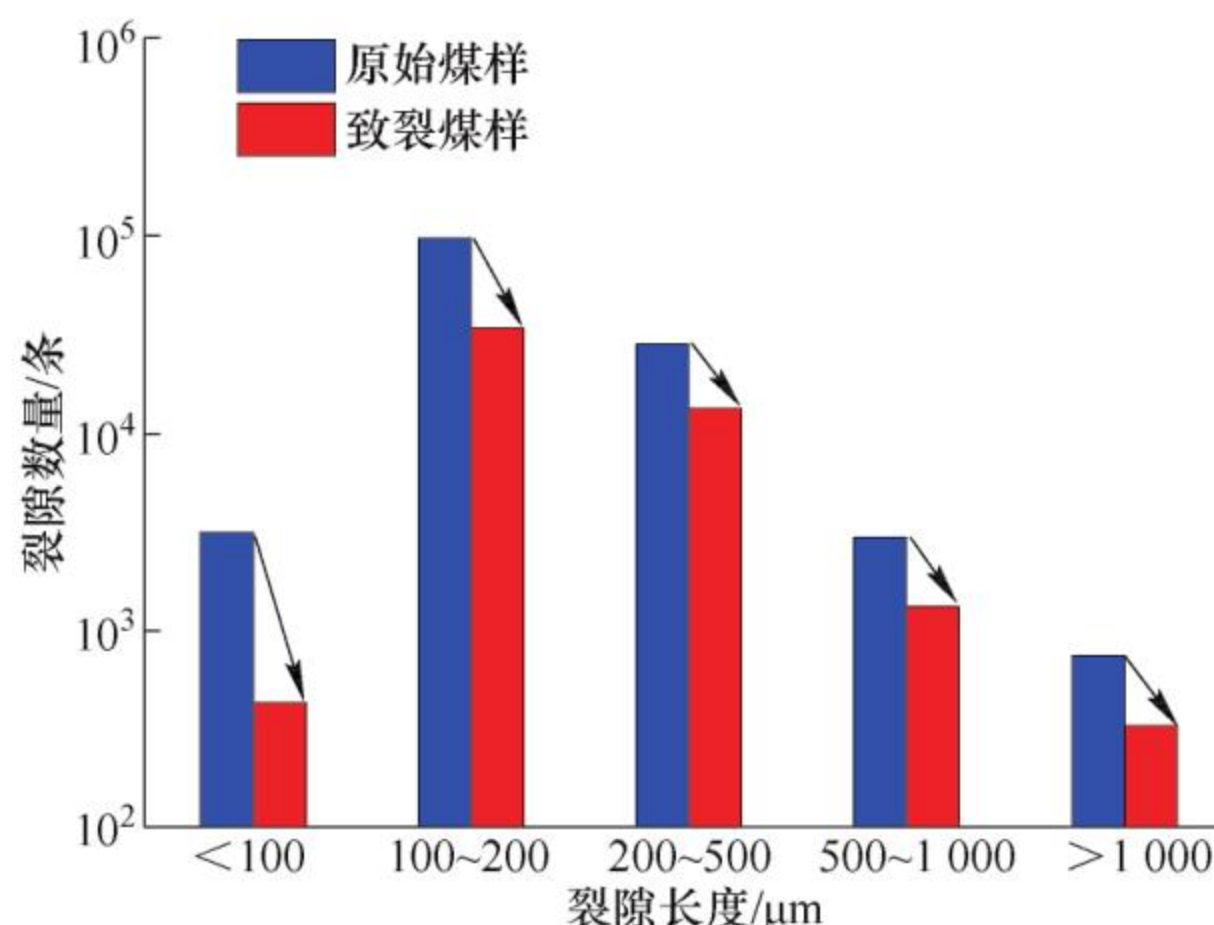
表2 煤样裂隙结构参数

Table 2 Fractures structurale parameters of for coal samples

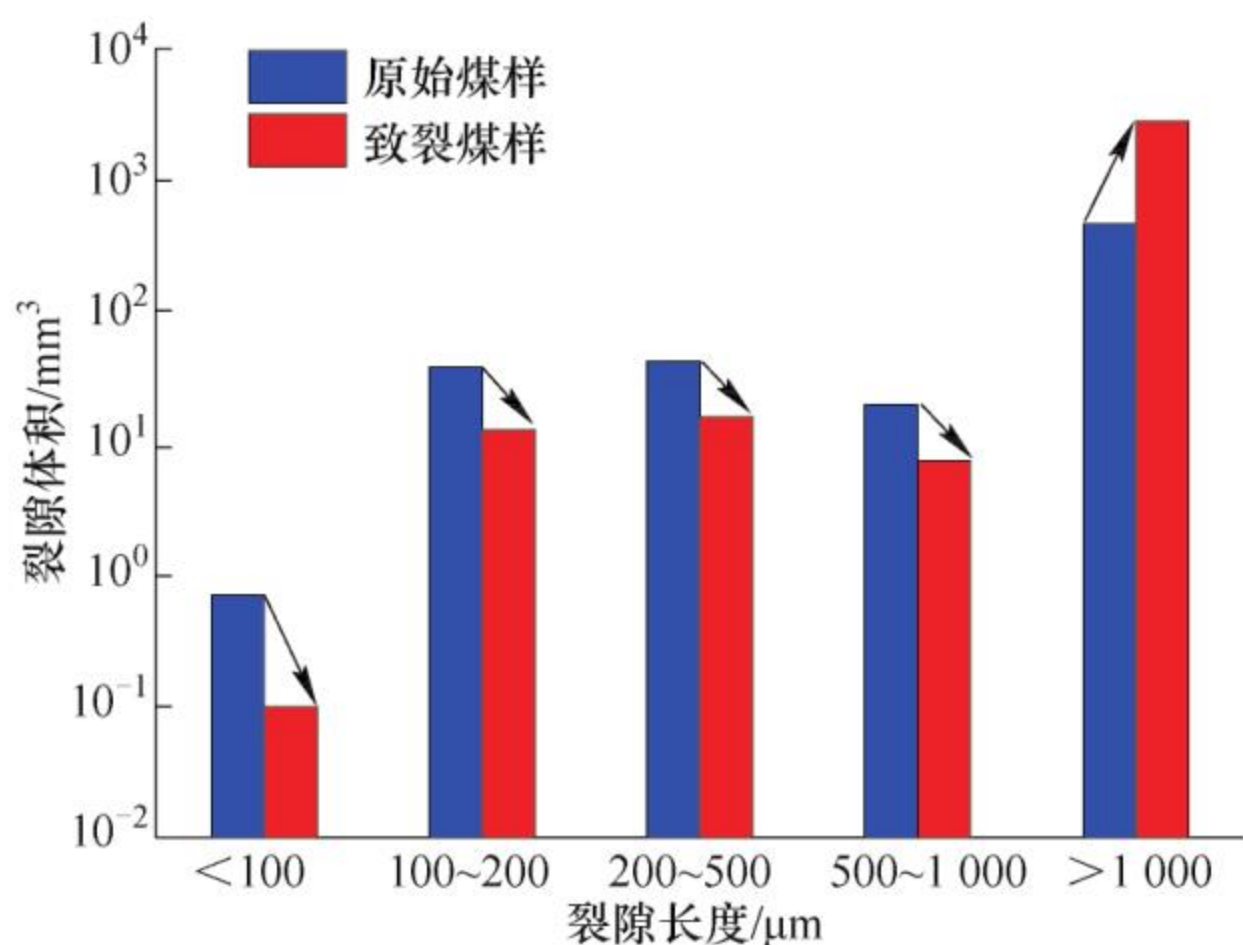
煤样	裂隙总数量/条	裂隙总体积/mm <sup>3</sup>	裂隙总表面积/mm <sup>2</sup>
原始煤样	129 500	564.72	24 630.50
致裂煤样	49 313	2 782.58	36 838.00



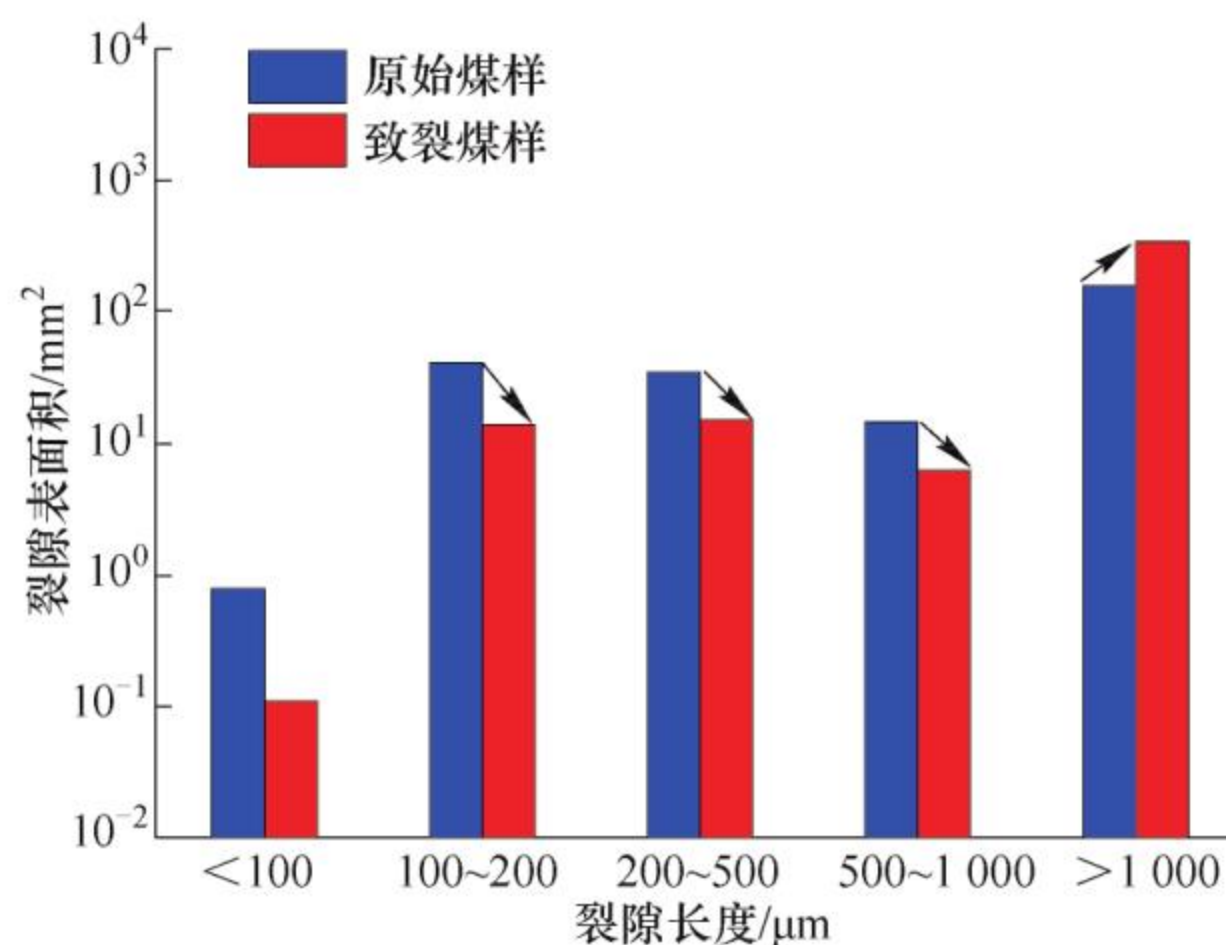
(a) 裂隙总数量、总体积与总表面积变化



(b) 裂隙数量变化



(c) 裂隙体积变化



(d) 裂隙表面积变化

图6 CO<sub>2</sub>相变致裂煤的裂隙数量、体积与表面积变化

Fig. 6 Number, volume, and surface area variation of fracture in the coal samples before and after CO<sub>2</sub>-PTF

可见,CO<sub>2</sub>相变致裂后,5个长度范围的裂隙数量均呈下降趋势;裂隙长度小于1 000 μm的裂隙体积明显降低,而长度大于1 000 μm的裂隙体积明显增大;裂隙表面积变化趋势与裂隙体积变化趋势一致。

综合分析裂隙结构参数变化特征可以看出,致裂后,长度小于1 000 μm的裂隙数量、体积、表面积明显降低,反映裂隙长度由小于1 000 μm向大于1 000 μm的扩张转化,促使长度大于1 000 μm的裂隙体积与表面积增大。同时,在致裂压力的影响下,长度大于1 000 μm的裂隙扩张贯通,也引起裂隙体积与表面积增大,造成其数量减少。

上述分析表明,CO<sub>2</sub>相变致裂对煤裂隙具有扩张和转化效应,即在CO<sub>2</sub>相变致裂压力的扩张作用下,小尺度裂隙转化为更大尺度的裂隙。

### 3.2 CO<sub>2</sub>相变致裂煤的三维裂隙演化机理

CO<sub>2</sub>相变致裂煤体产生裂隙过程主要分为两个阶段,前期动态的高压气体射流阶段以及后期准静态高压气体阶段。前期阶段,CO<sub>2</sub>高压气体射流从致裂器出口喷出作用在周围煤体上,在煤体周围形成宏观裂隙以及微米尺度的裂隙;后期阶段,气体压力一般为5~8 MPa,大于煤的抗拉强度(0.5~1.5 MPa),高压气体的“气楔效应”会促使微裂隙进一步延伸扩展促使煤体内部裂隙扩张,小尺度(<1 000 μm)微裂隙向大尺度(>1 000 μm)裂隙转化,造成小尺度裂隙数量、体积和比表面积减小,大尺度裂隙体积与表面积增大。因此,CO<sub>2</sub>相变致裂大幅度改善了煤体三维裂隙的连通性,有利于气体的运移和产出(图7)。

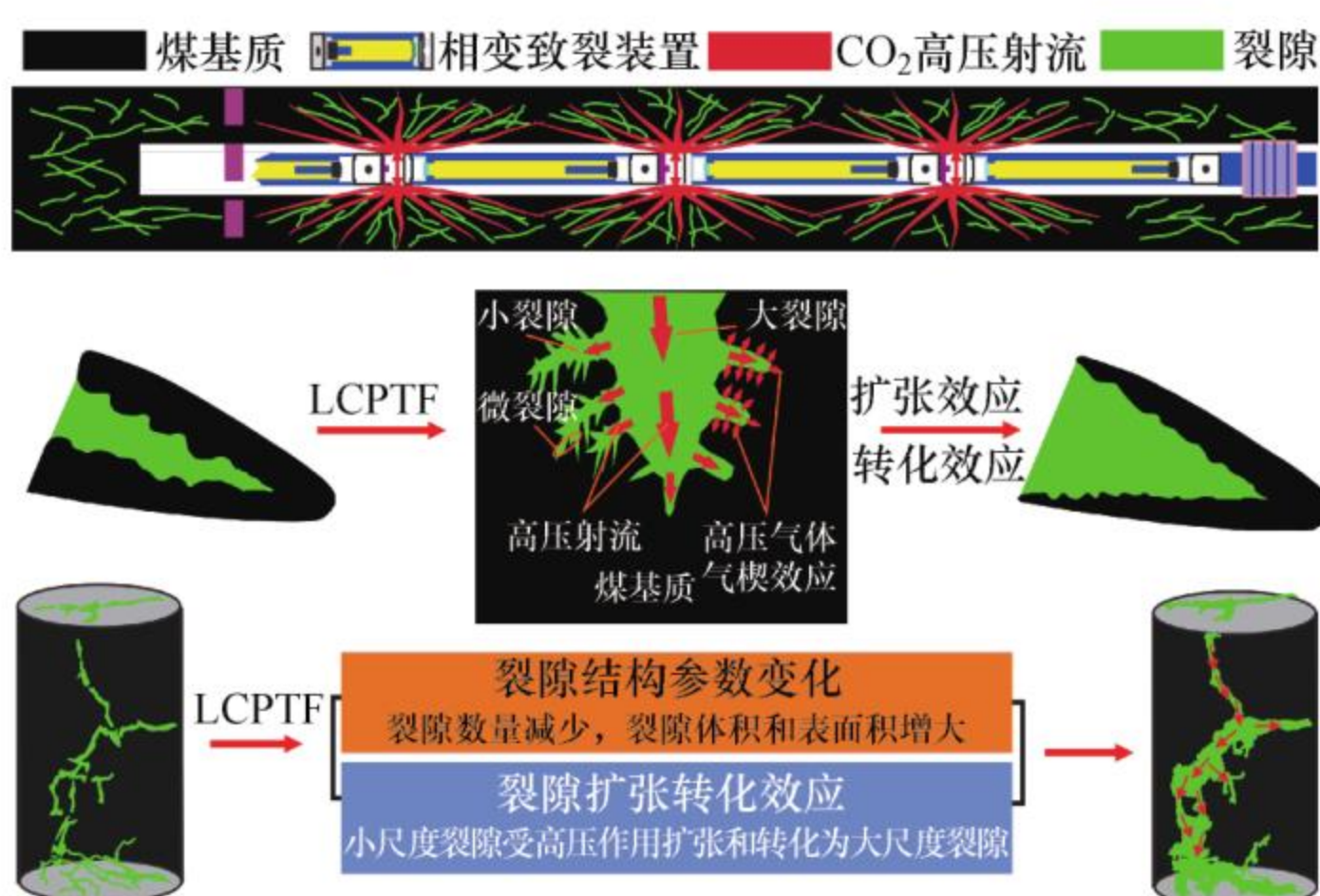


图7 CO<sub>2</sub>相变致裂煤的裂隙演化示意图

Fig. 7 Schematic diagram of fracture evolution in coal induced with CO<sub>2</sub>-PTF

## 4 结论

基于工业CT扫描,结合三维裂隙重构,利用平

板状裂隙模型对裂隙进行量化。分析了120 MPa压力下CO<sub>2</sub>相变致裂前后煤样内部裂隙的长度、数量、体积和表面积等相关结构参数变化,查明了CO<sub>2</sub>相变致裂煤的三维裂隙结构演化特征。主要结论如下:

(1) CO<sub>2</sub>相变致裂对煤的三维裂隙具有扩张-转化-贯通效应,促使裂隙总数量由129 500条减少至49 313条,减少了61.92%;裂隙总体积由564.72 mm<sup>3</sup>增大至2 782.58 mm<sup>3</sup>,增大了392.73%;裂隙总表面积由24 630.50 mm<sup>2</sup>增加至36 838.00 mm<sup>2</sup>,增加了49.56%。

(2) CO<sub>2</sub>相变致裂具有裂隙扩张转化效应。在致裂压力的扩张作用下,小尺度裂隙转化为更大尺度的裂隙;长度小于1 000 μm的裂隙数量减少、裂隙体积和表面积明显减小;而长度大于1 000 μm的裂隙体积和表面积明显增大。长度1 000 μm是裂隙之间扩张转化的尺度临界值。此外,长度大于1 000 μm的裂隙之间扩张贯通,引起其数量降低。

(3) 揭示了CO<sub>2</sub>相变致裂改造煤裂隙的演化机理。CO<sub>2</sub>相变致裂煤体产生裂隙过程主要分为2个阶段,前期动态的高压气体射流阶段直接形成了宏观裂隙以及微米尺度的裂隙,后期准静态高压气体阶段裂隙扩张转化相互贯通。CO<sub>2</sub>相变致裂极大改善了煤体三维裂隙的连通性,有利于气体的运移和产出。

## 参考文献

- [1] 李勇,胡海涛,王延斌,等. 煤层气井低产原因及二次改造技术应用分析[J]. 矿业科学学报,2022,7(1):55-70.  
LI Yong, HU Haitao, WANG Yanbin, et al. Analysis of low production coalbed methane wells and application of secondary reconstruction technologies [J]. Journal of Mining Science and Technology, 2022, 7(1): 55-70.
- [2] 齐消寒,王品,侯双荣,等. 不同功率微波预处理煤样增透效果及能量变化研究[J]. 矿业科学学报, 2024, 9(1): 66-76.  
QI Xiaohan, WANG Pin, HOU Shuangrong, et al. Study on the effect of penetration enhancement and energy change of coal samples pretreated with different microwave powers [J]. Journal of Mining Science and Technology, 2024, 9(1): 66-76.
- [3] 袁亮. 煤矿典型动力灾害风险判识及监控预警技术“十三五”研究进展[J]. 矿业科学学报, 2021, 6(1): 1-8.

- YUAN Liang. Risk identification, monitoring and early warning of typical coal mine dynamic disasters during the 13th Five-Year Plan period[J]. *Journal of Mining Science and Technology*, 2021, 6(1): 1-8.
- [4] 李勇, 徐立富, 刘宇, 等. 深部煤层气水赋存机制、环境及动态演化[J]. *煤田地质与勘探*, 2024, 52(2): 40-51.
- LI Yong, XU Lifu, LIU Yu, et al. Occurrence mechanism, environment and dynamic evolution of gas and water in deep coal seams[J]. *Coal Geology & Exploration*, 2024, 52(2): 40-51.
- [5] 李勇, 徐立富, 张守仁, 等. 深煤层含气系统差异及开发对策[J]. *煤炭学报*, 2023, 48(2): 900-917.
- LI Yong, XU Lifu, ZHANG Shouren, et al. Gas bearing system difference in deep coal seams and corresponded development strategy [J]. *Journal of China Coal Society*, 2023, 48(2): 900-917.
- [6] 张雪洁, 陈明义, 张同浩, 等. 表面活性剂水溶液抑制煤体瓦斯解吸作用的研究进展[J]. *矿业科学学报*, 2022, 7(6): 738-751.
- ZHANG Xuejie, CHEN Mingyi, ZHANG Tonghao, et al. Research progress of surfactant aqueous solution inhibiting the desorption of gas in coal[J]. *Journal of Mining Science and Technology*, 2022, 7(6): 738-751.
- [7] 谢和平, 王金华, 姜鹏飞, 等. 煤炭科学开采新理念与技术变革研究[J]. *中国工程科学*, 2015, 17(9): 36-41.
- XIE Heping, WANG Jinhua, JIANG Pengfei, et al. New concepts and technology evolutions in scientific coal mining [J]. *Engineering Sciences*, 2015, 17(9): 36-41.
- [8] 袁亮, 林柏泉, 杨威. 我国煤矿水力化技术瓦斯治理研究进展及发展方向[J]. *煤炭科学技术*, 2015, 43(1): 45-49.
- YUAN Liang, LIN Baiquan, YANG Wei. Research progress and development direction of gas control with mine hydraulic technology in China coal mine[J]. *Coal Science and Technology*, 2015, 43(1): 45-49.
- [9] 董庆祥, 王兆丰, 韩亚北, 等. 液态 CO<sub>2</sub> 相变致裂的 TNT 当量研究[J]. *中国安全科学学报*, 2014, 24(11): 84-88.
- DONG Qingxiang, WANG Zhaofeng, HAN Yabei, et al. Research on TNT equivalent of liquid CO<sub>2</sub> phase-transition fracturing[J]. *China Safety Science Journal*, 2014, 24(11): 84-88.
- [10] LU T K, WANG Z F, YANG H M, et al. Improvement of coal seam gas drainage by under-panel cross-strata stimulation using highly pressurized gas[J]. *International Journal of Rock Mechanics and Mining Sciences*, 2015, 77: 300-312.
- [11] 周建伟, 王晓蕾, 李云. 深孔控制 CO<sub>2</sub> 预裂爆破在煤巷掘进消突中的应用[J]. *煤炭技术*, 2014, 33(9): 30-32.
- ZHOU Jianwei, WANG Xiaolei, LI Yun. Application for CO<sub>2</sub> parameter design of deep-hole controlling presplitting blasting in coalroad driving[J]. *Coal Technology*, 2014, 33(9): 30-32.
- [12] 苏伟伟. 石门揭煤区液态 CO<sub>2</sub> 致裂增透加速消突技术[J]. *煤矿安全*, 2019, 50(2): 144-147, 151.
- SU Weiwei. Technology of rapid outburst elimination by liquid CO<sub>2</sub> fracturing in region of coal uncovering[J]. *Safety in Coal Mines*, 2019, 50(2): 144-147, 151.
- [13] 曹运兴, 张新生, 张军胜, 等. CO<sub>2</sub> 相变致裂煤的显微构造特征与成因机制[J]. *煤田地质与勘探*, 2023, 51(2): 137-145.
- CAO Yunxing, ZHANG Xinsheng, ZHANG Junsheng, et al. Characteristics and formation mechanisms of microstructures in coal treated with CO<sub>2</sub> phase transition fracturing[J]. *Coal Geology & Exploration*, 2023, 51(2): 137-145.
- [14] CHEN H D, WANG Z F, CHEN X E, et al. Increasing permeability of coal seams using the phase energy of liquid carbon dioxide[J]. *Journal of CO<sub>2</sub> Utilization*, 2017, 19: 112-119.
- [15] 车玉燕, 邹冠贵, 殷裁云, 等. 雨汪井田超压含煤地层孔隙特征及孔隙体积模量演变规律[J]. *矿业科学学报*, 2022, 7(3): 275-285.
- CHE Yuyan, ZOU Guangui, YIN Caiyun, et al. The evolution law of pore characteristics and pore bulk modulus for overpressured coal-bearing formation in Yuwang Minefield[J]. *Journal of Mining Science and Technology*, 2022, 7(3): 275-285.
- [16] ZHANG S H, TANG S H, TANG D Z, et al. The characteristics of coal reservoir pores and coal facies in Lulin district, Hedong coal field of China[J]. *International Journal of Coal Geology*, 2010, 81(2): 117-127.
- [17] 李天, 任大忠, 甯波, 等. 煤层孔隙结构多尺度联合表征及其对可动流体的影响[J]. *矿业科学学报*, 2023, 8(4): 569-582.
- LI Tian, REN Dazhong, NING Bo, et al. Multi-scale joint characterization of coal seam pore structure and its influence on movable fluid[J]. *Journal of Mining Science and Technology*, 2023, 8(4): 569-582.
- [18] 吕华永, 刘飞, 李良晖, 等. 顶煤预制裂隙定向水力压裂研究[J]. *矿业科学学报*, 2018, 3(6): 553-560.
- LÜ Huayong, LIU Fei, LI Lianghui, et al. Study on directional hydraulic fracturing of prefabricated fissures in top coal[J]. *Journal of Mining Science and Technology*, 2018, 3(6): 553-560.

- [19] 杨立云,董鹏翔,王启睿,等. 爆生气体驱动双共线 I 型裂纹的扩展行为[J]. 矿业科学学报,2023,8(4):538-547.  
YANG Liyun, DONG Pengxiang, WANG Qirui, et al. Propagation behavior of two collinear mode I cracks driven by explosive gas[J]. Journal of Mining Science and Technology,2023,8(4):538-547.
- [20] DOU H R, XIE J N, XIE J, et al. Study on the mechanism of the influence of HNO<sub>3</sub> and HF acid treatment on the CO<sub>2</sub> adsorption and desorption characteristics of coal[J]. Fuel,2022,309:122187.
- [21] 骆浩浩,张渊通,左进京,等. 冲击荷载下运动裂纹与空孔相互作用的焦散线试验研究[J]. 矿业科学学报,2022,7(2):210-216.  
LUO Haohao, ZHANG Yuantong, ZUO Jinjing, et al. Caustics experimental study on the interaction between moving cracks and voids under impact loading[J]. Journal of Mining Science and Technology, 2022, 7(2):210-216.
- [22] ZHANG Z, LIU G F, CAO Y X, et al. Experimental investigation of CS<sub>2</sub> extraction to enhance the permeability of coal[J]. Transport in Porous Media, 2021,136(3):899-922.
- [23] 刘伟吉,张有建,祝效华,等. 高压电脉冲破岩机理数值模拟研究[J]. 矿业科学学报,2023,8(5):642-653.  
LIU Weiji, ZHANG Youjian, ZHU Xiaohua, et al. Numerical simulation study of rock breaking mechanism by high voltage electric pulse[J]. Journal of Mining Science and Technology,2023,8(5):642-653.
- [24] BAI X, ZHANG D M, ZENG S, et al. An enhanced coalbed methane recovery technique based on CO<sub>2</sub> phase transition jet coal-breaking behavior[J]. Fuel, 2020,265:116912.
- [25] XIA B W, LIU X F, SONG D Z, et al. Evaluation of liquid CO<sub>2</sub> phase change fracturing effect on coal using fractal theory[J]. Fuel,2021,287:119569.
- [26] LIU X F, NIE B S, GUO K Y, et al. Permeability enhancement and porosity change of coal by liquid carbon dioxide phase change fracturing[J]. Engineering Geology,2021,287:106106.
- [27] LIU H, LIU G F, ZHANG Z, et al. Effects of liquid CO<sub>2</sub> phase transition fracturing on mesopores and micropores in coal[J]. Energy & Fuels,2022,36(17):10016-10025.
- [28] 张震,刘高峰,李宝林,等. CO<sub>2</sub>相变致裂煤的纳米孔隙尺度改造效应[J]. 岩石力学与工程学报,2023,42(3):672-684.  
ZHANG Zhen, LIU Gaofeng, LI Baolin, et al. Transformed effect of nano-pores in coal by CO<sub>2</sub> phase transition fracturing [J]. Chinese Journal of Rock Mechanics and Engineering,2023,42(3):672-684.
- [29] LIU G F, LI B L, ZHANG Z, et al. Effects of liquid CO<sub>2</sub> phase transition fracturing on methane adsorption of coal[J]. Energy & Fuels,2023,37(3):1949-1961.
- [30] CAO Y X, ZHANG J S, ZHAI H, et al. CO<sub>2</sub> gas fracturing: a novel reservoir stimulation technology in low permeability gassy coal seams[J]. Fuel, 2017, 203:197-207.
- [31] CAO Y X, ZHANG J S, ZHANG X S, et al. Micro-fractures in coal induced by high pressure CO<sub>2</sub> gas fracturing[J]. Fuel,2022,311:122148.
- [32] 白鑫,张东明,王艳,等. 液态 CO<sub>2</sub> 相变射流压力变化及其煤岩致裂规律[J]. 中国矿业大学学报,2020,49(4):661-670.  
BAI Xin, ZHANG Dongming, WANG Yan, et al. Pressure variation and coal fracturing law of liquid CO<sub>2</sub> phase transition jet[J]. Journal of China University of Mining & Technology,2020,49(4):661-670.
- [33] 刘大锰,李振涛,蔡益栋. 煤储层孔-裂隙非均质性及其地质影响因素研究进展[J]. 煤炭科学技术,2015,43(2):10-15.  
LIU Dameng, LI Zhentao, CAI Yidong. Study progress on pore-crack heterogeneity and geological influence factors of coal reservoir[J]. Coal Science and Technology,2015,43(2):10-15.
- [34] 冯雪健,沈永星,周动,等. 基于CT数字岩心深度学习的煤裂隙分布识别研究[J]. 煤炭科学技术,2023,51(8):97-104.  
FENG Xuejian, SHEN Yongxing, ZHOU Dong, et al. Multi-scale distribution of coal fractures based on CT digital core deep learning[J]. Coal Science and Technology,2023,51(8):97-104.
- [35] 赵明凯,孔德森. 考虑裂隙面粗糙度和开度分形维数的岩石裂隙渗流特性研究[J]. 岩石力学与工程学报,2022,41(10):1993-2002.  
ZHAO Mingkai, KONG Desen. Study on seepage characteristics of rock fractures considering fracture surface roughness and opening fractal dimension[J]. Chinese Journal of Rock Mechanics and Engineering,2022,41(10):1993-2002.
- [36] 李相臣,陈德飞,康毅力,等. 基于CT扫描的煤岩孔裂隙表征[J]. 煤田地质与勘探,2016,44(5):58-62,70.  
LI Xiangchen, CHEN Defei, KANG Yili, et al. Characterization of pores and fractures of coal based on CT scan[J]. Coal Geology & Exploration,2016,44(5):58-62,70.
- [37] 郑江韬,齐子豪,刘佳存,等. 基于卷积神经网络的煤岩微裂隙提取方法[J]. 矿业科学学报,2022,7(6):680-688.

- ZHENG Jiangtao, QI Zihao, LIU Jiacun, et al. Segmentation of micro-cracks in fractured coal based on convolutional neural network[J]. *Journal of Mining Science and Technology*, 2022, 7(6): 680-688.
- [38] 杜锋, 王凯, 董香栾, 等. 基于 CT 三维重构的煤岩组合体损伤破坏数值模拟研究[J]. *煤炭学报*, 2021, 46(S1): 253-262.
- DU Feng, WANG Kai, DONG Xiangluan, et al. Numerical simulation of damage and failure of coal-rock combination based on CT three-dimensional reconstruction [J]. *Journal of China Coal Society*, 2021, 46(S1): 253-262.
- [39] ZHANG Z, LIU G F, WANG X M, et al. Fractal characterization on fracture volume in coal based on CT scanning: principle, methodology, and implication [J]. *Fractals*, 2022, 30(6): 2250124-81.
- [40] WANG Z Z, PAN J N, HOU Q L, et al. Anisotropic characteristics of low-rank coal fractures in the Fukang mining area, China [J]. *Fuel*, 2018, 211: 182-193.
- [41] KUMAR H, LESTER E, KINGMAN S, et al. Inducing fractures and increasing cleat apertures in a bituminous coal under isotropic stress via application of microwave energy [J]. *International Journal of Coal Geology*, 2011, 88(1): 75-82.
- [42] WENIGER S, WENIGER P, LITTKER R. Characterizing coal cleats from optical measurements for CBM evaluation [J]. *International Journal of Coal Geology*, 2016, 154/155: 176-192.

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