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煤层气井煤粉沉降模型修正与运移实验研究

王一兵¹, 张飞^{2,3}, 来鹏¹, 廖正凯¹, 梅文博^{2,3}, 杨琦^{2,3}, 李贵川^{2,3}, 张锦涛⁴, 鲜保安⁴, 毕延森⁴

(1. 新疆亚新煤层气投资开发(集团)有限责任公司, 新疆 乌鲁木齐 830000; 2. 中联煤层气有限责任公司, 北京 100015; 3. 三气共采省技术创新中心, 山西 太原 030032; 4. 河南理工大学资源环境学院, 河南 焦作 454000)

摘要: 煤层气采用排采泵排水降压方式开发时, 煤粉产出与运移是影响煤层气井生产特征的重要因素。由于煤层非均质性、储层改造与排采制度等影响, 煤层气井各生产阶段煤粉产出与运移特征各不相同。基于沁水盆地潘庄、寿阳和柿庄等区块煤层气井煤粉采集分析, 揭示排采产出煤粉形态、质量浓度和成分特征。为研究煤粉颗粒形状因子对静态沉降末速影响, 根据煤层气井产出煤粉颗粒粒径分布特征, 引入煤粉形状因子表征参数对煤粉颗粒静态沉降末速计算模型进行修正, 并通过室内实验进行验证分析。同时, 根据室内模拟井筒煤粉运移实验结果探明煤粉颗粒运移临界流速, 分析评价了不同粒径煤粉运移临界排量。研究表明: 煤层气井产出煤粉主要成分为黏土矿物(平均质量分数为74.4%), 煤粉粒径随着煤层气生产阶段呈现先增大后减小规律, 集中分布在2~50 μm; 将煤粉形状因子引入颗粒静态沉降末速模型后计算值与实验结果高度吻合(相关系数 $R^2=99%$), 提高了井筒煤粉临界运移流速计算精度; 结合潘河、柿庄等研究区煤层气井生产制度与室内模拟井筒煤粉运移实验, 提出了>180~250、>150~180、38~380 μm煤粉颗粒临界运移流速分别为0.020、0.010、0.035 m/s, 对应的最小产水量分别为5.2、2.6、8.5 m³/d; 单井日产水量大于最小产水量可减少井筒煤粉堆积和卡泵风险, 为煤层气井生产制度优化及连续稳定生产提供技术支持。

关键词: 煤层气; 煤粉; 沉降; 模型修正; 运移实验

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Study on pulverized coal settlement model modification and migration experiment in coalbed methane wells

WANG Yibing¹, ZHANG Fei^{2,3}, LAI Peng¹, LIAO Zhengkai¹, MEI Wenbo^{2,3}, YANG Qi^{2,3}, LI Guichuan^{2,3}, ZHANG Jintao⁴, XIAN Bao'an⁴, BI Yansen⁴

(1. Xinjiang Yaxin Coalbed Methane Investment and Development (Group) Co., Ltd., Urumqi, Xinjiang 830000, China;

2. China United Coalbed Methane Co., Ltd., Beijing 100015, China;

3. Innovation Center of Three-gas Co-production Technology, Taiyuan, Shanxi 030032, China;

4. School of Resources and Environment, Henan Polytechnic University, Jiaozuo, Henan 454000, China)

Abstract: Coalbed methane (CBM) is developed through pump drainage and depressurization. The production and migration of pulverized coal are important factors affecting the production characteristics of CBM wells. Due to the influence of coal heterogeneity, reservoir stimulation, and drainage system, the characteristics of pulverized coal production and migration vary across different production stages of CBM wells. Based on the collection and analysis of pulverized coal from CBM wells in the Panzhuang, Shouyang, and Shizhuang blocks of the Qinshui Basin, the morphology, concentration, and composition characteristics of pulverized coal produced during drainage were revealed. To investigate the influence of the shape factor of pulverized coal particles on the static settling final velocity, the characterization parameters of the pulverized coal shape factor were introduced to modify the calculation model for static settling final velocity based on the particle size distribution characteristics of pulverized coal produced from CBM wells. The modified model was then validated and analyzed through laboratory experiments. Additionally, based on the results of laboratory simulation experiments of pulverized coal migration in wellbores, the critical flow velocity for particle migration was determined, and the critical discharge rate for the migration of pulverized coal of different particle sizes was analyzed and evaluated. The results showed that the main components of pulverized coal from CBM wells were clay minerals, with an average mass fraction of 74.4%. The particle size of pulverized coal was concentrated in the range of 2~50 μm. The particle

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第一作者简介: 王一兵(1966—), 男, 博士, 高级工程师, 从事煤层气勘探、开发研究工作。地址: 新疆乌鲁木齐高新区(新市区)正扬路街道冬融街566号2号楼2024-FK区044号, 邮政编码: 830000。E-mail: 704938737@qq.com

通信作者简介: 张锦涛(1998—), 男, 在读硕士研究生, 从事煤层气勘探、开发研究。地址: 河南省焦作市高新区世纪路2001号河南理工大学资源与环境学院, 邮政编码: 454000。E-mail: 1403914458@qq.com

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size of the pulverized coal first increased and then decreased in the CBM production stage. The calculated results were in good agreement with the experimental results ($R^2 = 0.99$) by introducing the pulverized coal shape factor into the particle static settling final velocity model, thereby improving the accuracy of critical migration velocity calculation of pulverized coal in the wellbore. Based on the production systems of CBM wells in the Panhe and Shizhuang study areas and laboratory simulated wellbore pulverized coal migration experiments, the critical migration velocities for pulverized coal particles of $>180\sim 250$, $>150\sim 180$, and $38\sim 380\ \mu\text{m}$ were $0.020\ \text{m/s}$, $0.010\ \text{m/s}$, and $0.035\ \text{m/s}$, respectively. The corresponding minimum water production rates were $5.2\ \text{m}^3/\text{d}$, $2.6\ \text{m}^3/\text{d}$, and $8.5\ \text{m}^3/\text{d}$, respectively. A daily water production of a single well exceeding the minimum water production can reduce the risk of pulverized coal accumulation and pump sticking within the wellbore, providing technical support for optimizing production systems and achieving continuous and stable production of CBM wells.

Keywords: coalbed methane; pulverized coal; settlement; model modification; migration experiment

中国煤层气资源储量丰富^[1-3],随着深部煤层气勘探开发取得产量与技术突破,煤层气高效开发不仅增加天然气产量^[4-5],同时,对于实现“碳达峰、碳中和”目标具有重要意义^[6-8]。然而,煤层气井生产过程中无法避免产生煤粉^[9-11]。过量煤粉产出会导致井筒堵塞或排采泵卡泵问题,必须通过井下作业排除堆积煤粉并检修排采泵后才能恢复生产,甚至部分井出现不同程度减产现象,严重影响了煤层气生产连续性^[12-14]。因此,通过煤层气井煤粉产出与运移特征研究^[15-16],优化煤层气井生产制度,对煤层气连续生产具有重要实际意义^[17-20]。

张越等^[21-24]认为煤层脆性较大、胶结性差、孔隙系统发育,煤层气开采过程容易产生大量煤粉。魏迎春等^[25-26]采用X射线衍射实验方法探明煤粉的成分主要来自煤本身和黏土矿物,其中黏土矿物主要是高岭石、伊利石和绿泥石。相比原生结构煤,构造软煤在煤层气生产过程中会产生更多煤粉^[27-29]。刘升贵等^[28,30]根据沁水盆地南部和鄂尔多斯盆地的煤层气井生产数据,揭示了各阶段产出煤粉颗粒粒径分布特征。上述研究成果阐明了煤层气井煤粉形成机理、成分与粒径分布特征等,有待进一步开展分析判定煤层气井产出煤粉颗粒形态特征,为揭示煤粉沉降与运移作用机制提供基础。

层流、过渡流和紊流状态下静止球形颗粒沉降末速计算公式均基于静止液体中理想球形颗粒的受力分析^[31-32]。GOLDSTEIN^[33]通过分析球形颗粒表面在层流中阻力特性,采用解析方法推导出球形颗粒层流沉降过程中的阻力系数。相关学者基于球形颗粒在非牛顿流体中的沉降和迁移规律,通过数值模拟得到了阻力系数的修正相关公式^[34]。张芬娜等^[35]提出适度携煤粉理论,建立了煤粉悬浮运移模型。刘春花等^[36]建立煤粉储层沉降运移模型,并根据现场资料分析了煤粉颗粒粒径和裂缝通道大小对煤粉运移的影响。东振等^[37]建立煤粉临界携流速度计算方法,并讨论了影响煤粉运移速度的煤层物性参数。前人对煤粉运移和沉降模式、阻力系数、煤粉颗粒粒径与裂缝尺寸作用机理,提出其临界携流速度,为煤层气井煤粉运移规律认识具有重要意义。引入煤粉颗粒形状因素至煤粉运移特征研究,准确揭示煤层气井筒煤粉悬浮与迁移。

在实验研究方面,申焱华等^[38]通过实验研究给出固体颗粒的临界运移最小速度。刘爱萍等^[39]主要结合理论分析和沉降实验解决了颗粒形状计算问题和特定地区的最小携砂速度计算公式。邹雨时等^[40]通过物理模拟实验模拟了煤粉侵入煤储层裂缝的过程。韩国庆等^[41]通过静态沉降和动态沉降实验得出符合实际情况的煤粉沉降速度计算公式。曹立虎等^[42]通过自主研发装置模拟得出水平井筒内煤粉的流动类型为层流。崔金榜等^[43]主要通过物理模拟实验进行水平井的煤粉运移规律,实验主要控制参数为井筒倾角、流量、压差,实验结果认为在实际生产过程中合理控制排水流量和井底压力可以达到适度排煤粉目的。王东营^[44]基于全尺寸多相复杂流动实验装置,得到水携煤粉和水气携煤粉过程中煤粉床高度的半理论和半经验模型。王博洋等^[45]通过室内实验揭示不同类型孔缝约束下差异流体作用对煤粉运移影响。慕甜等^[46]以捞砂煤粉为研究对象,开展多相流条件下不同粒径煤粉启动-运移试验模拟。张芬娜等^[47]通过实验得出适用于深部煤层气井煤粉颗粒沉降末速计算公式。前人通过室内实验方法定性和半定量揭示了煤粉沉降、启动、运移作用机理和关键影响因素,进一步结合现场生产参数与煤粉产出情况量化表征煤粉动态运移规律,并给出推荐的煤层井排水速度,为防止煤粉沉积及预防卡泵事故提供指导。

国内外学者通过理论与实验方法对煤粉沉降规律进行了研究^[48-50],揭示了煤层气开采过程中煤粉沉降、运移机理和关键影响因素,进一步实验探明煤粉颗粒形状因子对煤粉颗粒沉降影响,进而修正煤粉颗粒静态沉降末速计算模型;结合煤层气井排水速度量化表征井筒煤粉动态沉降特征,为煤层气井生产制度优化提供技术支持。

1 煤层气井煤粉产出特征

通过对沁水盆地潘河、寿阳、柿庄南、柿庄北区块产出液中煤粉的粒径、质量浓度、成分、形态特征进行研究,揭示煤粉产出特征,可为制定良好的防煤粉生产策略提供依据,有效指导现场生产。

1.1 产出煤粉的粒径特征

煤粉颗粒粒径大小是影响煤粉卡泵的重要因素。研究不同粒度大小煤粉的特征能够更加有效地认识并解决煤粉卡泵问题。为了更加明确煤储层中煤粉的粒径特征,利用 Mastersizer 3000+激光粒度仪对采集的煤粉溶液

进行了湿法粒径测试(图1)。煤层气井产出煤粉的粒径分布区间较大,其中寿阳区块产出煤粉的粒径较大且曲线波动较多;大部分煤层气井产出煤粉的粒径介于2~50 μm 左右,煤粉颗粒粒径区间变化较小。对采取的样品结果进行整理分析后,发现煤层气井产出煤粉的粒径随着煤层气生产阶段先增大后减小(表1)。

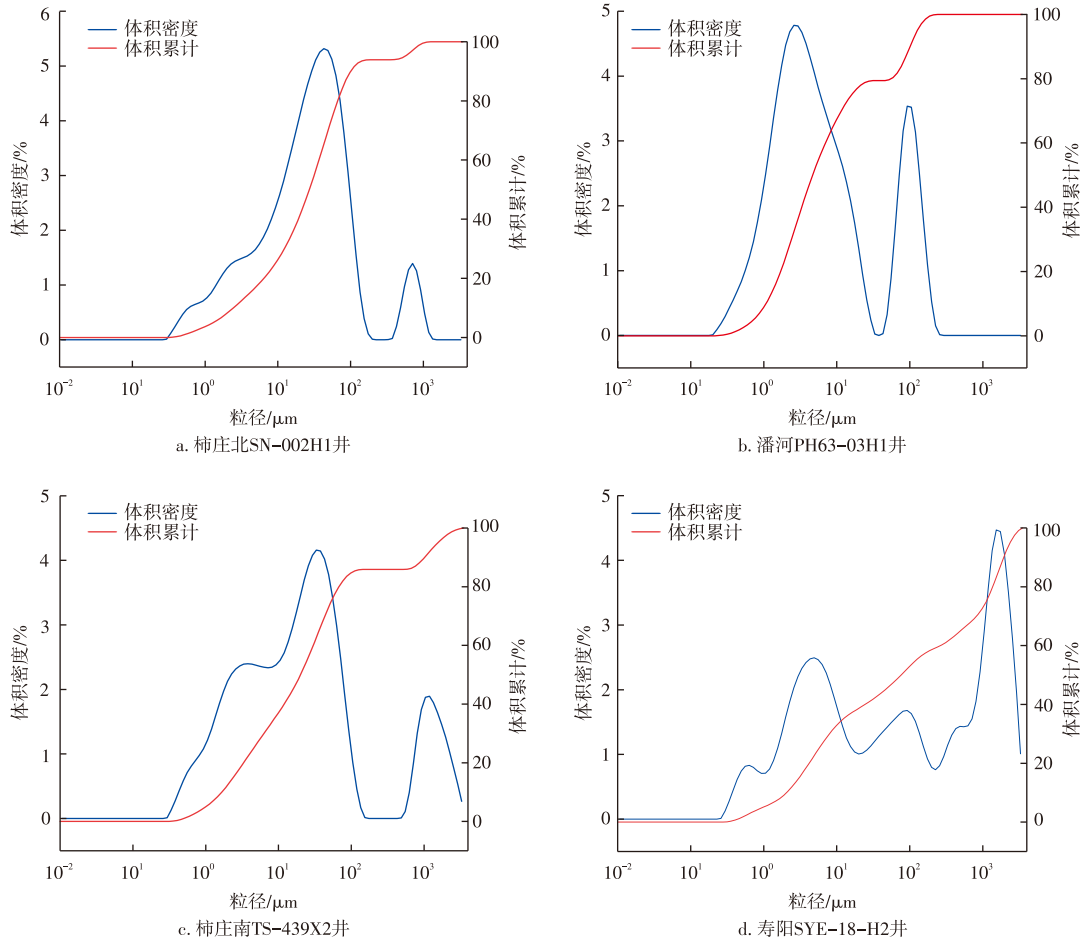


图1 沁水盆地柿庄北、潘河、柿庄南、寿阳区块煤层气井产出煤粉颗粒粒径特征

Fig. 1 Particle size characteristics of pulverized coal produced from coalbed methane wells in Shizhuang North, Panhe, Shizhuang South, and Shouyang blocks of Qinshui Basin

表1 沁水盆地柿庄北、潘河、柿庄南、寿阳区块煤层气井不同生产阶段煤粉颗粒粒径分布特征

Table 1 Particle size distribution characteristics of pulverized coal at different production stages of coalbed methane wells in Shizhuang North, Panhe, Shizhuang South, and Shouyang blocks of Qinshui Basin

生产阶段	生产特征	粒径分布/ μm
排水降压	产水上升	0.447~48.300
上产期	产气上升、排水下降	3.170~76.000
稳产期	气体稳定生产	0.734~121.000
衰减期	产气下降、基本不产水	4.344~50.000

1.2 产出煤粉的形态特征

通过扫描电镜实验对比煤储层和井筒中煤粉形态

(图2)。煤储层中煤粉、生产携带出的煤粉、井筒中煤粉的形态特征具有较大差异。煤储层中煤粉颗粒主要形状为不规则的块状、柱状等,棱角分明,煤粉颗粒较大,粒径分布不均匀,介于0.100~0.500 mm。但是在气液固三相流的搬运剥蚀后,煤粉被搬运至井筒中,其颗粒形态特征发生了较大的变化,由原来的块状变为粒状、次圆状、片状、簇状集合体形式等。井筒中煤粉的形态特征与井口中采取的煤粉样品的形态特征具有一致性。煤粉颗粒在多相流的搬运剥蚀下较易发生破碎,导致煤粉颗粒粒径减小。一般来说,煤粉颗粒的形状特征越接近于球体越容易被携带运移。

1.3 产出煤粉的质量浓度特征

煤粉质量浓度是煤层气井产出煤粉的重要特征,也

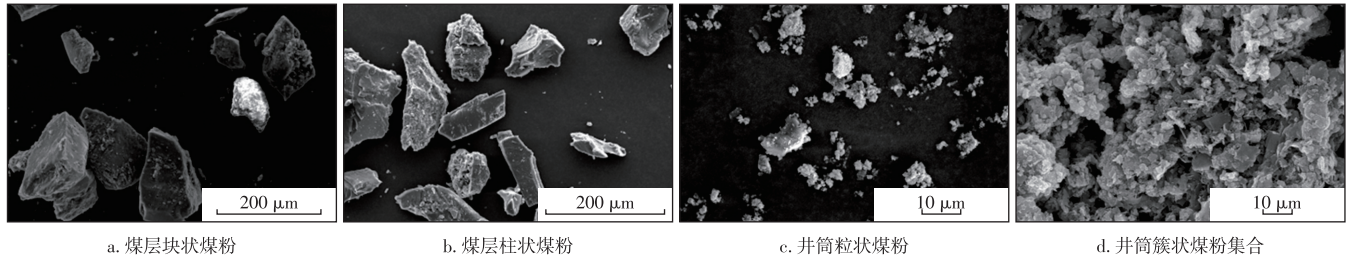


图2 煤储层和井筒中煤粉形态对比

Fig. 2 Comparison of pulverized coal morphology in coal reservoirs and wellbores

是造成泵效降低、埋泵和卡泵的关键参数,由实验室称重法测得。实验样品共分3批次采取,测试结果如表2所示,煤粉产出与生产阶段具有相关性,产出煤粉的质量浓度随生产周期增加呈现急剧增加后缓慢下降,从排水降压到上产期(气-水两相流)阶段为煤粉产出的高发期。潘河区块煤层气井在初始排水阶段煤粉质量浓度较小,随着煤层气产出,煤粉质量浓度不断增大,分析认为在地层水单相流阶段主要为对煤储层剥蚀煤粉的产出,对煤粉的携带能力较弱。但是随着气体的继续产出,逐渐由地层水单相流变为气-水两相流,对煤粉的携带能力不断增强,所以产出煤粉的质量浓度相对也会有所增加。在后期阶段由于气体产量衰减,基本无地层水产出,所以煤粉的质量浓度降低。

表2 沁水盆地柿庄北、潘河、柿庄南、寿阳区块煤层气井产出煤粉的质量浓度特征

Table 2 Mass concentration characteristics of pulverized coal produced from coalbed methane wells in Shizhuang North, Panhe, Shizhuang South, and Shouyang blocks of Qinshui Basin

生产阶段	质量浓度/(g/L)	平均质量浓度/(g/L)
排水降压	0.001~0.500	0.074
上产期	0.001~27.600	1.648
稳产期	0.004~22.000	1.270
衰减期	0.020~1.300	0.500

1.4 产出煤粉成分特征

不同煤岩组分、无机矿物成分及含量都会对煤粉的产出造成影响。采用XRD(X射线衍射)实验对产出的煤粉样品进行组分分析。煤层气井排采出煤粉的成分以黏土矿物为主,黏土矿物质量分数介于59.3%~85.3%,平均在74.4%(图3)。黏土矿物主要为高岭石、绿泥石和云母等。高岭石集合体对骨架颗粒的附着力较差,高岭石晶体之间结合力也很弱。高岭石集合体在高速流体的作用下容易从骨架颗粒上脱落。这些高岭石颗粒附着在粉煤颗粒上^[51],随着排采被排出。选

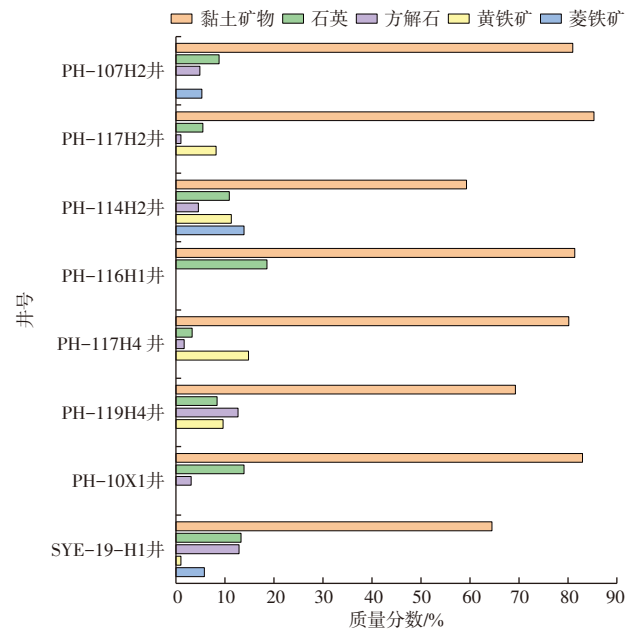


图3 沁水盆地柿庄北、潘河、柿庄南、寿阳区块煤层气井产出煤粉中无机矿物质量分数

Fig. 3 Inorganic mineral mass fractions in pulverized coal produced from coalbed methane wells in Shizhuang North, Panhe, Shizhuang South, and Shouyang blocks of Qinshui Basin

取玉溪矿煤储层煤粉样品进行实验,实验结果如表3所示,储层(YX-1、YX-2)煤粉以有机质为主,煤层气井(PH-117H5、SYE-30X2)排采出的煤粉以无机矿物为主,原始储层里的煤粉矿物含量及种类均少于排采产出的煤粉。无机矿物更容易受到排采的影响被剥蚀搬运,所以排采出的煤粉成分以无机矿物为主。

表3 储层煤粉成分与部分煤层气井成分对比

Table 3 Comparison of pulverized coal composition in reservoirs and selected coalbed methane wells

样品编号	高岭石/%	石英/%	铁云母/%	方解石/%	铁白云石/%	其他/%	有机质/%
YX-1	3.94	0.95	0.87	0.48	0.55		93.20
YX-2	4.28	1.68	1.23	0.96		0.96	91.31
PH-117H5	46.67	6.16		4.46		8.19	34.45
SYE-30X2	12.33	10.87	6.46	4.00		19.32	46.17

注:有机质主要指动植物遗体和排泄物等生物体组成的化合物。

2 煤粉颗粒静态沉降模型修正

沉降末速是煤粉颗粒在静水中沉降时被携带运移的临界速度,为煤层气井现场排水量设计的重要依据。通过煤粉颗粒静态沉降实验,确定不同粒径煤粉的沉降末速,引入修正系数(α)对经典理论公式进行修正,采用室内实验进行验证分析。

2.1 理想球形颗粒静态沉降末速公式

理想球形颗粒的表面光滑规则。将其置于静止液体中,仅考虑颗粒重力与浮力矢量运算得到颗粒沉降末速,该速度仅受颗粒和液体密度影响。理想球形颗粒静态沉降末速计算公式如式(1)^[41,47,51]:

$$V = \sqrt{\frac{4(\rho_s - \rho)gd_s}{3C_D\rho}} \quad (1)$$

式中: V 为沉降末速,单位m/s; ρ_s 为煤粉颗粒密度,单位kg/m³; ρ 为液体密度,单位kg/m³; g 为重力加速度,单位m/s²; d_s 为煤粉颗粒直径,单位m; C_D 为阻力系数。

式(1)中的 C_D 常为固体颗粒雷诺数(Re)的单值函数^[52], Re 定义如式(2):

$$Re = \frac{\rho V d_s}{\mu} \quad (2)$$

式中: Re 为固体颗粒雷诺数; μ 为流体黏度,单位mPa·s。

通常情况下,由于 Re 取值不同,颗粒所处沉降区域存在差异,对应的沉降末速计算公式可划分为3种。

当 $Re < 1$ 时,颗粒处于层流区,沉降末速计算公式如式(3)所示:

$$V = \frac{(\rho_s - \rho)gd_s^2}{18\mu} \quad (3)$$

当 $1 \leq Re < 1 \times 10^3$ 时,颗粒处于过渡区,沉降末速计算公式如式(4)所示:

$$V = \frac{0.152^{0.714} \sqrt{g(\rho_s - \rho)/d_s^2}}{0.429 \sqrt{\mu/\rho}} \quad (4)$$

当 $1 \times 10^3 \leq Re < 2 \times 10^5$ 时,颗粒处于紊流区,沉降末速计算公式如式(5)所示:

$$V = 1.74^{0.5} \sqrt{\frac{g(\rho_s - \rho)}{\rho d_s^{0.5}}} \quad (5)$$

2.2 煤粉颗粒静态沉降末速公式修正

采用理想球形颗粒静态沉降末速公式计算得到的理论结果与物理实验结果的曲线趋势基本一致,但是实验测得的煤粉颗粒静态沉降末速明显大于理论计算结果

(图4)。这是由于理论计算公式假设条件与煤粉颗粒实际情况之间存在差异:理论计算颗粒假定为理想球体,但实际煤粉颗粒呈现出片状、块状、圆锥状、棱柱状等不规则形状。

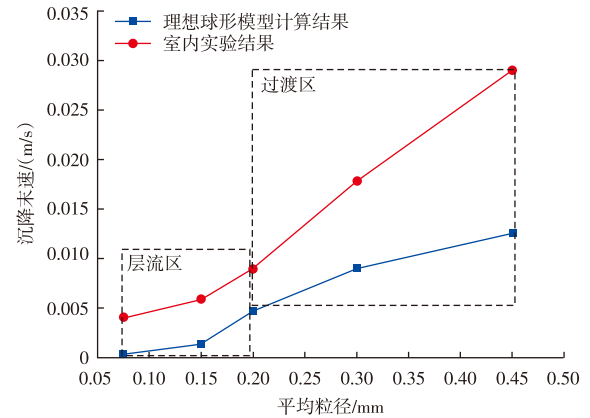


图4 煤粉静态沉降末速理论值与实验结果曲线

Fig. 4 Theoretical value and experimental result curves of static settling final velocity of pulverized coal

为了探讨理论计算与实验研究数据之间的关系,对煤粉球体模型进行修正。通过计算实验测量结果与理论公式计算结果的比值(表4),分别得到不同粒径大小煤粉颗粒所对应的修正系数(α)。 α 具有客观的物理意义,其数值的大小用于表述实际煤粉颗粒与理想球体的差异大小,也被称为煤粉形状因子^[53]。煤粉颗粒与修正系数存在着一定的函数关系(图5)。

表4 煤粉颗粒实验结果与理论计算值对比

Table 4 Comparison between experimental results and theoretical calculation values of pulverized coal particles

粒径/ μm	平均粒径/mm	实验结果/(mm/s)	理想球形模型计算结果/(mm/s)	修正系数 α
>250~380	0.450	29.000	12.600	2.300
>180~250	0.300	17.800	9.000	1.980
>150~180	0.200	9.000	4.700	1.910
75~150	0.150	5.900	1.400	4.210
38~75	0.075	4.100	0.300	13.670

通过对数据进行拟合得到式(6):

$$\begin{cases} \alpha = 5.73d_s^2 - 2.17d_s + 2.12, & d_s > 0.2 \\ \alpha = 44.551e^{-15.74d_s}, & d_s \leq 0.2 \end{cases} \quad (6)$$

进而得到煤粉颗粒静态沉降末速计算公式:

$$V = \alpha \sqrt{\frac{4(\rho_s - \rho)gd_s}{3C_D\rho}} \quad (7)$$

通过式(7)修正理论计算公式,使其更接近实际煤粉颗粒沉降状态。

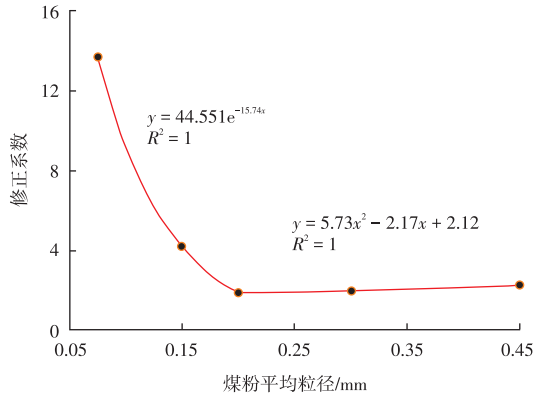


图5 修正因子拟合曲线

Fig. 5 Fitting curve of correction factor

2.3 煤粉颗粒静态沉降末速公式验证

通过式(2)以及煤粉颗粒静态沉降末速数据可以计算出不同煤粉颗粒粒径所对应的 Re ,从而判断煤粉颗粒的沉降区域,再根据煤粉颗粒所处的沉降区域进行相应理论计算公式的计算,得出所对应的颗粒阻力系数。根据颗粒粒径计算出所对应的修正系数,将其代入式(7),即可计算出不同煤粉颗粒所对应的实际沉降末速,再将计算结果与实验测试结果进行对比,结果如图6所示。经过修正后的煤粉颗粒静态沉降末速结果相对于理论结果更接近实验结果,相关系数 $R^2=99%$,可以通过该公式进行沉降末速的计算,提高井筒煤粉运移临界流速计算精度。

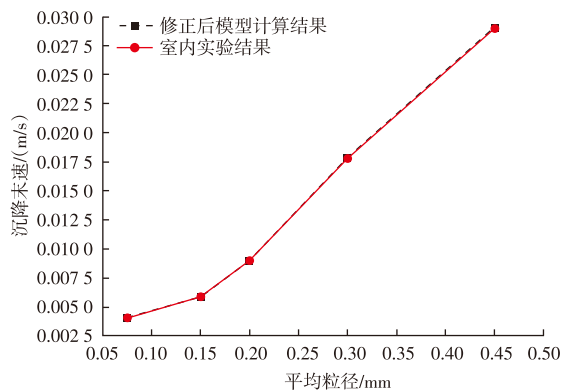


图6 修正后理论沉降末速与实验结果对比曲线

Fig. 6 Comparison between theoretical settling final velocity and experimental results after modification

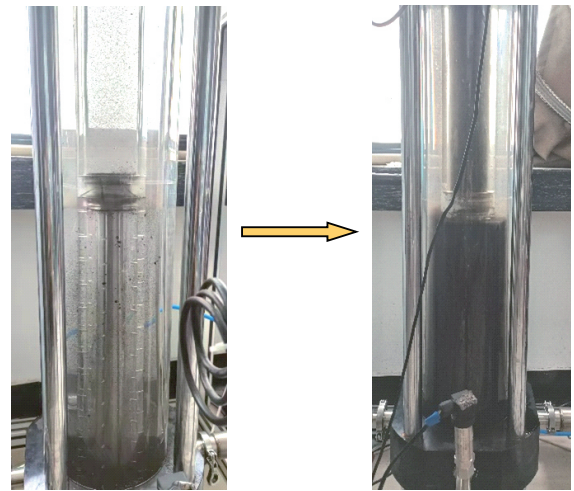
3 井筒煤粉运移实验

通过煤层气井动态沉降测试实验平台,在模拟井筒中搭配音叉密度计监测实验中煤粉的沉降运移过程。相较于前人,煤粉动态沉降实验增加了量化表征。在室内进行测试验证音叉密度计监测的可行性,为煤层气生产

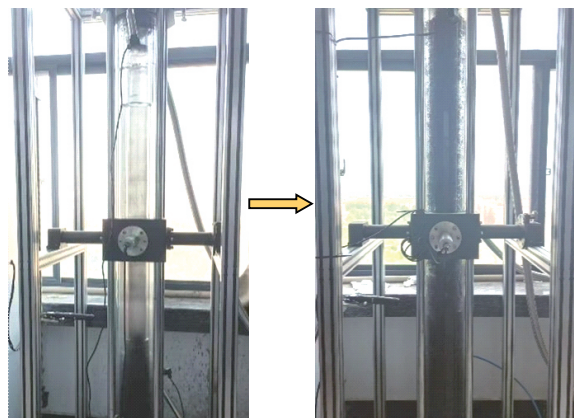
现场的应用奠定理论基础。同时通过设置与现场生产相契合的实验条件进行煤粉动态测试,为现场煤层气生产煤粉防控措施提供实验数据与理论基础。

3.1 实验装置及原理

实验装置主要为自行研制的煤层气井煤粉动态运移测试系统(图7)。实验系统主要由模拟井筒、音叉密度计、动力传输系统、流量测定系统、数据采集系统和煤粉加入装置组成。其实验原理为通过改变搅拌罐中煤粉的质量浓度来模拟煤层气井生产过程中煤层产出煤粉的质量浓度,改变螺杆泵泵入速度来模拟生产过程中的排水速度,并通过音叉密度计对煤粉溶液进行测量。



a. 井底煤粉状态变化



b. 井筒煤粉状态变化

图7 井筒中煤粉运移模拟实验

Fig. 7 Simulation experiment of pulverized coal migration in wellbore

3.2 实验方案及步骤

根据研究区产出煤粉的粒径分布特征以及实验室相关条件配置符合现场生产特征的煤粉样品。确定煤粉动态沉降运移实验的样品粒径介于 $38\sim 380\ \mu\text{m}$,且由产出

煤粉颗粒粒径分布特征进行划分,比例为 $>150\sim 380\ \mu\text{m}$: $>75\sim 150\ \mu\text{m}$: $>38\sim 75\ \mu\text{m}=1:2:7$,即动态沉降实验过程中,样品粒径按照此比例进行配置。同时为了增加实验效果,提高煤粉样品的质量浓度,具体实验方案如表5所示。排水速度计算公式如式(8):

$$V_p = \frac{Q}{3600A_s} \quad (8)$$

式中: V_p 为排水速度,单位m/s; Q 为煤层气井平均产水量,单位 m^3/h ; A_s 为油管横截面积,单位 m^2 。

研究区内煤层气井产水量为 $0.06\sim 1.34\ \text{m}^3/\text{h}$,实验装置的油管横截面积为 $2.8\times 10^{-3}\ \text{m}^2$,计算得到的实验装置排水速度如表5所示。

表5 混合粒径煤粉颗粒动态沉降实验方案

Table 5 Experimental scheme of dynamic settlement of pulverized coal with mixed particle sizes

煤粉颗粒粒径/ μm	煤粉质量浓度/(g/L)	排水速度/(m/s)
38~380	10, 15, 20, 25, 30	0.006, 0.015, 0.025, 0.035, 0.045, 0.055, 0.062
>180~250	1, 2, 4, 6, 8, 10, 15, 20	0.005, 0.010, 0.015, 0.020, 0.025, 0.030, 0.035
>150~180	1, 2, 4, 6, 8, 10, 15, 20	0.005, 0.010, 0.015, 0.020, 0.025, 0.030, 0.035

实验主要步骤:①按照实验方案准备实验所需的煤粉样品,使用高速粉碎机以及国家标准筛对其进行筛分备用;高速粉碎机与标准筛均采用实验室标准设备;②在实验开始前,检查实验设备的各阀门是否处于关闭状态,密封性是否完好,待实验开始时打开相对应的阀门进行实验;③根据方案向搅拌罐中加入清水和煤粉,打开搅拌机进行搅拌,使其充分混合均匀;④通过改变螺杆泵转速控制注入模拟井筒中的排水速度;⑤观察音叉密度计采集数据的稳定性,待数据稳定之后开始进行数据记录;⑥获取实验数据,进行总结分析。

3.3 实验结果分析

不同水流速度条件下煤粉质量浓度的变化如图8所示,整体上煤粉质量浓度随着排水速度的增大而增大。在煤粉颗粒粒径为 $>180\sim 250\ \mu\text{m}$ 的动态沉降实验过程中(图8a):当流速低于 $0.020\ \text{m/s}$ 时,大量煤粉沉积在井筒底部,堵塞孔道,进入油管内的煤粉量较少,音叉测量数值较小,表明此时的煤粉质量浓度较低,排水速度不易使煤粉被携带运移;当排水流速大于 $0.020\ \text{m/s}$ 时,音叉测量数据变化较大,液体流速增加,煤粉质量浓度迅速上升,波动较大,表明此时有大量的煤粉被携带运移。流速较小时,壁面上附着的颗粒较少,可以清楚地观察到单个颗粒的形态。挂壁煤粉量最大值对应流速为 $0.020\ \text{m/s}$,

煤粉携带量增强,沉积在井筒底部的煤粉被运移;随着流速继续增大,管壁附着的煤粉颗粒被冲刷下来,煤粉充满整个油管与环空,煤粉质量浓度增大,颜色加深。

$>150\sim 180\ \mu\text{m}$ 煤粉动态沉降实验的过程相似(图8b)。在搅拌罐中加入煤粉,随着质量浓度的变化,音叉传感器监测数值整体上趋于上升趋势;由于流体流速增大,煤粉更易被携带冲刷;当加入的煤粉质量浓度分别为 $15\ \text{g/L}$ 和 $20\ \text{g/L}$ 时,煤粉质量浓度在井筒中随着水流速度的变化趋势更明显,此时整个井筒区域颜色加深。

实验结果表明: $>180\sim 250\ \mu\text{m}$ 煤粉临界运移流速为 $0.020\ \text{m/s}$, $>150\sim 180\ \mu\text{m}$ 煤粉临界运移流速为 $0.010\ \text{m/s}$,动态运移的排水速度均大于煤粉静态沉降末速。为使得结果更契合生产实际,对 $38\sim 380\ \mu\text{m}$ 的混合煤粉样品进行相同的处理,结果如图9所示, $38\sim 380\ \mu\text{m}$ 煤粉颗粒临界运移流速为 $0.035\ \text{m/s}$ 。对于混合粒径煤粉颗粒来说,不同煤粉质量浓度音叉密度计测量值与排水速度具有很强的相关性,与前文对于不同粒径范围内的实验结果具有一致性。

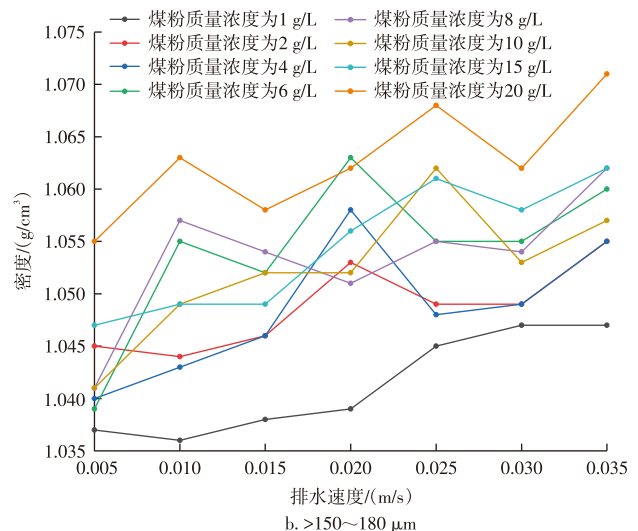
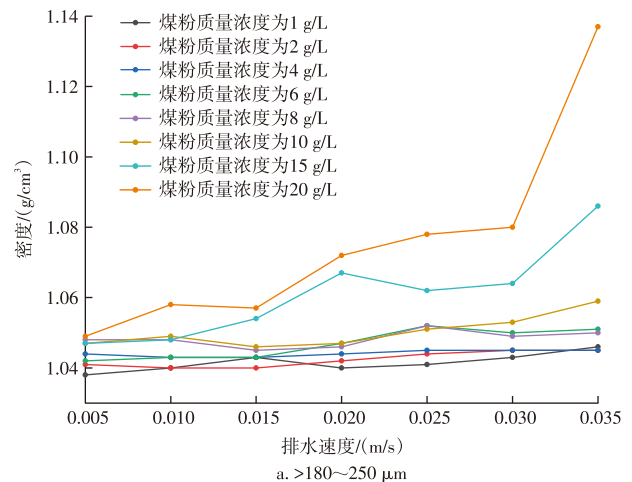


图8 煤粉质量浓度变化曲线

Fig. 8 Variation curves of pulverized coal mass concentration

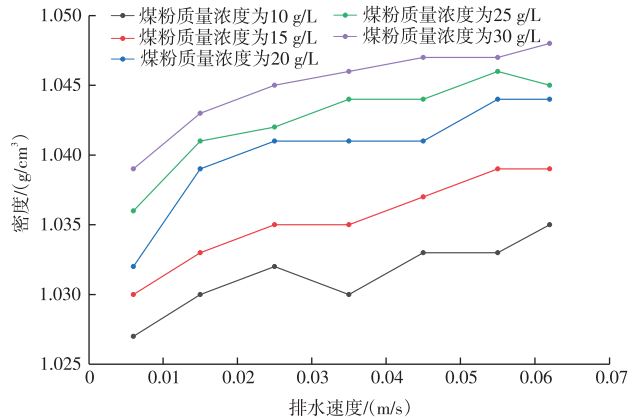


图9 38~380 μm混合煤粉质量浓度变化曲线

Fig. 9 Variation curves of mass concentration for 38~380 μm mixed pulverized coal

在实验初始阶段煤粉颗粒随水流缓慢上升,随着排水速度的增加,井底煤粉随流体通过筛眼进入油管,直至煤粉充斥整个油管内部。因此,增大排水速度可以提高煤粉运移量:如图7a所示,当排水速度小于0.035 m/s时,大量煤粉沉降于井底,只有少量煤粉随着水流被携带运移至井口,此时煤层气井埋泵卡泵等事故发生概率增加;如图7b所示,当排水速度大于等于0.035 m/s时,音叉密度计的测量值有较大的增长波动,流体将井底沉降煤粉携带至井口,减少埋泵卡泵等事故风险。对不同排水速度下的音叉传感器密度曲线进行纵向对比分析,在相同排水速度条件下,音叉传感器能及时反映煤粉质量浓度的变化,从而据此调整排采工况。

4 结论

1) 潘河、寿阳和柿庄等区块煤层气井产出煤粉颗粒粒径集中分布于2~50 μm,煤粉颗粒粒径随着生产周期呈现先增大后减小规律,煤粉以无机黏土矿物为主,为块状、片状、簇状集合体。

2) 考虑煤粉颗粒形状因子影响,引入修正系数对理想球形颗粒静态沉降末速模型进行了修正,修正模型计算结果与室内实验结果更加吻合。

3) 室内实验探明沁水盆地潘河、柿庄等区块煤层气井产出的>180~250、>150~180、38~380 μm粒径煤粉颗粒临界运移流速分别为0.020、0.010、0.035 m/s,对应的煤层气井最小产水量分别为5.2、2.6、8.5 m³/d,单井产水量大于最小产水量可减少井筒煤粉堆积和卡泵的风险。

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