Research on the Effective Influence Radius of Hydraulic Reaming in Mining Seam

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Abstract: According to the present situations that the construction amount of the gas drainage boreholes in mining seam is large and the gas drainage effect in low permeability coal seams doesn’t yield perfect, the hydraulic reaming technology in mining seam is proposed to increase the gas drainage efficiency. Through the gas flow method, the effective influence radius of hydraulic reaming is determined. And the fluid-solid coupling model of gas drainage along boreholes after hydraulic reaming is established theoretically. Then the change laws of gas content around the boreholes in the coal seam are simulated and analyzed. The results indicate that hydraulic reaming can effectively promote the stress-relief and permeability-increase of the coal mass around the boreholes, and the coal mass around the reaming boreholes can be divided into gas flow increase zone, gas flow delay attenuation zone and fast decay zone. The effective influence radius of hydraulic reaming is 5.5~6 m. The simulation results are basically in accordance with the field investigation.

Keywords: Hydraulic reaming, effective influence radius, flow method, numerical simulation.

1. INTRODUCTION

In the high gassy and low permeability coal seams, there exist a series of problems corresponding to the gas drainage boreholes in the mining seam, which include the smaller effective influence range, the larger amount of construction, the longer pre-drainage time and the worse effects of gas drainage. Thus the existing gas drainage in mining seam can’t completely satisfy the urgent demands of safety production in coal mines. As a result, the major coal enterprises and related research institutes tested all kinds of technical measures for pressure relief and permeability increasing, such as hydraulic fracturing, shallow hole loose explosion, deep hole pre-splitting blasting, hydraulic extrusion and hydraulic flushing, etc. Relevant analysis shows that the former technical measures have the remarkable effect in the limited range or under the certain conditions, whose limitations are accordingly obvious. For instance, the induced cracks are easily compacted after hydraulic fracturing, the efficiency of seaming for the fracturing boreholes need to be improved [1, 2]. Due to the shallow charging, the shallow hole loose explosion easily induce the coal and gas outburst [3]. Although the deep hole pre-splitting blasting obtain the ideal increasing permeability effect in the soft and low permeability coal seams [4], but it isn’t likely for the large scale promotion owing to the complex charging technology. And operation process of hydraulic extrusion is more complicated [5]. However, the hydraulic flushing is more suitable for the coal seam with the loose texture and a certain property of artesian flow [6].

In addition, the above measures are more suitable for the locations such as the floor roadway, the working face for rock cross-cut coal uncovering or the heading face, and so on. Because these measures usually need to remain the protective rock pillar or construct without person, there exist the missing of direct and effective technical measures for pressure relief and permeability increasing in mining seams, which are the key regions for gas control. So the hydraulic reaming technology in mining seam is proposed for achieving the final goals of increasing the permeability of coal seams, enlarging the valid influence range for borehole drainage and raising the gas drainage efficiency, according to the characteristics of the harder coal quality and the lower permeability, as well as the larger construction amount of gas drainage boreholes for the 21 coal seam of a coal mine in Anhe coalfield.

2. SUMMARY OF HYDRAULIC REAMING TECHNOLOGY IN MINING SEAM

2.1. Sketch of Test Location

The test working face is with the strike length of 1010~1018 m and the inclination length of 150 m. The mining seam is 21 coal seam located in the lower part of Shanxi group in Permian. The occurrence of coal seam is relatively stable. The dip angle of coal seam is 12~24°, and the thickness of coal seam is 6.6~7.4 m, with the average of 7.0 m. Moreover, the consistent coefficient of coal is 0.63. Note that the original gas content of coal seam is 7.42 m³/t and the effective influence radius is 1.3~1.5 m for gas drainage of boreholes in mining seam lasting 30 days.
2.2. Process Overview

The hydraulic reaming technology of mining seam is applied to the constructed boreholes along the mining seam. The water in the storage tank is pressurized with the help of the continuous pressurizing function of emulsion pump and flows sequentially through the high pressure hose, high pressure rotary water tail and high pressure pipe. Then it ejects from the nozzles of reaming bit, finally formats high pressure continuous water jet. Since the high pressure drill pipe and reaming bit are rotated, advanced and retreated by the mine drill, the high pressure water jet can cut and strip the coal body around the boreholes. Thus this technology can enlarge the borehole diameter, increase the exposed area of coal seam and the radial pressure-relief range of the borehole. Then the final aims are achieved, which are the increases in the permeability of coal seam and the gas drainage effects.

2.3. Selection of Devices

The drill for hydraulic reaming is the drill carriage used for deep holes in coal mine with the type of CMS1-6200/80. And the diameter of drill pipe is 73 mm. The diameter of drill bit is 84 mm. Furthermore, the tube connected the drill carriage with the emulsion pump is the wire spirally-wound hose with the internal diameter of 38 mm and withstand voltage of 38 MPa. And the other end of tubes is linked with the tail of drill pipe. The connections are reinforced by the quick connecters and U clips. The type of nozzle is selected for 3Φ1.5 mm. Besides, the nozzles are fixed on the special drill bit of Φ75 mm. The type of emulsion pump is BRW200/31.5, supported by the auxiliary emulsion box of FRx1000. The working water pressure of pump is 14–20 MPa. In addition, the dual function and high water pressure meter with the type of SGS is installed away from the tail of drill carriage about 5–8 m, monitoring water pressure and flow changes. And the low concentration methane sensor is fixed in the return air side of working face for monitoring the changes in gas concentration of return air flow during hydraulic reaming.

2.4. Process Flow

Construct the borehole of Φ84 mm to the depth of 85 m with deep hole drill carriage → Return pipes → Change hydraulic reaming drill bit → Drill to the depth of 85 m → Ream the borehole outward and pipe by pipe → Until the return water becomes clear to a certain depth → Return pipes and ream until the inward position from the orifice of 20 m, as well as controlling the output amount of coal per one meter between 0.3 ton to 0.4 ton → Check the gas concentration of leeward side → Check the output amount of coal → Return pipes and seam the borehole.

3. INVESTIGATION OF EFFECTIVE INFLUENCE RADIUS FOR HYDRAULIC REAMING BY FLOW METHOD

3.1. Sketch of Flow Method

What is the main basis for the investigation of effective influence radius for hydraulic reaming by flow method is that the drainage boreholes, along which gas flow fluctuates obviously during hydraulic reaming and conforms to unconventional attenuation law after hydraulic reaming, locate in the effective influence range. The specific reason is that the high pressure water jet impacts and crushes the coal body, then compels the mixture with coal and water to exhaust outwards. Then the surrounding stress of the boreholes redistributes accordingly. So the coal mass in the certain zones around boreholes is stress-relief and the stress concentration zone transfers to the deep coal mass. Meanwhile, the stress wave caused by the high pressure water jet produces radial compressive stress and tangential tensile stress on the coal mass in the process of propagation, which are favorable to the formation of radial cracks and accelerating the gas flow, then promoting the increase in gas drainage quantity.

3.2. Layout of Boreholes

Two groups of boreholes are arranged in the test area, and each group includes one reaming borehole and two boreholes for investigation in one group, as shown in Fig. (1). Setting the inspection boreholes in Fig. (1a) as the example, the investigation details for flow method can be expressed as follows: Before hydraulic reaming, No. 7 and 9 drainage boreholes are constructed and then connected with the drainage system for extraction. Then No. 8 borehole for reaming is launched. The gas flow for No. 7 and 9 boreholes are continuously observed for 30 days before and after hydraulic reaming. At the same time, a group of regular drainage boreholes is arranged for the comparison and analysis of gas flow for drainage boreholes in the adjacent unaffected zone for reaming. Note that the second group of inspection boreholes is similar as the former one.

3.3. Results Analysis

The changes in gas flow of every inspection borehole before and after hydraulic reaming are shown in Fig. (2). The abscissa represents the inspection date, and the ordinate represents the daily mean gas flow of the drainage boreholes. Note that the ordinate of intersection point for vertical dotted line and flow curve represents the average data in the reaming process, shown in Fig. (2a, b).

It can be seen from Fig. (2) that in the process of reaming No. 8 borehole, the cracks in coal mass between No. 7 borehole and No. 8 borehole due to the impact action of water jet, linked with each other in a certain extent. So the gas flow of No. 7 borehole drew down to 0.207 m³/min from 0.218 m³/min. The probable reason is that the air flew into No. 7 borehole along the cracks through No. 8 borehole. Meanwhile, the water jet infiltrated the coal mass around No. 8 borehole, restraining gas desorption to some extent. In two or three days after reaming, gas drainage in No. 8 borehole also started. The gas flow climbed higher up to 0.225 m³/min or so, owing to the stress-relief of coal mass around No. 7 borehole. As the drainage time increases, the gas flow of No. 7 borehole undulated up and down under the action of the negative pressure fluctuations of gas drainage system, but basically kept around 0.195 m³/min lasting for 15 days. Then gas flow in No. 7 borehole greatly reduced, expressing most new fractures began to close in the process of in-situ stress.
recovery. After reaming No. 8 borehole, the gas flow of No. 9 borehole firstly dropped to 0.21 m³/min. Although it then fluctuated, it was basically stable at around 0.19 m³/min, and finally decreased gradually.

Analyzing the probable reasons, it can be found that the coal mass of No. 9 borehole located in the transition zone between the stress concentration zone and the original stress zone of No. 8 reaming borehole. And partial cracks extending to this zone started to close and didn’t develop any more forward, because the coal mass was under the concentrated stress. So the permeability coefficient of coal seam reduced correspondingly. In the process of reaming No. 11 borehole, gas flow of No. 10 borehole firstly showed a slight upward trend to 0.064 m³/min from 0.06 m³/min in the day before reaming. And the gas flow gradually decreased as the increase in drainage time. It can be concluded that the hydraulic reaming did a certain action of stress-relief and permeability-increase on the coal mass around No. 10 borehole, which soon dissipated with the end of reaming. And the coal mass of No. 10 borehole located in the transition zone between the stress-relief zone and the stress concentration zone caused by hydraulic reaming. However, the gas flow of No. 12 borehole firstly drew down to 0.08 m³/min, and kept for a long time then began to decrease constantly. Compared with No. 9 borehole, the gas flow attenuation coefficient was much lower, indicating that the coal mass of No. 12 borehole located in the stress concentration zone induced by the hydraulic reaming, so the gas flow decreased but wasn’t like the rapid decline of regular gas drainage boreholes. In addition, the total gas drainage amount of one month for the investigation boreholes around the reaming ones was 2.17 times than the one of the adjacent regular drainage boreholes unaffected by hydraulic reaming. And the average gas flow attenuation coefficient was only 0.31 of regular drainage boreholes. This also proved the validity and reliability of hydraulic reaming technology.

In summary, the coal mass around the reaming borehole can be divided into gas flow increase zone, gas flow delay attenuation zone and gas flow fast decay zone in turn from the wall of borehole to the depths of coal mass, according to the change in gas flow. And in gas flow increase zone, the stress is relief and the permeability increases for the coal mass due to the impaction of water jet, then the gas flow increases accordingly. In gas flow delay attenuation zone, the partial cracks extending to this zone start to close under the concentrated stress and the gas flow decreases consequently. But the attenuation coefficient of gas flow decreases due to the local action of stress-relief and permeability-increase. In gas flow fast decay zone, as the coal mass isn’t affected by the impaction of water jet, the gas flow follows the rapid attenuation rule of the low permeability coal seam. Thus, it can be concluded that the coal mass within 6 meters of reaming boreholes belongs to gas flow increase zone, which is to be effective influence range of hydraulic reaming. And the gas flow delay attenuation zone includes the coal mass in the range within 6–7.5 m around the reaming boreholes. Furthermore, the gas flow fast decay zone refers to the coal mass about 7.5 m outside of reaming boreholes, which is also the unaffected range for hydraulic reaming. In a word, the effective influence radius of hydraulic reaming in mining seam can be determined as 5.5–6 m.

### 4. NUMERICAL SIMULATION

In order to verify the validity of the flow method, the fluid-solid coupling numerical model of gas drainage for in-seam boreholes after hydraulic reaming is built for discussing the change rules of gas content in coal mass around the drainage boreholes after reaming. Moreover, the change rules are compared and analyzed with the measured data for more accurately determining the effective influence radius of hydraulic reaming. So the following hypothesis is firstly made, including: I. the coal mass is porous medium and saturated by methane; II. the coal mass is a homogeneous isotropic elastic medium; III. ignore the effect of the changes in temperature and gas adsorption and desorption on coal deformation and gas seepage process.

#### 4.1. Mathematical Model

##### 4.1.1. Governing Equations of Coal Deformation

The skeleton deformation of coal mass containing gas is widely expected to obey Terzaghi’s effective stress principle [7-9]. According to the law of conservation of momentum, the equation of stress equilibrium is expressed with effective stress and pore pressure as

$$\sigma_{ij}^e + (\alpha p \delta_i^e) + F_i = 0$$  \(1\)
in which $\sigma_{ij}^{\ast}$ is the effective stress tensor of coal mass containing gas (Pa), $\gamma = 1, 2, 3$, $\alpha$ is Biot’s coefficient (= $K/k$), $K$ is the bulk modulus of coal mass containing gas (Pa), $k$ is the effective bulk modulus of coal grains (Pa), $\delta_{ij}$ is the Kronecker delta as 1 for $i=j$ and 0 for $i \neq j$, $p$ is pore pressure (Pa), and $F_i$ is the body force (Pa).

According to the continuity conditions of deformation, the strain component of coal mass containing gas $\varepsilon_{ij}$ is defined as

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i})$$

where $u_{ij}$ and $u_{ij}$ are the displacement components of coal mass containing gas.

The coal deformation is assumed to linear elastic, and the deformation constitutive equation of coal mass containing gas can be expressed as

$$\sigma_{ij} = 2G\varepsilon_{ij} + \frac{2Gv}{1-2v}\varepsilon_{ii}\delta_{ij} + \alpha \rho \varepsilon_{ij}$$

where $\sigma_{ij}$ is the total stress tensor of coal mass containing gas (Pa), $G$ is the shear modulus of coal mass containing gas (Pa), and $v$ is the Poisson’s ratio of coal mass containing gas.

Substituting Eq. (2) and (3) into Eq. (1) yields the deformation governing equation of coal mass containing gas as

$$Gu_{i,j} + \frac{G}{1-2v}\varepsilon_{ij} + \alpha \rho \varepsilon_{ij} + F_i = 0$$

### 4.1.2 Dynamic Evolution Equations of Porosity and Permeability

Based on the definition of porosity and only considering the effects of changes in gas pressure on the skeleton deformation of coal mass, the dynamic evolution equation of porosity in coal mass containing gas can be expressed as [10, 11]

$$\varphi = 1 - \frac{1 - \varphi_0}{1 + \varepsilon_0}(1 - \frac{\Delta \varphi}{K})$$

where $\varphi$ is the porosity of coal mass containing gas, and $\varphi_0$ is the initial porosity, $\varepsilon_0$ is the volumetric strain of coal mass containing gas, $\Delta \varphi$ denotes the changes in gas pressure ($=p-p_0$), and $p_0$ is the initial gas pressure (Pa).

Based on the Kozeny-Carman equation as $k/k_0 = (\varphi/\varphi_0)^3$, the dynamic evolution equation of permeability can be expressed as

$$k = \frac{k_0}{1 + \varepsilon_0}(1 - \frac{\Delta \varphi}{K})$$

where $k$ is the permeability of coal mass containing gas (m$^2$), and $k_0$ is the initial permeability (m$^2$).

### 4.1.3 Governing Equations of Seepage Field

According to the mass conservation law, the gas propagation equation of coal seam can be defined as

$$\frac{\partial m}{\partial t} + \nabla \cdot (\rho_0 \cdot v_s) = Q_i$$

where $m$ is the gas content (kg/m$^3$), including two parts as free gas content $m_g$ and adsorbed gas content $m_a$, $t$ is the time (s), $\rho_0$ is the density of gas (kg/m$^3$), $v_s$ is the gas seepage velocity (m/s), and $Q_i$ is a source term (kg/(m$^2 \cdot s$)).
Based on the ideal gas equation of state [12] and the Langmuir’s isothermal adsorption equation [13], the gas content can be expressed as

$$
m = \frac{M_g \phi p + abc p_{\phi}}{RT (1 + bp)} \tag{8}
$$

where $M_g$ is the molar mass of gas (=16 kg/kmol), $R$ is the universal gas constant (=8.314 kJ/(kmol·K)), $T$ is the temperature (K), $a$ is the limited adsorption quantity unit mass of coal (m³/kg), $b$ is the adsorption constant of coal (MPa⁻¹), $c$ is the correction parameter of coal ($= \frac{\rho_c (100 - A - M)}{100(1 + 0.31M)}$, kg/m³), in which $\rho_c$ is the density of coal (kg/m³), $A$ is the ash content of coal (%), $M$ is the moisture of coal (%), and $p_s$ is the standard atmospheric pressure (Pa), and $p_0$ is the gas density under the standard atmospheric pressure (kg/m³).

As the gas propagation in coal seam is assumed to obey the Darcy’s law, meanwhile considering the influence of Klinkenberg’s effect, the gas seepage velocity can be expressed as [14]

$$
v_s = -\frac{k m}{\mu p} \nabla p \tag{9}
$$

where $\mu$ is the dynamic viscosity coefficient of gas (=1.08×10⁻⁶ Pa·s), and $m$ is the Klinkenberg’s coefficient (Pa).

According to the hypothesis of III and only considering the effect of gas pressure and stress with strain on porosity, the change law of the porosity of coal mass containing gas can be expressed as [14]

$$\frac{\partial \phi}{\partial t} = (1 - \phi)(\frac{\partial e_v}{\partial t} + \frac{1}{K_s} \frac{\partial p}{\partial t}) + \frac{\partial p}{\partial t} \tag{10}
$$

Substituting Eqs. (8) ~ (10) into Eq. (7), the governing equation of the seepage field can be rewritten as

$$2 \alpha p \frac{\partial e_v}{\partial t} + 2[abc p_{\phi} + \frac{p(1 - \phi)}{K_s} + \phi] \frac{\partial p}{\partial t} - \nabla \cdot \left[ \frac{k}{\mu p} (1 + \frac{m}{p}) \nabla p \right] = 0 \tag{11}
$$

4.2. Geometric Model and Physical Parameters

According to the basic hypothesis and experimental data, the simulation analysis of hydraulic reaming can be simply calculated by the two-dimensional plane strain mode. The height of computational domain is 7 m, and the length is simultaneously 100 m. The corresponding locations of boreholes are shown in Fig. (1). The reaming borehole locates in the middle of the domain and the inspection boreholes locate on the left and right sides of the reaming borehole. Besides, the reaming boreholes’ radius is converted to per meter of coal output as 0.4 t, owing to the boreholes after reaming is regarded as a cylinder, so the radius of No.8 and 11 boreholes is 0.304 m, and the radius of other drainage boreholes is 0.042 m. The physical parameters required for the calculation are listed as Table 1.

4.3. Initial Conditions and Boundary Conditions

Initial conditions: The initial gas pressure of coal seam $p(x,y,0)$ is equal to 0.37 MPa, and the initial displacement of stress field $u_i$ is equal to 0 ($i=1,2$).

Boundary conditions: I. Stress boundary conditions: The top boundary of coal seam endures the weight of overburden rock stratum, with the stress of 12.9 MPa. And the weight of coal mass self is also considered; II. Displacement boundary conditions: The vertical bottom of the model is fixed, and the horizontal displacement of the left boundary and the right one is limited as 0; III. Boundary condition of seepage filed: The outside boundaries of the model is air-tight, and the wall of boreholes is the boundary for drainage as $p(x,y,t) = p_\phi = x^2 + y^2 = r^2$

where $p_\phi$ is the negative gas drainage as the measured value of -39 kPa.

5. ANALYSIS OF THE SIMULATION RESULTS

The distribution of residual gas content of the coal mass around the reaming boreholes after extracting for 30 and 40 days respectively, are shown in Fig. (3). It can be seen from Fig. (3a), while No.8 borehole is extracted for 30 days after hydraulic reaming, the maximum residual gas content of coal seam between No.8 and 9 boreholes is 5.82 m³/t, reduced by

<table>
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<th>Parameters</th>
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<tbody>
<tr>
<td>Elastic modulus $E$ (MPa)</td>
<td>2460</td>
<td>Original gas content (m³/t)</td>
<td>7.42</td>
</tr>
<tr>
<td>Poisson’s ratio $\nu$</td>
<td>0.3</td>
<td>Dynamic viscosity of gas (Pa·s)</td>
<td>1.08×10⁶</td>
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<td>Compression strength (MPa)</td>
<td>7.0</td>
<td>Compression coefficient of gas</td>
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<tr>
<td>Internal friction angle (°)</td>
<td>33.4</td>
<td>Adsorption constant of coal $a$ (m³/t)</td>
<td>38.389</td>
</tr>
<tr>
<td>Density of coal (kg/m³)</td>
<td>1400</td>
<td>Adsorption constant of coal $b$ (MPa⁻¹)</td>
<td>0.582</td>
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<tr>
<td>Initial porosity (%)</td>
<td>6.82</td>
<td>Moisture content of coal $M$ (%)</td>
<td>0.59</td>
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<tr>
<td>Initial permeability of coal seam (m²)</td>
<td>5.52×10⁻⁷</td>
<td>Ash content of coal $A$ (%)</td>
<td>14.03</td>
</tr>
<tr>
<td>Original gas pressure (MPa)</td>
<td>0.37</td>
<td>Buried depth of coal seam (m)</td>
<td>490</td>
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20.59% than the original one. And the maximum residual gas content between No.7 and 8 boreholes is 5.395 m³/t, reduced by 27.29% than the original one. While the boreholes are extracted for 45 days, the maximum residual gas content between No.8 and 9 boreholes is 5.403 m³/t, reduced by 27.18%. And the maximum residual gas content between No.7 and 8 boreholes is 4.943 m³/t, reduced by 33.38% than the original one. In addition, the residual gas content of coal seam in the middle of No.8 and 9 borehole is just 5.3 m³/t, similar with the test value of 5.32 m³/t, verifying the correctness of the numerical model. From the decline degree of gas content, it can be found that the residual gas content of the inspection borehole away from the reaming borehole as 5.5 m, reduced by 30% or more, after the gas extraction of 45 days. It also can be seen from Fig. (3b), while No.11 borehole is extracted for 30 days after hydraulic reaming, the maximum residual gas content of coal seam between No.10 and 11 boreholes is 5.257 m³/t, reduced by 29.15% than the

Fig. (3). Distribution of residual gas content after different drainage time.
original one. And the maximum residual gas content between No.11 and 12 boreholes is 5.655 m$^3$/t, reduced by 23.79% than the original one. While the boreholes are extracted for 45 days, the maximum residual gas content between No.10 and 11 boreholes is 5.057 m$^3$/t, reduced by 31.85%. And the maximum residual gas content between No.11 and 12 boreholes is 5.174 m$^3$/t, reduced by 30.27% than the original one. Moreover, from the decline degree of gas content, it can be found that the residual gas content of the inspection borehole away from the reaming borehole as 6 m, reduced by 30% or more, after the gas extraction of 45 days. But the residual gas content of the inspection borehole away from the reaming borehole as 6.5 m, barely reduced by 30%, after the gas extraction of 45 days. According to “Provisional regulations for the gas drainage up to the standards of coal mine” and the actual gas drainage conditions for this coal mine, the gas content of coal mass among the boreholes with extracting for 45 days after hydraulic reaming, is reduced by 30%, which is regarded as the critical investigation value of effective influence radius of hydraulic reaming. Thus the effective influence radius of hydraulic reaming is 5.5–6 m and not beyond 6.5 m, in accordance with the field investigation results.

CONCLUSION

I. According to the characteristics that the construction amount of the gas drainage boreholes in mining seam is large and the gas drainage effect in low permeability coal seams doesn’t yield perfect, the hydraulic reaming technology in mining seam is proposed correspondingly. And through the field test, the technical parameters and the process flow of hydraulic reaming are determined.

II. Based on the changes in gas flow of the inspection boreholes before and after hydraulic reaming, the coal mass around the reaming borehole can be divided into gas flow increase zone, gas flow delay attenuation zone and gas flow fast decay zone in turn from the wall of borehole to the depths of coal mass. And the coal mass within 6 meters of reaming boreholes belongs to gas flow increase zone, which is to be effective influence range of hydraulic reaming. The gas flow delay attenuation zone includes the coal mass in the range within 6–7.5 m around the reaming boreholes. Furthermore, the gas flow fast decay zone refers to the coal mass about 7.5 m outside of reaming boreholes, which is also the unaffected range for hydraulic reaming.

III. The fluid-solid coupling model of gas drainage along boreholes after hydraulic reaming is established. And the distribution of gas content around the boreholes in the coal seam after hydraulic reaming are obtained. Finally, the effective influence radius of hydraulic reaming is determined as 5.5–6 m, not beyond 6.5 m. The reliability of flow method and the effectiveness of hydraulic reaming technology are verified by the simulation results.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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