Analysis of coal seam degassing efficiency using boreholes and hydraulic fracturing

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Abstract. The effect produced by hydraulic fracturing on the filtration resistance of coal seam zone subject to drainage by parallel boreholes is considered. The resistances to the gas inflow depending on the orientation of fractures, thickness of seam, and distance between the boreholes are analyzed. The efficiency of single and multistage hydraulic fracturing in forming multiple transverse and main longitudinal cracks is compared.

1. Introduction

The safety and effectiveness of underground mining methods for mining coal seams characterized by high methane content and hazardous emission depend on the degree of their degassing in advance of mining (pre-drainage). Hydraulic fracturing is a highly perspective method for intensification of coalbed methane (CBM) drainage. Among its several known modifications, a non-directional water-based hydraulic fracturing without using proppants (to keep fractures open) is the most widespread in Russia, [1, 2]. The works involving this technique are carried out either during one stage within specially drilled hundreds of meters long boreholes or in several stages, with each implemented within a short interval of a degassing well, by creating multiple (several tens) transverse and main longitudinal cracks with up to 10 m radii [3-5].

This paper provides results of a comparative analysis of the known hydraulic fracturing enhancing effects on underground gas drainage using parallel boreholes.

2. Filtration resistance of gas drainage hole area in coal seam

A coal seam represents a block-structured medium where gas is filtered through cleavage cracks. At this, most of methane content is localized in microblocks, whose dimensions range from a few millimeters to a few centimeters, while permeability of the interblock cracks is negligibly low. According to the methane emission model presented in [6], the process of methane diffusion from microblocks takes less time, than its filtration (drainage) from coal seam. The ability of gas to be drained from the coal seam (deliverability) is therefore controlled by the coal seam permeability [7], while the efficiency of degassing operations is determined by filtration resistance of the drainage zone. In-mine hydraulic fracturing is intended to reduce this resistance and increase the hydrodynamic “perfection” of degassing wells.

For analysis of the efficiency of coal seam degassing schemes, we use approximate analytical solutions that are illustrative and along with that provide sufficient accuracy for practical calculations. An ideal flow of gas to the well bore can be described by the equation: 

\[ P_f^2 - P_w^2 = \alpha Q + \beta Q^2, \]

where
$Q$ is the volumetric gas flow rate; $P_k$, $P_w$ are its pressures, respectively, on the constant pressure boundary and in the borehole; $\alpha$ and $\beta$ are coefficients of filtration resistance of coal seam zone [8]. Inasmuch as the term $\beta Q^2$ does not exceed 5–10% of $\alpha Q$, and the spatial distribution of resistances $\alpha$ and $\beta$ across the coal seam is usually unknown, we use a simplified linear dependence written as [9]

$$P_k^2 - P_w^2 = \frac{\mu P_0}{k_h h} \theta Q,$$  \hspace{1cm} (1)

where $\theta$ is effective (reduced) coefficient of filtration resistance caused by the borehole hydrodynamic imperfection confirmed by the coalbed uncovering; $k_h$ is coal permeability along the seam, m$^2$; $h$ is the coal seam thickness, m; $\mu$ is methane viscosity Pa·s; $P_0$ is atmospheric pressure, Pa.

Figure 1 shows schemes for coal seam degassing with parallel boreholes of length $L$, including: type I—without involving hydraulic fracturing (HF); type II—with hydraulic fracturing along the well axis (longitudinal HF), in the normal to coal bed direction (intersecting HF); type III—with longitudinal hydraulic fracturing parallel to the formation plane (layer-wise fracturing); type IV—with hydraulic fracturing generating several parallel cracks transversal to the borehole axis (here and elsewhere, multistage transverse hydraulic fracturing).

![Figure 1. Methane drainage schemes for parallel wells involving: no hydraulic fracturing (type I); longitudinally intersecting fracturing (type II); longitudinal layer-wise fracturing (type III); multi-stage transverse fracturing (type IV); $a$, $b$—length and width of the drained area; $l_f$—length of hydraulic fracturing induced cracks; $d$—distance between transverse fractures.](image)

Consider the effects of hydraulic fracturing on the magnitude of coefficient $\theta$. The filtration flow is assumed to be steady, the fluid pressure in borehole and failure zones to be constant, and the coal seam roof and base to be impermeable. Given that in underground hydraulics[10], the drainage zone of a drilled well is commonly divided into (i) inner region of radius $h/2$ with a flat radial flow of ideal gas and (ii) outer region with a plane-parallel flow (as far as the constant pressure boundaries). The coefficient of filtration resistance in the inner region will be found using the Dupuy formula for a vertical well in a homogeneous bed, adjusted for the isotropic permeability a [11]. For estimation of the filtration resistance in the outer drainage area of a horizontal well with a rectangular impermeable constant pressure boundary, we use the formula given in [12]. After fitting both solutions at the interface between the inner and outer
filtration regions we obtain the final expression of the coefficient $\theta$ for a single well of type I drainage scheme (Figure 1):

$$
\theta_i = \frac{1}{\pi} \text{arzech} \left( \cosh \left( \frac{\pi b}{2a} \right) \right) + \frac{\chi h}{\pi L} \ln \left( \frac{\chi h}{(1+\chi)R} \right), \quad (2)
$$

where $\chi = \sqrt{k_h/k_v} \geq 1$ is index of anisotropic permeability; $k_v$ is coal permeability measured perpendicular to the bedding plane; $R$ is wellbore radius ($R < h/2$).

If the crack intersecting the coal seam has infinite conductivity, then the filtration resistance of the type II drainage zone corresponds to the resistance of the ideal gallery and is equal to the first term in the right part (2). In the case of the final conductivity of a rectangular crack of length $l = h$, of width $L$, opening $w$, and permeability $k_j$ ($k_j \geq k_h$) the filtration resistance of type II drainage zone can be written as $\theta_{II} = A + F_{II}$ [13], where $A$ is the first term in the right part (2); $F_{II}$ is additional resistance to gas inflow to the borehole from the crack at their intersecting the generating line of borehole surface. The desired resistance is determined by assuming the filtration pattern in the crack and its surroundings to be bilinear. We will model the flow curvature effect caused by wellbore (the second term in the right part (2)) with a layer of reduced permeability around the drainage gallery. Using the electrohydrodynamic analogy method [10], we obtained the following desired solution of the problem for $k_j \gg k_h$:

$$
F_{II} \approx \frac{1}{4} \left( \frac{A}{B} + 1 \right) \frac{k_j h}{k_j w} \frac{h}{L}, \quad (3)
$$

where $B$ is the second term on the right side (2). Without taking into account the flow curvature effect: $F_{II} = k_j h^2/4k_j w L$. Similarly, taking into account the problem’s geometry, we obtain an expression for the coefficient of filtration resistance for type III drainage zone with a layer-wise failure of a length $l_j$ ($b > l_j > 2R$) (Figure 1)

$$
\theta_{III} \approx \frac{\chi^2}{\pi} \frac{a h}{L} \text{arzech} \left( \cosh \left( \frac{\pi b}{2h} \right) \right) + \frac{\chi^2}{4} \frac{k_j l_j}{k_j w} \frac{h}{L}. \quad (4)
$$

The coefficient of filtration resistance for type IV drainage zone is found by its dividing around each transverse fracturing into rectangular sections with sides $b$ and $d$ and a rectangular constant pressure boundary, where $d = L/(N - 1)$ is the distance between the transverse fracturing; $N$ is the number of ruptures along the well. The distance $d$ is chosen so that it does not exceed the length of the transverse cracks $l_s$. Then their mutual influence in the case of low-permeability coals can be neglected [14]. We also believe that the flow to the borehole directly from the coal seam is much lower than from hydraulic fracturing induced cracks. The value of $\theta_{IV}$ is determined using the same assumptions as before using the total resistance of coalesced the $bd$ sections (connected in parallel). Note that given the transversal crack intersecting the well along the circumference and the plane-radial nature of the gas flow, the additional resistance to the gas inflow from the crack differs from (3). The numerical estimation of this resistance is given in [15]. Here we use a simplified approach applicable to oil and gas fields development based on replacement of a horizontal well and rectangular crack with an equivalent system of a vertical well [16] and circular crack of radius $(l_s^* h/C)^{1/2}$, where $C$ is a coefficient depending on the crack configuration and its intersection with well [17]:

$$
\theta_{IV} \approx \frac{\chi^2}{\pi} \frac{a h}{L} \text{arzech} \left( \cosh \left( \frac{\pi b}{2h} \right) \right) + \frac{\chi^2}{4} \frac{k_j l_j}{k_j w} \frac{h}{L}. \quad (4)
$$
\[ \theta_N \approx \frac{1}{\pi N} \text{arcch} \left( \frac{\cosh \left( \frac{\pi L}{2bN} \right)}{\sin \left( \frac{\pi l}{2b} \right)} \right) + \frac{1}{2\pi N} \cdot \frac{k_h h}{k_j w} \ln \left( \frac{hl_s}{CR^2} \right), \]  

where \( l_s \) is the length of a crack generated by transversal hydraulic fracturing \( h < l_s < b; a - L \sim d \).

According to the comparison with numerical calculations, the estimates using the formula (5) are suitable for practical applications at \( L/d < 10 \) [15].

3. Results of numerical studies and their discussion

Figure 2 shows the filtration resistances during coal seam drainage by a single well according to schemes I – IV, which were calculated using formulas (2) – (5) at \( a = 200 \text{ m}, L = 150 \text{ m}, 2R = 100 \text{ mm}, L_f = b/2 \) depending on the distance between boreholes \( b \) at \( h = 2 \text{ m}, \chi = 1.83, d = 5 \text{ m} \) (Figure 2a) and \( h = 2 \text{ m}, \chi = 1, d = 10 \text{ m} \) (Figure 2b) and coalbed thickness \( h \) at \( b = 10 \text{ m}, \chi = 1.83, d = 5 \text{ m}, \) (Figure 2c) and \( b = 5 \text{ m}, \chi = 1, d = 10 \text{ m} \) (Figure 2d).

![Figure 2](image)

**Figure 2.** Filtration resistances in the coalbed drainage zone drained with a single well according to the types I–IV schemes depending on the distance between wells \( b \) and coalbed thickness \( h \).

The plots in Figure 2 show that in thin coal seams (up to 2 m), layer-wise longitudinal hydraulic fracturing reduces the filtration resistance of the coal seam drainage zone to a greater extent, as compared to the intersecting hydraulic fracture.

In such coalbeds, normal-intersecting longitudinal hydraulic fracturing competes in the efficiency with the degassing intensification by infill drilling of degassing wells, which, due to its better technological effectiveness, is widely used for subsurface mining of gas-bearing coal seams. The use of multistage transverse hydraulic fracturing (type IV) technology appears to be significantly effective only with high density of cracks (5–7 m from each other) along the wellbore. As such, this type of hydraulic fracturing is complicated by low coal strength and potential collapse of uncased degassing wells, and variability of their depth profiles which challenges the sealing off interval.

Let us briefly discuss the use of proppants with in-mine hydraulic fracturing, which is still rare in Russia. Table 1 shows the calculated relationships between the filtration resistances of coalbed
drainage zones drained with wells without hydraulic fracturing (type I) and with normally intersecting hydraulic HF (type II) and with crack opening from 0.005 to 0.5 mm.

Table 1. A relationship between coefficients of filtration resistance in the coalbed drainage zones drained with single boreholes according to types I and II schemes ($\theta_1 / \theta_{II}$)

| No. | Variable parameters, m | Crack opening $w$, mm |
|-----|------------------------|------------------------|
|     | $b$  | $h$  | 0.005 | 0.01 | 0.05 | 0.5 |
| 1   | 3    | 1    | 1.59  | 1.91 | 1.97 | 1.97 |
| 2   | 7    | 1    | 1.28  | 1.40 | 1.41 | 1.41 |
| 3   | 15   | 1    | 1.14  | 1.19 | 1.19 | 1.19 |
| 4   | 3    | 3    | 2.17  | 5.41 | 6.86 | 6.87 |
| 5   | 7    | 3    | 1.83  | 3.15 | 3.51 | 3.52 |
| 6   | 15   | 3    | 1.52  | 2.06 | 2.17 | 2.17 |
| 7   | 3    | 5    | 1.87  | 7.48 | 13.00 | 13.08 |
| 8   | 7    | 5    | 1.73  | 4.68 | 6.16 | 6.18 |
| 9   | 15   | 5    | 1.55  | 2.97 | 3.41 | 3.42 |

The calculations show that, the effectiveness of in-mine hydraulic fracturing of coal is doubtful at $w \leq 0.01$ mm. If we assume that $k_f = w^2 / 12$ is true (the Boussinesq-type equation), then the optimal opening of local hydraulic fractures in low-permeability coals is about 0.05 mm. Under conditions of crack compression greater than 4 MPa, this opening value can only be obtained when proppants keep the cracks open. Given a low compression induced by rock pressure (up to 3-4 MPa), a crack without a proppant may produce a two-fold increase in methane inflows from coal seam with thickness $>3$ m, and up 1.5-fold increase in coal seams with a thickness $<1$ m.

Note that improving the drainage of the coal seam by hydraulic fracturing reduces the risk of accidents at the expense of higher degree of degassing within a specified time interval, which is favored by both a more rapid pressure drop in formation waters that block the methane release into the cleavage microcracks [17], and by enhanced coal seam permeability to gas.

4. Conclusions
In anisotropic coal seams, the highest reducing effect on filtration resistance of the coal seam drainage zone is provided by multi-stage transverse hydraulic fracturing generating a high density of cracks per well. In the case of relatively isotropic and anisotropic coals with thickness up to 3 m, the layer-wise hydraulic fracturing has proven to be sufficiently effective.

The technological simplicity of this technology and acceptable efficiency against the multi-stage hydraulic fracturing technique allow to consider it to be more promising. The limiting factor is the formation of intersecting hydraulic fractures that tend to dominate in coal seams, which is associated with the developed coal cleavage.

In the case of thin isotropic coals, it is easier to reduce the distance between wells by 30% in order to increase the degassing efficiency, than to create longitudinally intersecting main cracks in them. To intensify degasification of coal seams, it is sufficient to create hydraulic fracturing induced cracks 0.05 mm in diameter.

An increase in crack opening above this value leads to a slight decrease in filtration resistance of the drainage zone. Hydraulic fracturing of gassy coal seams without proppant is effective at low compression pressures (no more than 3–4 MPa) the cracks are exposed to, however, under high rock pressures its efficiency is low. Improving the in-mine hydraulic fracturing efficiency in coal
seams appears to be most promising with development of the technique for layer-wise longitudinal hydraulic fractures and their filling with proppant.

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