Risk reduction in underground mining of coal-bearing coal seams with hydraulic fracturing

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Abstract. The paper discusses influence exerted by the parameters of hydraulic fracturing on flow coefficient in parallel holes in pre-mining degasification of coal seam non-unloaded from rock pressure. The rates of coal degasification without hydraulic fracturing, as well as with nondirectional and multistage hydraulic fracturing are compared. Effect of different-type fracks on risk reduction in underground coal mining is assessed. The obtained results allow estimating efficiency of the hydraulic fracturing modifications currently in use in coal mines.

1. Introduction

The influence of in-seam hydraulic fracturing on risk reduction in underground coal mining is estimated with regard to the effective guidelines on hazard analysis and accident risk assessment in coal mines [1] approved by the Federal Environmental, Industrial and Nuclear Supervision Service of Russia.

One of the key factors to affect the Accident Risk Index (ARI) in coal mines is the quality of pre-mining degasification. The latter is of the special concern in coal seams with supercritical methane content (ARI = 0.7) and in outburst-hazardous mines (ARI = 1). According to [1], for risk reduction, it is required that methane removal before actual mining is not less than 50% of absolute gas content of coal.

A promising method to enhance pre-mining degasification efficiency in coal seams is hydraulic fracturing. There a few known modifications of this technology. The most wide-spread is unpropped in-seam hydraulic fracturing [2, 3]. This type fracturing is carried out by one stage in special holes up to a hundred meters long. Another technology is multistage hydraulic fracturing with fractures created lengthwise or across a drainage hole [4–6].

This study compares influence of the existing methods of hydraulic fracturing on the efficiency of gas drainage of coal seam by parallel holes.

2. Flow resistance in degasification zone of drainage hole

Structurally, a coal seam is a block medium, and gas flows in cheats. Blocks with the major methane content are usually millimeters or, less often, centimeters in size, and their permeability is negligibly small. As in the model of methane extraction in [7], the time of gas diffusion from microblocks is less than the time of gas flow to hole. Gas recovery depends on permeability of coal seam [8], while efficiency of degasification is governed by flow resistance in the degasification zone. The application target of hydraulic fracturing is to decrease the flow resistance and to enhance hydrodynamic quality of drainage holes.
The comparative analysis of degasification efficiencies uses approximated analytical solutions as they are illustrative and at the same time sufficiently accurate for common use.

The equation of the perfect gas inflow is of the form of: \( P_k^2 - P_w^2 = \alpha Q + \beta Q^2 \), where \( Q \) is the gas flow rate; \( P_k \) and \( P_p \) are the gas pressure at the external boundary and in the hole, respectively; \( \alpha \) and \( \beta \) are the flow resistances [9]. Since \( \beta Q^2 \) makes not more than 5–10% of \( \alpha Q \) while distribution of \( \alpha \) and \( \beta \) in a seam is usually unknown, the analysis of gas flow uses the linear relation given by [10]:

\[
P_k^2 - P_w^2 = \frac{\mu P_0}{k_s h \theta} Q,
\]

where \( \theta \) is the flow resistance factor conditioned by hydrodynamic imperfection of a hole in terms of the coal seam access; \( k_s \) is the coal seam permeability, \( m^2 \); \( h \) is the seam thickness, \( m \); \( \mu \) is the methane viscosity, \( Pa \cdot s \); \( P_0 \) is the atmospheric pressure, \( Pa \).

Let us consider effect of hydraulic fracturing on the factor \( \theta \) which, all other things being equal, governs gas inflow in drainage hole.

Figure 1 depicts schematically variants of coal seam degasification by parallel holes with length \( L \) without hydraulic fracturing (type I), with hydrofracturing (HF) in the plane of a hole (hereinafter, longitudinal fracturing) cutting the seam normally to its plane (hereinafter, normally cutting HP, type II), or in parallel to its plane (hereinafter, fiberwise HP, type III), as well as with multistage hydraulic fracturing (MSHF), with a few mutually parallel created fractures oriented orthogonally to the hole (hereinafter, transverse HP, type IV). The flow is assumed as steady-state, the pressure in the hole and in the fractures is constant \( P_w \), the roof and floor of the seam with thickness \( h \) are impermeable.

The degasification zone of a hole is divided in accordance to underground hydraulics [11] into an inner zone with radius \( h/2 \), with plane radial flow of ideal gas, and an outer zone up to external boundary, with steady plane-parallel flow. The flow coefficient in the inner zone is written using Dupuy’s formula for a vertical hole in a uniform seam with allowance for anisotropy of permeability [12]. In case of the outer degasification zone of a horizontal hole with rectangular impermeable external boundary, the flow coefficient is written using the formula from [13]. After coordinating solutions at boundary of the inner and outer zones, the final expression for \( \theta \) is given by:
\[ \theta_i = \frac{1}{\pi} \text{arccch} \left( \frac{\cosh \left( \frac{\pi b}{2a} \right)}{\sin \left( \frac{\pi L}{2a} \right)} \right) + \frac{\chi h}{\pi L} \ln \left( \frac{\chi h}{1 + \chi} \right) R, \]  

(2)

where \( a, b \) are the sizes of the seam site to be drained (see figure 1); \( \chi = \sqrt{k_h/k_v} \geq 1 \) is the exponent of permeability anisotropy; \( k_v \) is the permeability of coal normally to bedding; \( R \) is the hole radius \( (R < h/2) \).

If a dip joint possess an infinite transmittivity, then the flow coefficient in the degasification zone of type II corresponds to the flow coefficient of an ideal gallery and equals the first member on the right-hand side of (2). In case of the finite transmittivity of a rectangular fracture with length \( h \), with \( L \), opening \( w \) and permeability \( k_f (k_f \geq k_h) \), the flow coefficient in the degasification zone of type II can be written as \([14]\):

\[ \theta_{II} = A + F_f, \]

where \( A \) is the first member on the right-hand side of (2); \( F_f \) an extra resistance to gas flow from the fracture linearly intersecting the hole. The wanted resistance is found from the assumption of the bilinear behavior of the flow nearby the fracture, by approximating the skin-effect due to flow distortion by the hole (second member on the right-hand side of (2)) by a reduced permeability layer around a drainage gallery. Using the method of electro-hydrodynamic analogies \([11]\) produces the problem solution for \( k_f >> k_h \):

\[ F_f = \frac{k_v h^2}{4 k_f w L}. \]

(3)

Similarly, considering arrangement of the drainage gallery in the seam, we write the expression for the flow coefficient in the degasification zone of type III containing a fracture with length \( l (b > l > 2R) \) (Figure 1):

\[ \theta_{III} \approx \frac{\chi^2}{\pi} \frac{ah}{L^2} \text{arccch} \left( \cosh \left( \frac{\pi b}{2h} \right) \right) + \frac{\chi^2}{4} \frac{k_h l}{k_f w L}. \]

(4)

The flow coefficient in for fractures of type IV is found by dividing the degasification zone into small rectangular areas with sides \( b \) and \( d \) around each transverse created fracture with rectangular external boundary, where \( d = L/(N-1) \) is the spacing of the transverse fractures, and \( N \) is the number of transverse fractures in the hole. The spacing of the fracture is selected so that to be less than the transverse fracture length \( l_s \). In this case, mutual influence of the fractures in low-permeable coal can be neglected. Interference of transverse hydrofractures was studied, for instance, in \([15]\). It is also assumed that inflow from the seam is much less than from the created fractures.

The value of \( \theta_{IV} \) is obtained with the same assumptions, in terms of the total resistance of the sections \( bd \) connected in parallel. Since the fracture and hole intersect long a circle with radius \( R \) and the flow is plane-radial as a consequence, extra resistance to gas inflow from fracture arises and is to be found using numerical methods \([16]\). In actual development of oil and gas reservoirs, simplified approaches are often used. They can be based on replacement of a horizontal hole by an equivalent vertical hole \([17]\), on replacement of the hole with fractures by the hole without fracture with equivalent radius, etc. Here, it is suitable to apply the same method as with finding \( F_f \), with replacement of the rectangular fracture by the disk fracture with effective radius \( (l_s^2 h/C)^{1/2} \). \( C \) is a coefficient dependent on the fracture shape and on the location of the fracture and hole intersection \([17]\):
\[
\theta_{iv} \approx \frac{1}{\pi N} \arccosh \left( \frac{\cosh \left( \frac{\pi L}{2bN} \right)}{\sin \left( \frac{\pi h}{2b} \right)} \right) + \frac{k_h}{2\pi N} k_f w \cdot \ln \left( \frac{h l_s}{C R^2} \right),
\]

where \( l_s \) is the length of the transverse hydraulic fracture; \( h < l_s \leq b; a-L \sim d \). From the comparison with numerical calculations, the estimates by (5) are applicable within the range of \( L/d < 10 \) \[16\].

3. Results

Table 1 presents \( \theta \) calculated from (2)–(5) at \( a = 200 \text{ m}; L = 150 \text{ m}; k_h = 10^{-5} \mu \text{m}^2; \chi = 1.414; l = 0.8b; N = 20; w = 0.5 \text{ mm}; k_f = w^2/12 \) (Boussinesq equation \[18\]); \( C = \pi \). The minimum values of the flow coefficient in each combination of parameters are marked with shadow.

In small-thickness coal seams (less than 2 m thick), the maximum reduction in the flow coefficient of the degasification zone results from HP type III along the bedding. In such seams, the normally cutting HP competes effectively with close-spaced pattern of drainage hole drilling which is widely applied in underground extraction of gas-bearing coal.

Table 1. Values of flow coefficient.

| No. | Variables | Flow coefficients per HP types |
|-----|-----------|--------------------------------|
|     |           | I                    | II                 | III                | IV                 |
| 1   | 3         | 1                   | 0.0066             | 0.0033             | 0.0028             | 0.0211             |
| 2   | 5         | 1                   | 0.0088             | 0.0056             | 0.0036             | 0.0128             |
| 3   | 10        | 1                   | 0.0143             | 0.0111             | 0.0048             | 0.0066             |
| 4   | 15        | 1                   | 0.0199             | 0.0167             | 0.0056             | 0.0046             |
| 5   | 3         | 3                   | 0.0229             | 0.0307             | 0.0089             | 0.0211             |
| 6   | 5         | 3                   | 0.0251             | 0.0056             | 0.0069             | 0.0128             |
| 7   | 10        | 3                   | 0.0307             | 0.0011             | 0.0087             | 0.0066             |
| 8   | 15        | 3                   | 0.0362             | 0.0167             | 0.0107             | 0.0046             |
| 9   | 3         | 5                   | 0.0436             | 0.0033             | 0.0313             | 0.0211             |
| 10  | 5         | 5                   | 0.0458             | 0.0056             | 0.0148             | 0.0128             |

Multistage transverse hydraulic fracturing (type IV) produces considerable effect at high spacing of the created fractures along holes (5–7 m, nor more). However, it is difficult to implement multistage hydraulic fracturing in uncased holes drilling in coal, thus, this method have limited prospects in coal mines.

As for propped in-seam hydraulic fracturing, it is yet rarely applied in Russia. Table 2 gives calculated flow coefficients in degasification zone without HP (type I) and with normally cutting HP (type II) at fracture opening from 0.005 to 0.5 mm.

Table 2. Ratio \( \theta_1/\theta_0 \) in degasification zones of type I and II.

| No. | Variables | Fracture opening \( w, \text{ mm} \) |
|-----|-----------|-------------------------------------|
|     |           | 0.005     | 0.01      | 0.05      | 0.5       |
| 1   | 3         | 1.59      | 1.91      | 1.97      | 1.97      |
| 2   | 7         | 1.28      | 1.40      | 1.41      | 1.41      |
| 3   | 15        | 1.14      | 1.19      | 1.19      | 1.19      |
| 4   | 3         | 2.17      | 5.41      | 6.86      | 6.87      |
| 5   | 7         | 1.83      | 3.15      | 3.51      | 3.52      |
| 6   | 15        | 1.52      | 2.06      | 2.17      | 2.17      |
| 7   | 3         | 1.87      | 7.48      | 13.00     | 13.08     |
| 8   | 7         | 1.73      | 4.68      | 6.16      | 6.18      |
| 9   | 15        | 1.55      | 2.97      | 3.41      | 3.42      |
4. Discussion
The calculation show that if \( w \leq 0.005 \text{ mm} \), hydraulic fracturing of coal is inefficient. In case that \( k_f = \frac{w^2}{12} \), the optimal opening of local fractures in low-permeable coal is 0.05 mm.

Unpropped hydrofracturing under low lateral compression can double fluid inflow in seams 3 m thick and more and enhance the inflow up to 1.5 times in seams 1 m thick and thinner.

Enhancement of coal drainage with hydraulic fracturing reduces ARI as rate of degasification increases at the shortened period of pre-mining drainage. This effect is contributed to by drop of pressure of the formation water blocking methane flow to cleats [19] and by increased gas permeability of coal seam. An increase in the degasification rate to 0.5–0.59, 0.6–0.60 and more than 0.7 reduces ARI by 0.3, 0.4 and 0.5, respectively [1].

The expressions of the flow coefficients presented in this paper for degasification zones of drainage holes make it possible to predict efficiency of in-seam hydraulic fracturing of different types, as well as their effect on coal degasification performance.

5. Conclusions
The influence of hydraulic fracturing on flow coefficient in various coal degasification patterns has been discussed.

The research findings enable predicting efficiency of different-type hydrofracturing patterns and their effect on accident risk in underground mining of gas-bearing coal.

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