Acoustic emission of rock mass under the constant-rate fluid injection

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Abstract. The authors study acoustic emission in coal bed and difficult-to-cave roof under injection of fluid by pumps at a constant rate. The functional connection between the roof hydrofracture length and the total number of AE pulses is validated, it is also found that the coal bed hydroloosening time, injection rate and time behavior of acoustic emission activity depend on the fluid injection volume required until the fluid breakout in a roadway through growing fractures. In the formulas offered for the practical application, integral parameters that characterize permeability and porosity of rock mass and process parameters of the technology are found during test injection.

1. Introduction
Coal mines widely use hydraulic technologies. For example, in order to eliminate long-span overhanging of rocks and rock falls on powered support, directional hydraulic fracturing is commonly applied in roof rocks [1]. Aimed to enhance gas permeability of coal, hydraulic dissection is carried out: water is fed in holes drilled in coal and a pattern of fractures is created [2]. Local enhancement of gas permeability and unloading of face area is possible with high-pressure water injection in holes [3].

Hydrotreating can also be used to wet coal as it has been found that coal with the moisture content higher than 6% never experiences outbursts [4]. Under such moisture content, gas is blocked in microcracks and pores and has no ability to become free and to raise pore pressure; coal becomes more plastic owing to which abutment pressure zone is displaced deeper in rock mass while outburst and rockburst hazard is decreased.

Water can be fed in the modes of low-pressure water infusion of coal or hydraulic loosening. During low-pressure fluid injection recommended for coal of high water permeability, water creates no additional fractures and flows in the existing natural cracks, microflaws and pores, and uniformly humidifies coal. In the mode of hydraulic loosening recommended for low water-permeable coal, injected fluid creates additional network of fractures for coal moistening.

Any mode of hydraulic treatment of coal is characterized by certain rate of fracturing. As fractures propagate stepwise, the rate of fracture propagation is understood as a number of “steps” per unit time. No mechanism of fracture propagation control during hydraulic treatment in mines exists, all hydrotreating methods only provide for recording of pressure and water injection rate. In the meanwhile, a growing fracture is a source of acoustic emission, and AE recording allows registering, first, the fact of stepwise fracture propagation and, second, the rate of the stepwise fracture propagation in time, and, after modifying the method, positioning of a growing fracture and AE energy [5, 6].
The hydrotreating methods include various parameters. These parameters characterize efficiency of a method, technology of the method and pumping unit. These three groups of parameters are denoted as check, production and hydraulics.

The check parameters are:

- Directional hydraulic fracturing of difficult-to-cave roof rocks—required length and direction of a created fracture to ensure caving and reduce area of overhanging rocks;
- Hydraulic treatment to reduce hazard of dynamic events—coal moisture content (in low-pressure water infusion, low-pressure soak treatment, hydraulic loosening) and face slip value (hydraulic squeezing).

The check parameters are determined in accordance with the guidelines [3] as their later edition [7] lacks the necessary information.

The technology parameters are: the number of holes simultaneously connected to pumping unit, the length and diameter of holes, the length and size of of sealing, arrangement of man-made fracture-initiating slots relative to roadways and roof rocks layers and the time of hydraulic treatment. The technology parameters are selecting in accordance with [7] and coordinated with the assumed cycle of drivage or extraction of coal. Substantiation of technology parameters if hydraulic fracturing in difficult-to-cave roof rocks follows the regulations [8] and additional recommendations on a specific coal bed, e.g. [9].

The hydraulics parameters are pressure and rate of injection.

In this manner, we assume the optimal hydraulic parameters of a hydrotreating mode the values of pressure and rate of injection such that the check parameter is attained in minimum possible time.

Coal bed and coal roof under hydrotreating are solids subjected to rock pressure and behaving elastically. The difference between coal bed and roof rocks lies in strength, permeability and porosity. However, both in coal bed and roof rocks, injected fluid fills the cavity of a propagating fracture permeates in its walls. For this reason, the AE-based approach to the control over hydrotreating processes in coal bed and roof rocks can be the same.

Most of the currently operating pumping units without hydraulic accumulator ensure nearly constant injection irrespective of permeability and porosity of rock mass. For example, hydraulic treatment pumpers NBVU-30M, UNV-2, IN-35 and 2UGN, or water–oil emulsion pumping models T used in directional hydraulic fracturing in roof rocks, specifically, T-200/32 Ex-Z [10–12.

For this reason, we analyze applicability of AE-based determination of optimal parameters of hydraulic loosening of coal and hydrofracturing of roof rocks using the mentioned pumpers. Hereinafter, we denote the both hydraulic processes as hydrotreating, except for the cases of specific character of them.

2. Problem formulation

The medium of hydrotreating is assumed elastic as AE during fracture growth takes place in the form of unloading waves while unloading is mostly an elastic process even in plastic materials [13].

AE receiving transducers are either vibration meters, velocimeters or accelerometers; thus, the overall description of the fracture propagation process means finding of space and time distribution of displacements, velocities and acceleration of points in the transducer-adjacent medium, or, put it otherwise, finding of a displacement field of these points.

In-site handling of this problem has some complications, first, a fractures as an AE source is a complex object and needs considerable idealization of its properties in mathematical modeling. Second, complex structure of coal beds results in repeated reflection of signals from different discontinuities and interfaces present in the layered medium coal bed and enclosing rocks. Third, transformation of types of acoustic waves, or their attenuation and dispersion, etc. can happen [14]. And, finally, for real crack—AE sources, it is comparatively difficult to formulate the boundary and initial conditions on the faces.

This circumstances make it impossible to obtain general solution of the formulated problem using the modern analytical methods owing to insuperable mathematical difficulties, except for some simple
special cases given additional simplifying hypotheses are introduced. Therefore, we limit ourselves to recording of stepwise fracture propagation and assume that a jump inside the sensor sensitivity zone will be perceived by the sensor.

The stepwise fracture propagation behavior is assessed in [15] as a process of opening of an arbitrary oriented fracture in the field of biaxial compression under action of fluid injected in it. It is shown that when pressure in the fracture reaches a critical value \( P_{\text{cr}} \), the fracture loses equilibrium and starts growing. The fracture growth velocity is much higher than the fluid fill velocity; for this reason, the pressure lowers in the fracture, and the fracture stops growing [15]. In accordance with the nonlinear Darcy law, there is a functional connection between the pressure and the fluid injection rate [16], thus, the critical injection pressure \( P_{\text{cr}} \) fits with the critical injection rate \( q_{\text{cr}} \).

In our case, one fracturing “step” is matched with one AE pulse and fracture propagation rate is characterized by AE activity, which the number of AE pulses per unit time.

It is supposed in [17] that during injection of fluid in hole drilled in coal, not one but a number of similar-type (approximately identical orientation and initial length) fractures can grow. For this case, the solution of the problem on the number of “steps” (or AE pulses) \( I \) during growth of fracture from the initial length \( l_0 \) to \( l \) and on the relation of the average fracture length \( l \) on porosity and permeability of rocks is given by:

\[
I = nk \ln \frac{l}{l_0},
\]

where \( n \) is the number of simultaneously growing fractures; \( k \) is the coefficient of correlation between \( l_0 \) and \( l \);

\[
\ell = \frac{q(2\sqrt{mK\Delta P\mu} - \mu b)}{2\Delta hnmK\Delta P},
\]

where \( q \) is the injection rate; \( h \) is average width of fracture surface; \( m, K \) are porosity and permeability of rocks, respectively; \( \Delta P = P_1 - P_2 \), \( P_1 \) is the fluid pressure on the hole wall; \( P_2 \) is the pore pressure; \( \Delta P \) is the difference of the pressure of free gas, if present, in hole; \( b \) is the average width of fractures; \( \mu \) is the dynamic viscosity of injected fluid.

The formula (2) at a relative error not higher than 10% and vanishing with the increase in \( t \) is only applicable when [17]:

\[
t > t_p \approx \frac{2\mu b^2}{mK\Delta P}.\]

At the real coal hydroloosening parameters: \( \mu = 1 \text{ sP}; \ b = 0.1 \text{ cm}; \ m = 3–8\%; \ K = 0.1 \text{ mD}; \Delta P = 5–10 \text{ MPa}, \) the permissible time \( t_p \) is 25–130 s (at the most often recorded parameters, \( t_p \) is 30–40 s). Inasmuch as hydraulic loosening of coal can take from tens minutes to a few hours, the formula (2) is is usable to analyze this process except for a short period in the beginning.

Porosity of sandstone is commensurable with the porosity of coal [18] and permeability varies in a wide range [19] but is assumable to be less by an order of magnitude than in coal. The pump pressure of the model T-200/32 Ex-Z is is several times higher in sand than in coal bed. Consequently, \( t_p \) during hydraulic fracturing of roof composed of sandstone is little more than hydraulic fracturing in coal bed. So, the formula (2) as the formula (1) is applicable to analyzing hydraulic fracturing of roof except for 1–2 min in the beginning of the process. However, in this case \( n = 1 \) as a rule, total time of hydraulic fracturing is 5–10 min, and recording of stepwise fracture propagation events is performed irrespective whether the inequality (3) is satisfied or not.

Under such conditions, we analyze applicability of AE-based determination of hydraulic parameters in hydrotreating of rocks from mine roadways. The solution of this problem in terms of pumps with adjustable pumping velocity (e.g. in valve-adjustable water withdrawal from high-pressure water passageways in hydraulic mines during hydroloosening of coal bed) ensuring optimal constant AE activity is given in [20]. In this article, we present the same problem solution for pumps
with the constant pumping rate \( q \approx \text{const} \), i.e. we show the AE behavior in time such that to ensure check parameters of hydrotreating.

### 3. Problem solution

We assume that under hydraulic loosening and hydraulic fracturing, fluid is fed in hole until the tip of the growing fracture reaches the surface of the nearest roadway or hole drilled from the roadway. Under hydroloosening of coal bed, this minimal distance is approximately the sealing length of the hole. Under roof hydrofracturing, this distance depends on the hydrofracturing technology, thus, we assume this minimal value as the distance to the nearest exposed surface of the roadway. In the both case, this value is denoted by \( l_1 \).

Substituting (2) in (1), we find total number \( I \) of AE pulses during growth of \( n \) fractures from an initial length \( l_0 \) to \( l \):

\[
I = nk \ln \left[ \frac{q(2\sqrt{mK\Delta P\mu t - \mu b})}{2\pi \ln l_0/mK\Delta P} \right].
\]

From (4) we determine the critical injection rate \( q_{cr} \) such that induces the forced propagation of fractures. In as much as \( nk \neq 0 \), the condition \( I = 0 \), being valid for \( P < P_{cr} \), yields:

\[
q_{cr} = \frac{2\pi \ln l_0/mK\Delta P}{2\sqrt{mK\Delta P\mu t - \mu b}}.
\]

During directional fracturing of roof rocks, as a rule, \( n = 1 \) and the expression (5) gives the minimal injection rate of feasibility of the technology.

Let us find optimal injection parameters that allow injecting fluid volume \( Q \) in a hole with a free section length \( \ell_f \) and sealed section length \( \ell_1 \) at the constant injection rate until fracture reaches the roadway surface.

Under such conditions, the rate \( q \) and time \( t \) of injection are related as:

\[
q = \frac{Q}{t}.
\]

Fluid breakout in the roadway can take place unless and until the average half-length of growing fractures reaches approximately the value \( \ell_1 \). Inserting this condition and (6) in (2) yields the quadratic equation in regard to \( t \):

\[
t - \frac{Q\sqrt{\mu t}}{2\pi \ln l_1/mK\Delta P} + \frac{Q\mu b}{2\pi \ln l_1/mK\Delta P} = 0.
\]

The roots of the equation are:

\[
t_{1,2} = \frac{Q^2 \mu}{(2\pi \ln l_1)^2/mK\Delta P} \left( 1 \pm \sqrt{1 - \frac{2\pi \ln l_1 b}{Q}} \right)^2.
\]

The expression (2) is valid for any \( t > t_p \). Consequently, the roots of (7) should satisfy this condition.

Rewrite Eq. (2) with regard to (6):

\[
\ell = \frac{d_1}{\sqrt{t}} - \frac{d_2}{t},
\]

where

\[
d_1 = \frac{Q\sqrt{\mu}}{2\pi \ln l_1/mK\Delta P}; \quad d_2 = \frac{Q\mu b}{2\pi \ln l_1/mK\Delta P}.
\]

The graphic representation of the relation (9) is shown in the Figure 1. The function \( \ell = \ell(t) \) in the form of (9) has the peak at:
\[ t_m = \left( \frac{2d_2}{d_1} \right)^2. \]  

(10)

Placing the expressions for \( d_1 \) and \( d_2 \) in (10 and comparing with (3), we obtain \( t_p = 2t_m \). Consequently, the root \( t_1 \) to the left of the point \( t_{m0} \) disagrees with the condition \( t > t_p \) at any \( Q \).

**Figure 1.** Relationship of the fracture \( \ell \) and the injection time \( t \) at different injection volumes \( Q \): 1, 2, 3—at \( Q_1, Q_2, Q_3 \), respectively; \( Q_1 > Q_2 > Q_3 = Q_{\text{min}} \); \( t_{\text{opt}(2)}, t_{\text{opt}(3)} \)—optimal injection times at which \( Q_2 \) and \( Q_3 \) volumes of fluid enter the hole by the moment of fluid breakout in the roadway, respectively.

The volume \( Q \) of fluid injection until breakout in the roadway under hydraulic loosening of coal bed is governed by the rate of injection. At very high \( q \), fracture rapidly grows down to the plane of the hole bottom. Fluid has not time to fill small fissures and pores in coal and rock. As \( q \) is being decreased, the time of injection until fluid breakout in the roadway grows, and, accordingly, the fluid volume permeating in the hole walls grows, too. This is the explanation of the increase in \( Q \) as the injection rate is being decreased.

In this manner, in order that the root \( t_2 \) satisfies the condition \( t_2 > t_p \), it is required to ensure high volume of injection. The minimal injection volume \( Q_{\text{min}} \), with the mentioned condition to be satisfied, conforms with the injection time \( t_2 = t_p \). Let us find this value from Eq. (2) given that \( \ell = \ell_1; q = Q/t; t = t_p \):

\[ Q_{\text{min}} = \frac{4\pi nh\ell_1}{2\sqrt{2} - 1}. \]  

(11)

The related injection rate:

\[ q_{\text{max}} = \frac{Q_{\text{min}}}{t_p}. \]  

(12)

substitution of (11) and (3) in (12) yields:

\[ q_{\text{max}} = \frac{2\pi nh\ell_1 mK\Delta P}{(2\sqrt{2} - 1)\mu b}. \]  

(13)
Thus, when the injection rate \( q_{cr} \leq q \leq q_{\text{max}} \), all values of the root \( t_2 \) of (7) fulfill the condition \( t \geq t_p \).

In order to control the mode of hydrotreating using AE, all fluid injection time \( t \) can be divided into \( j \) equal control intervals with the duration \( T \) so that \( t_i < T < t_s \), where \( t_r \)—duration of an \( i \)-th AE pulse, \( t_s \)—total injection time up to the end of hydrotreating, and the injection mode can be characterized by the parameter \( \Delta I \), which is the AE activity equaling the number of AE pulses in the control interval \( T \):

\[
\Delta I = \frac{\partial T}{\partial t}.
\]  

(14)

From (4) we have:

\[
\frac{\partial I}{\partial t} = \frac{nk\sqrt{mK\Delta P\mu}}{\sqrt{t(2\sqrt{mK\Delta P\mu t} - \mu b)}}.
\]  

(15)

Transformation of (15) with regard to (2) produces:

\[
\frac{\Delta I}{\partial t} = \frac{qk\sqrt{\mu}}{2\ell n h\sqrt{mK\Delta P t}}.
\]  

(16)

Then the wanted value is given by:

\[
\Delta I = \frac{qkT\sqrt{\mu}}{2\ell n h\sqrt{mK\Delta P t}}.
\]  

(17)

From Eq. (6) we find the optimal value of the injection rate \( q_{\text{opt}} \) reachable at \( t = t_2 \) (refer to Eq. (8)):

\[
q_{\text{opt}} = \frac{mK\Delta P(2\pi n h \ell_f)^2}{Q\mu\left(1 + \sqrt{1 - \frac{2\pi n h \ell_f}{Q}}\right)^2}.
\]  

(18)

Such injection rate induces AE activity found from the expressions (14) and (15):

\[
\Delta I_{\text{opt}} = \frac{kTn_f \ell_f}{2t - b n h \sqrt{\mu}}.
\]  

(19)

where \( n_f = n / \ell_f \)—relative number of fractures per one meter of free-flow section of the hole, m\(^{-1}\).

Application of the derived equations in the determination of coal bed hydroloosening parameters, namely, optimal injection time, optimal injection rate and the conformable optimal AE activity, requires knowing many characteristics of permeability and porosity of coal, geometrical sizes, number of cracks, etc. The experimental measurement of these parameters is labor-consuming, low accurate and sometimes even impossible. For this reason, it seems to be expedient to introduce integral coefficients to account for the whole set of parameters in the obtained equations and top determine them to during test injection.

Furthermore, it is possible to analytically simplify the equations (8) and (18). To this effect, we take the cofactor:

\[
\left(1 + \sqrt{1 - \frac{2\pi n h \ell_f}{Q}}\right)^2.
\]  

(20)

The numerator of the radical expression contains the value proportional to the total volume of cavities of growing fractures and commensurable with the fluid volume \( Q_{\text{min}} \) injected in the time \( t_f \) at the
maximal injection rate (refer to the formula (11)). Coal bed hydroloosening is carried out at \( q < q_{\text{max}} \) and \( t \gg t_{p} \), thus, the major volume of the injected fluid enters the walls of the growing fractures (flaws and pores) and the minor volume fills the growing fractures. For this reason, it can be assumed that \( 2\pi h n \ell_{1} b / Q < 1 \). In this case, it is valid to use the approximation [21]:

\[
\sqrt{1 - 2\pi h n \ell_{1} b / Q} \approx 1 - \pi h n \ell_{1} b / Q .
\] (21)

Then the expression (20) takes on form:

\[
\left( 1 + \sqrt{1 - 2\pi h n \ell_{1} b / Q} \right)^{2} \approx \frac{(2Q - \pi h n \ell_{1} b)^{2}}{Q^{2}} .
\] (22)

Replacing the cofactor in accordance with (22) allows presenting the formulas (8) and (18) in the more convenient form:

\[
T_{\text{opt}} = a(Q - V)^{2} ;
\] (23)

\[
q_{\text{opt}} = \frac{Q}{a(Q - V)^{2}} ,
\] (24)

where \( a = a_{1} a_{2} ; \)

\[
a_{1} = \frac{\mu}{(\pi h n_{1})^{2} m K \Delta P} — \text{coefficient conditioned by rock mass permeability and porosity and by injection parameters, cm}^2 ; \quad a_{2} = (\ell_{1} \ell_{f})^{-2} — \text{process parameter, m}^4 ; \quad V = \frac{\pi}{2} h n_{1} \ell_{1} \ell_{f} b — \text{coefficient proportional to the total volume of growing fractures, m}^3 .
\]

4. Recommendations on application of the problem solution results

AE activity during coal bed hydroloosening at optimal rate is defined by the expression (19). This expression is inconvenient for application as it inexplicitly connects AE activity and hydraulic parameters on injection. In this connection, we analyze possibility to express the optimal AE activity in terms of hydraulic parameters. In this case, it should be taken into account that at different stages of fluid injection, the number of growing fractures can change owing the the injection pressure variation. In addition, the properties of the wetted rock mass also change. For this reason, the expression (19) should be added with the relations of the pressure difference \( \Delta P \), fracture number \( n \) and time but these analytical expression are unknown. So, for the practical use, the formula (19) can be presented in the simplified form:

\[
\Delta I_{\text{opt}} = \frac{\delta_{1}(q)}{t - \delta_{2}(q) \sqrt{t}} ,
\] (25)

where

\[
\delta_{1}(q) = \frac{n k T}{2} ; \quad \delta_{2}(q) = b \frac{\mu}{2 \sqrt{m K \Delta P}} .
\] (26)

The relation (25) is valid at sufficiently high values of \( t \). When \( t \) is close to the value \( (\delta_{2})^{2} \), where it has a peculiarity, for \( \Delta I_{\text{opt}} \) it knowingly yields overestimates. This is the consequence of the simplification made when deriving the formula (2).

So we have that in order to determine optimal hydraulic parameters for coal bed hydroloosening with AE-based monitoring, it is required to find coefficients included in Eqs. (24) and (25) during test injection. With the coefficients known, the optimal injection rate for the optimal injection volume should be found from (24). Then, using (25) the optimal time behavior of AE activity under optimal injection rate is determined using (25).

Later on, monitoring of coal bed hydroloosening is reduced to the experimental finding of injection pressure and injection rate such that the time behavior of AE activity remains optimal.
We think that the described procedure is applicable in monitoring of hydraulic segregation of coal bed using surface holes for the purposes of pre-mine drainage [2]. In this case, the value of \( l_1 \) is governed by the dimension of the coal bed section to be disjoined, and the coefficients \( a_1, a_2 \) and \( V \) can be approximately determined from the data of test loosening of this bed from a closely spaced roadway.

For the AE-based monitoring of roof hydrofracturing, test hydrofracturing should be carried out at an early stage of longwalling. The control process includes simultaneous recording of AE pulses \( I_e \) and breakout of fluid in a neighbor hole drilled at a distance \( l_e \) from the hydraulic fracturing hole. From the formula (1), the coefficient \( k_e \) for the given area of rock mass can be found:

\[
k_e = \frac{\gamma}{V \cdot a_1 \cdot a_2}.
\]

Then, assuming the the coefficient \( k_e \) and the initial fracture length \( l_0 \) are constant in the roof of this longwall section, the growing fracture length \( l \) can be determined using the number of the recorded AE pulses:

\[
l = l_0 + \sqrt{\frac{I_e \cdot V}{k_e}}.
\]

5. Conclusion

Activity of acoustic emission is the quantitative characteristic of the intensity of fracture propagation in rocks under hydrotreating. The total number of AE pulses and the time behavior of AE activity allow, respectively, monitoring of hydraulic fracturing process in the difficult-to-cave roof and hydraulic loosening of coal bed at the optimal rate of fluid injection such that the wanted volume of fluid enters the growing fractures up to the fluid breakout in the nearest roadway.

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