NUMERICAL INVESTIGATION OF THE PROCESS OF THE SUDDEN EJECTION OF A WORKED COAL SEAM

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The initial stage of the ejection of coal before the breakthrough of the broken-down gas–coal mass into the working space is characterized by the rapid forcing out of the plastic zone of the coal near the end face. In the case of a small intensity, the ejection is damped in the initial stage, limited by the sudden forcing out of the worked coal seam.

In [1] a model of the sudeen forcing out of a worked coal seam was constructed. As unknown parameters characterizing the forcing out process there were taken the coordinate of the end face x_1, the coordinates of the beginning and the end of the zone of pulverized coal x_2 and x_3, and the coordinate of the boundary of the plastic zone x_4 (Fig. 1). Retaining the notation of [1], we write the system of equations describing the ejection process. It consists of relationships expressing the condition of the conservation of mass for three sections of the plastic zone

$$\int_{x_i}^{x_{i+1}} v(x)\,dx = \int_{x_i^0}^{x_{i+1}^0} v^0(x)\,dx + \beta_i \int_{x_4^0}^{x_4'} h\,dx, \tag{1}$$
$$\beta_i = 0 \text{ for } i = 1,\ 2,\ \beta_i = 1 \text{ for } i = 3,$$

and the relationships

$$\gamma H\pi + A\{[x_2(x_4 - x_2)]^{1/2} - [x_1(x_4 - x_1)]^{1/2}\} - A_1[x_3(x_4 - x_3)]^{1/2} + (Ax_4 + 2B)\left[\operatorname{arctg}(x_4x_2^{-1} - 1)^{1/2} - \operatorname{arctg}(x_4x_1^{-1} - 1)^{1/2}\right] + 2P\left[\operatorname{arctg}(x_4x_3^{-1} - 1)^{1/2} - \operatorname{arctg}(x_4x_2^{-1} - 1)^{1/2}\right] - (A_1x_4 + 2B_1)\operatorname{arctg}(x_4x_3^{-1} - 1)^{1/2} = 0; \tag{2}$$

$$h = (1 - \nu^2)E^{-1}\{-(1/2)Mx_4^2 - [x_2(x_4 - x_2)]^{1/2}[(1/2)A(2x_2 + x_4) + 2B - 2P] + [x_1(x_4 - x_1)]^{1/2}[(1/2)A(2x_1 + x_4) + 2B] + [x_3(x_4 - x_3)]^{1/2}[(1/2)A_1(2x_3 - x_4) + 2B_1 - 2P]\}, \tag{3}$$

containing the unknown parameters x_1, x_2, x_3, x_4, x_4', and P. In Eqs. (1) the vertical shift v(x) of the rock–coal interface is determined by the Kolosov–Muskhelishvili formulas [2] and the complex functions $\Phi(z)$ and $\Omega(z)$ given by the relationships (3.7) of [1]. The values of the corresponding coordinates at the moment of time t = 0 are designated in terms of x_i^0. The function of the vertical shift in each section of the integration v^0 coincides with the form of the function v, the balues of x_1, x_2, x_3, x_4, and P being replaced by x_1^0, x_2^0, x_3^0, x_4^0, and P^0. We note that the relationships (2) and (3) remain true at the initial moment of the ejection t = 0.

In Eqs. (1)-(3) the coefficients M, A, B, A_1, and B_1 are determined by the formulas

$$M = A\operatorname{arctg}(x_4x_2^{-1} - 1)^{1/2} - A\operatorname{arctg}(x_4x_1^{-1} - 1)^{1/2} - A_1\operatorname{arctg}(x_4x_3^{-1} - 1)^{1/2},\quad A = \tau_s h^{-1},$$
$$B = k\left[(1 - \tau_s^2k^{-2})^{1/2} + k\tau_s^{-1}\arcsin(\tau_sk^{-1})\right] - \tau_s x_1 h^{-1},$$
$$A_1 = kh^{-1},\ B_1 = k(\pi/2 + P/k - x_3/h).$$

By s we denote the absolute shift of the plug (x_1, x_2). The shift s is connected with the coordinates x_4 and x_2 by the relationship

$$s = (x_4 - x_2) - (x_4' - x_2^0). \tag{4}$$

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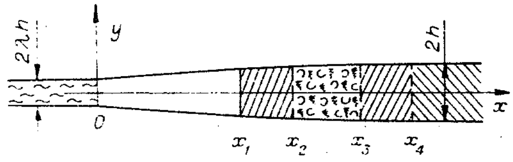

Fig. 1

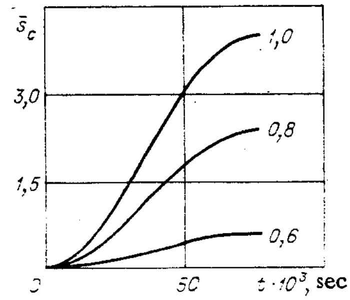

Fig. 2

We close the system of equations (1)-(4) by adding to it the equation of the motion of the plug in the form

$$m\ddot{s} = Pv(x_2) - \tau_s(x_2 - x_1), \tag{5}$$

$$m = \gamma g^{-1} \int_{x_1}^{x_2} v(x)\, dx.$$

Equation (5) is integrated taking account of the conditions

$$s = 0,\ ds/dt = 0 \ \text{ for } \ t = 0.$$

With the numerical solution of the differential equation (5), in each stage of the integration with respect to the time the system of transcendental equations (1)-(4) is solved. We note that for a given value of the shift s, the system of equations (1)-(4) will be closed with respect to the values of x_1, x_2, x_3, x_4, x_4', and P [3]. This system can be solved numerically by the method of differentiation with respect to the parameter s [4]. Assuming that x_1, x_2, x_3, x_4, x_4', and P are functions of the shift s, we differentiate relationships (1)-(4) with respect to s and convert them to the form

$$\frac{d\bar{x}_i}{d\bar{s}} = \frac{D_i}{D},\quad \frac{d\bar{P}}{d\bar{s}} = \frac{D_5}{D},\quad \frac{d\bar{x}_4'}{d\bar{s}} = \frac{D_6}{D},\quad i = 1, 2, 3, 4. \tag{6}$$

By D, D_i, D_5, and D_6 we denote determinants of the sixth order.

The system of equations (1)-(5) and the boundary conditions were brought into dimensionless form by dimensionless parameters introduced in the following manner:

$$\bar{x}_i = x_i/h,\ \bar{x}_4' = x_4'/h,\ \ \bar{v} = v/h,\ \ \bar{s} = s/h,$$
$$\bar{P} = P/\gamma H,\ \bar{k} = k/\gamma H,\ \bar{\tau}_s = \tau_s/\gamma H,$$
$$\tilde{\tilde{k}} = k(1 - \nu^2)/E,\ \tilde{\tilde{\tau}}_s = \tau_s(1 - \nu^2)/E.$$

(Below, all quantities having the dimensions of length will be referred to half the thickness of the coal seam h.)

The system of equations (6) was integrated numerically by the Runge–Kutta method in the segment $0 \leqslant s \leqslant s_k$ with the initial values

$$x_1 = x_1^0,\ x_2 = x_2^0,\ x_3 = x_3^0,\ x_4 = x_4' = x_4^0,\ P = P^0.$$

Formula (4) determines the absolute shift of the cross section x_2. Numerical integration of the system of equations (6) shows that not every positive shift s (motion of the cross section x_2 to the left) corresponds to a positive shift of the cross section x_1. Since we are interested in the ejection of the end-face plug into the working space, i.e., a shift of the cross section x_1 to the left, it is convenient to introduce into the discussion the quantity s_1, which is the absolute shift of the cross section x_1:

$$s_1 = (x_4 - x_1) - (x_4' - x_1^0).$$

With replacement of Eq. (4) by Eq. (7), the system (6) retains its form, with the exception of the sixth row of the determinants.

The changes in the values of s, s_1, x_1, x_2, x_3, x_4, and P with an increase in the shift of the cross section x_1 are given in Table 1 for the following numerical values of the parameters: $\bar{k} = 0.2$, $\bar{\tau}_s = 0.18$, $E/k = 2000$, and $\nu = 0.2$. The initial parameters of the process

TABLE 1.

$\bar{s}_1$	$\bar{s}$	$\bar{x}_1$	$\bar{x}_2$	$\bar{x}_3$	$\bar{x}_4$	$\bar{P}$
0	0	119,24	127,24	137,24	144,36	3,42
0,4	0,26	118,80	126,93	137,10	145,34	3,14
0,8	0,53	118,37	126,64	136,97	146,23	2,89
1,2	0,80	117,95	126,35	136,83	147,05	2,67
1,6	1,07	117,53	126,06	136,70	147,80	2,47
2,0	1,35	117,13	125,78	136,57	148,49	2,29
2,4	1,63	116,73	125,50	136,44	149,14	2,12
2,8	1,90	116,33	125,23	136,32	149,75	1,96
3,2	2,18	115,94	124,96	136,20	150,32	1,82
3,6	2,46	115,51	124,69	136,08	150,86	1,68
4,0	2,74	115,26	124,49	135,99	151,24	1,58

of sudden ejection for the above values of the parameters $\bar{k}$, $\bar{\tau}_s$, E/k, and ν were determined by the solution of the system of equations (3.9), (3.10), (3.12), and (3.13) of [1]. They are given in the first row of Table 1. The length of the plug l_{12}^0 at the initial moment of the ejection was taken equal to eight, and the length of the zone of broken-down coal l_{32}^0 was taken to 10h.

Calculations show that with a displacement of the plug, the shift of the cross section x_1 is 1.6 times as great as the shift in the cross section x_2, although this figure decreases somewhat with an increase in the sift of the cross section x_1; as a rule, it remains around 1.4 for real values of the shift of the cross section x_1 ($s_1 < 12h$). In the case where with a break in the adhesion at the contact surface between the ejected plug and the rock there is established a value of the tangential stress τ_s considerably less than the value of k, the ratio of the shifts $\bar{s}_1/\bar{s}$ practically does not change. Thus, with the above values of the parameters $\bar{k}$, E/k, and ν and a value of $\bar{\tau}_s$ equal to 0.09, the value of the ratio s_1/s rises by 0.3-0.5%. From Table 1 it can be seen that the ejection of the plug is accompanied by a certain hollowing out of its leading part, in contact with the free surface.

In view of this we write the equation of the motion of the center of gravity of the plug in the form

$$m\ddot{s}_c = Pv(x_2) - \tau_s(x_2 - x_1), \tag{8}$$

where the shift in the center of gravity of the plug s_c is connected with the coordinates x_4 and x_4' by the relationship

$$s_c = (x_4 - x_c) - (x_4' - x_c^0), \tag{9}$$

in which x_c denotes the coordinates of the center of gravity of the plug, determined by the formula

$$x_c = \frac{\int_{x_1}^{x_2} xv(x)\,dx}{\int_{x_1}^{x_2} v(x)\,dx}. \tag{10}$$

Solving the system of equations (6), we determine the dependence of x_1, x_2, x_3, x_4, and P on s_1. Consequently, the right-hand side of formula (8) will be a known function of s_1, and with the use of relationships (9) and (10), it becomes a known function of s_c. Therefore, we write (8) in the form

$$\ddot{s}_c = \omega(s_c). \tag{11}$$

Integrating (11) with the condition of the equality to zero at the initial moment of the ejection t = 0 of the shift in the center of gravity and the velocity of the plug, we find the velocity of the motion of the plug,

$$u_p = \left(2\int_0^s \omega(s)\,ds\right)^{1/2}.$$

and the time of its ejection,

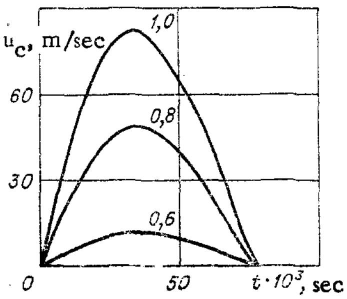

Fig. 3

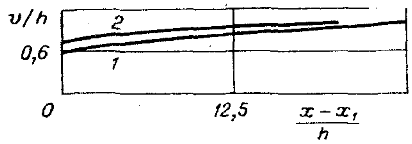

Fig. 4

$$t_f = \int_0^{s_f} \frac{ds}{\left(2\int_0^s \omega(s_1)\,ds_1\right)^{1/2}}.$$

The value of the shift in the center of gravity of the plug s_f at the moment of the end of the process t_f is determined by the condition of the reversion of the velocity of the motion of the plug to zero:

$$\int_0^{s_f} \omega(s)\,ds = 0.$$

Figures 2 and 3 show the change in the shift s_c and the velocity of the plug with time; in the calculations, instead of the equation of motion (8), the following more general equation of motion of the plug was considered:

$$m\ddot{s}_c = \alpha_t P v(x_2) - \tau_s(x_2 - x_1),$$

into which there is introduced the coefficient of transmission of the stresses α_t, equal to unity in the case where the transmission of the stresses in the zone of fractured coal corresponds to the distribution of the pressure in an ideal incompressible fluid. With application to our problem, the lower boundary of α_t is determined from the condition

$$\alpha_t^* P^0 v^0(x_2) - \tau_s(x_2^0 - x_1^0) = 0.$$

With α_t equal to α_t^*, the plug remains in a state of rest. From Figs. 2 and 3 it can be seen that, with a change in α_t from 0.6 to 1, the shift of the center of gravity of the plug does not exceed 4h, the ejection time of the plug lies within the limits of 76-78 msec, and the maximal velocity of the plug varies from 12 to 82 m/sec. Numerical values are given for the following values of the parameters characterizing the physicomechanical properties of the rock and the coal: $\gamma = 2.5$ g/cm³; $\nu = 0.2$; $\rho = 1.3$ g/cm³; $k = 0.2$; $\tau_s = 0.18$; $E/k = 2000$; $h = 1$ m; and $H = 1000$ m.

As is well known, solution of the problem with the condition of the closing of the lateral rock surrounding the coal seam gives a great extension of the hanging roof of the working space (see Table 1). In the practice of the working of coal seams, the hanging roof, as a rule, rests on caved-in layers of rock. We denote the thickness of the caved-in layers of rock by $2\lambda h$ (see Fig. 1). Taking account of the caved-in layers of rock does not, in principle, introduce any difficulties into the statement of the problem under consideration. The system of equations (1), (2), (8)-(10) describing the ejection process retains its form completely; the quantity h in the right-hand side of Eq. (3) is replaced by $(1 - \lambda)/h$. In this case, the proposed calculating methods were used without any kind of changes. The results of the numerical calculations, given in Table 1 and in Figs. 2 and 3, correspond to a value of the parameter λ equal to zero. Table 2 gives the initial parameters of the process of ejection for $\lambda = 0.4$ and 0.6. From the table it can be seen that, with an increase in λ, there is a certain decrease in the extension of the end-face plastic zone and a considerable decrease in the length of the hanging roof.

The form of the coal seam in the end-face plastic zone at the initial moment of ejection $t = 0$ is shown in Fig. 4. On the vertical axis there is plotted the distance from the axis of symmetry of the coal seam to the contact surface between the coal seam and the rock. Curve 1 was plotted for a value of the coefficient λ equal to zero. Curve 2 corresponds to a value of the parameter λ equal to 0.4. Taking account of the layers of caved-in rock leads to less deformation of the end-face zone of the coal seam.

TABLE 2

λ	l_{32}^0	l_{12}^0	x_1^0	x_2^0	x_3^0	x_4^0	P^0
0,4	10 11	8 4	69,26 70,65	77,26 74,65	87,26 84,65	89 89	3,67 3,23
0,6	8 10	8 4	43,72 45,57	51,72 49,57	59,72 59,57	61,38 61,40	3,21 3,12

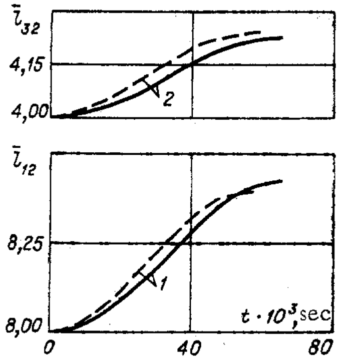

Fig. 5

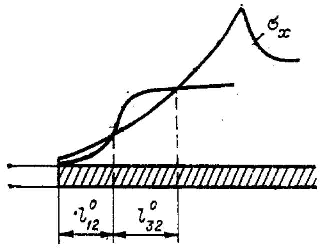

Fig. 6

Taking account of the effect of the layer of caved-in rock should obviously have a considerable effect on the value of the length of the plug l_{12} and on the zones of fractured coal l_{32} formed at the initial moment of the ejection t = 0. If we examine the case corresponding to equal values of l_{12}^0 as well as l_{32}^0, for $\lambda = 0$ and $\lambda = 0.4$, then a calculation of the process of the ejection of the plug shows that for $\lambda = 0.4$ the ratio of the quantities s_1/s remains practically the same for $\lambda = 0$; the maximal velocity of the ejection for $\alpha_t = 1$ increases to 88 m/sec; the time of the process decreases by 6-7 msec. From a comparison of the above values for $\lambda = 0$ and $\lambda = 0.4$ it can be seen that for identical lengths l_{12}^0 and l_{32}^0, taking account of λ does not, in principle, introduce any changes into the character of the process of ejection.

Figure 5 shows the change in the length of the plug and the zone of fractured coal in the ejection process for $\bar{l}_{12}^0 = 8$, $\bar{l}_{32}^0 = 4$, and $\alpha_t = 1$. The length of the end-face plastic plug with the selected values of the parameters characterizing the physicomechanical properties of the rock and the coal increases considerably during the ejection process (curve 1). The length of the zone of fractured coal (curve 2) also rises with the passage of time; the increase in $l_{32}(t)$ is accompanied by a decrease in the value of the load in the ejection process. The solid curves in Fig. 5 correspond to $\lambda = 0$, while the dashed curves correspond to $\lambda = 0.4$.

If the lengths of the plug and the zone of fractured coal at the moment of the end of the ejection process are known, we can determine their lengths at the initial moment, using an algorithm developed for calculating the process and plotting a series of graphs of the change in l_{12} and l_{32} as a function of the time t.

In conclusion, let us examine the considerations on the basis of which the values of l_{12} and l_{32} at the initial moment of ejection t = 0 can be determined. In [5, 6] it is shown that the fracturing of a coal seam with a sharp displacement of the maximum of the stress—strain diagram of the normal stresses into the depths of the massif can start in a section in which the gas pressure will exceed the normal stress σ_x, as a result of which the stress—strain diagram of the gas pressure cannot be reconstructed with the rate of redistribution of the stresses in the massif. To the left of the point of intersection of the stress—strain diagrams (Fig. 6) the coal will be in an unfractured state. The distance from the end face can, in the first approximation, be taken as the length of the plug at the initial moment of the process of sudden ejection. The process of pulverization of the coal, continuing for a period of 2-3 msec, leads to the formation of a zone of fractured coal. The cross section in which the stress σ_x is equal to the pressure of the gas at infinity can be taken as the boundary of the zone of fractured coal; for $x > x_3$, the stress σ_x is greater than the pressure of the gas at infinity p_∞. Averaging the normal component of the stress along the zone of fractured coal, we obtain a discontinuity in the stress–strain diagram of the normal stresses in the cross section x_2. The value of this discontinuity δ, determined by the relationship

$$Ax_2 + B = P + \delta,$$

will lie within the limits

$$0 < \delta < p_\infty - \sigma_x|_{x=x_2}.$$

For the selected values of the discontinuity δ, the initial parameters of the process of sudden ejection can be determined by the method proposed in [3].

The gas–coal mixture expelling the plug is situated in a tube of variable diameter v(x) (see Fig. 4). In the case of a breakdown of the plug, the gas–coal mixture will be carried out through the opening into the working space. The gasdynamic stage of the course of the ejection, before and after the breakthrough of the plug, must be considered, taking account of the contracting form of the working space, formed by the action of the stressed state around the working, varying during the course of the process.

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HEAT AND MASS TRANSFER DURING AN EXPLOSION IN SOLIDS

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The pressures in the detonation products of explosives have a magnitude of the order of 100 kbar, and the temperature of the gases at the initial instants reaches several thousands of degrees. Many actual solids, soils, and rocks contain in their structure a considerable amount of pores, micro- and macroscopic cracks, and gaps separating the medium into individual blocks. With these conditions, a gas having a high velocity can penetrate into these defects of the medium without performing any mechanical work in general on the deformation of the material or, with defined conditions, producing a "wedge" effect in the cracks. Since the freshly formed surfaces of solids have an enhanced sorption capability, part of the gas may be adsorbed into the medium and may undergo capillary condensation. The quantity of gas "absorbed" by the medium can be different depending on the total surface area of the cracks and pores and, in certain cases, can reach very considerable magnitudes. From a formal point of view, the entrainment of detonation products by solid media amounts to a nonadiabatic process of expansion of the explosion cavity in soils and rocks, while from the factual point of view it amounts to a reduction of the explosion efficiency or of its mechanical action.

In the Institute of Terrestrial Physics, Academy of Sciences of the USSR, under the directorship of I. L. Zel'manov, over the period of a number of years systematic experimental investigations have been conducted of microexplosions in sand with a different density of

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