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МЕТОД ОПИСАНИЯ ТЕЧЕНИЯ ВОЗДУХА ЧЕРЕЗ ВЫРАБОТАННОЕ ПРОСТРАНСТВО ОБРУШЕННЫХ ЛАВ В КАМЕННОУГОЛЬНЫХ ШАХТАХ

Во время эксплуатации угольных пластов происходит течение воздуха через зону обрушения, зависящее от применяемой системы проветривания лавы. Приток воздуха к зоне обрушения – одна из причин пожароопасности. Поэтому определение скорости течения воздуха в выработанном пространстве – это один из главных факторов, позволяющих предотвратить процесс самонагревания оставленного угля.

Ключевые слова: вентиляция шахт, подземные пожары, фильтрация воздуха через пористую среду.

METHOD OF DESCRIPTION OF AIR FLOW INSIDE GOAF OF LONGWALL WITH CAVING IN UNDERGROUND COAL MINES

While mining coal seams with caving there is air flow through a caving zone, which depends on the used ventilation system. Air flow into a caving zone is one of the factors causing a fire hazard. Therefore, it is important to know air flow velocity distribution in goaf as it is one of the factors allowing for the selection of the proper method for fighting coal self-combustion.

Key words: ventilation of mine, underground fires, filtration through porous media

Introduction

In the area of the extracted seam by means of caving method, as a result of roof rock mass dislocation, the caving zone is formed, where methane gathers in methane fields. Goaf forms a kind of «container» where air and methane mixture is formed and gathered. Gas composition in goaf is very changeable and depends, among others, on a ventilation system and intensity of methane emission from goaf.

The intensity of ventilating goaf is the main decisive factor about how great a fire hazard in goaf is. With little ventilation intensity, goaf gets filled with indifferent (inert) gases preventing the process of coal self-heating. However, great ventilation intensity results in taking out heat, which is the product of oxidation processes occurring in goaf; this way it hinders the process of coal self-heating. The middle range is most disadvantageous, in which during an adequate delivery of oxygen there is no effective goaf cooling. Heat accumulation in goaf accelerates the process of coal self-combustion

Model of airflow in goaf

As a result of strata dislocation rubble heap and fracture zones are formed behind a longwall face. Caving area of a longwall is filled with roof rock mass forming grains (blocks) of different granulation. Very loose packing of grains in the face zone becomes tighter and tighter, the greater the distance from a longwall face [5, 8]. Little rock grains fill the gob between bigger ones and the bigger ones supported non-uniformly and undergoing stress of rock mass crumble, filling the gob tighter

and tighter. Therefore for theoretical considerations over airflow in gob it is assumed that gob is a real porous medium where a linear Darcy's law of filtration is valid

An essential factor influencing airflow in a porous medium is a kind of flowing gas and a kind of process in which this airflow takes place. Therefore a vector of filtration velocity is determined by means of the following formula [3]:

$$v = -K\,grad\,p \qquad (1)$$

In order to consider gas flow in a porous medium the following should be known:

• an equation of continuity that can be expressed in the following form:

$$m\frac{\partial \rho}{\partial t} + div\rho v = 0 \qquad (2)$$

• an equation of state in the form of isotherm:

$$\frac{p}{\rho} = const = \frac{p_o}{\rho_o}, \qquad (3)$$

Assuming steady airflow, isothermal process and flat area without any source of flow results in an elliptic partial differential equation of the second order over pressure area in the following form:

$$\frac{\partial}{\partial x}(K\frac{\partial p}{\partial x}) + \frac{\partial}{\partial y}(K\frac{\partial p}{\partial y}) = 0 \qquad (4)$$

Most theoretical considerations over airflow in gob were based in mining literature on the formula above.

Co-efficient of goaf permeability

Co-efficient «*K*» in dependence (4) characterises a medium where airflow takes place. If gas flow in a porous medium is taken into consideration, co-efficient «*K*» is a filtration co-efficient. In the case of an isotropic medium co-efficient «*K*» is a scalar function dependent on spatial co-ordinates. However in anisotropic media this value characterises a medium but is dependent not only on spatial co-ordinates, but also on the direction considered; therefore it is a tensor of rank II. The solution to equation (4) depends on a function describing the value of co-efficient «*K*». For further considerations, it was assumed that filtration co-efficient changes along the length of goaf behind advance longwall and its value along the face of longwall is stable. Such description of changes in a filtration co-efficient was presented in work [8] on the bases of many researches conducted in mines.

On the basis of the considerations in work [8] it can be concluded that a co-efficient of gob permeability can be described by dependence taking the following form:

$$k(x) = \frac{\mu}{r_0 + ax^2}, \text{ m}^2, \text{ dla } 0 \le x \le \tfrac{2}{3}\cdot l \qquad (5)$$

However for value $x = \frac{2}{3}l$ the smallest value of co-efficient of gob permeability is obtained. After reaching the minimum the co-efficient of permeability increases until a longwall begins. Along the length where a co-efficient of gob permeability increases its value can be determined from the following dependence:

$$k(x) = \frac{\mu}{r_0 + a(\frac{4}{3}l - x)^2}, \text{ m}^2, \text{ for } \tfrac{2}{3}l \le x \le l \qquad (6)$$

However the values of co-efficients r_0, k_0, and a are dependent on bed separation resistance of the roof rock mass located over a selected seam. The change in the co-efficient of caving permeability behind the longwall face was approximated by the following dependence:

$$k_0 = \frac{\mu}{6}10^{-10}R_{rrs}^{\ 1.74}, \text{ m}^2 \qquad (7)$$

and the change in co-efficient a from dependence:

$$a = 6\cdot 10^9 R_{rrs}^{\ -1,74}, \text{ Ns/m}^4 \qquad (8)$$

Changes in the co-efficient of gob permeability obtained on the basis of experimental research and on the description by dependences (5 & 6) are presented in fig.1.

Numerical solution to equations describing airflow in gob

Boundary conditions for equation (4) are usually defined as distributions of pressure in

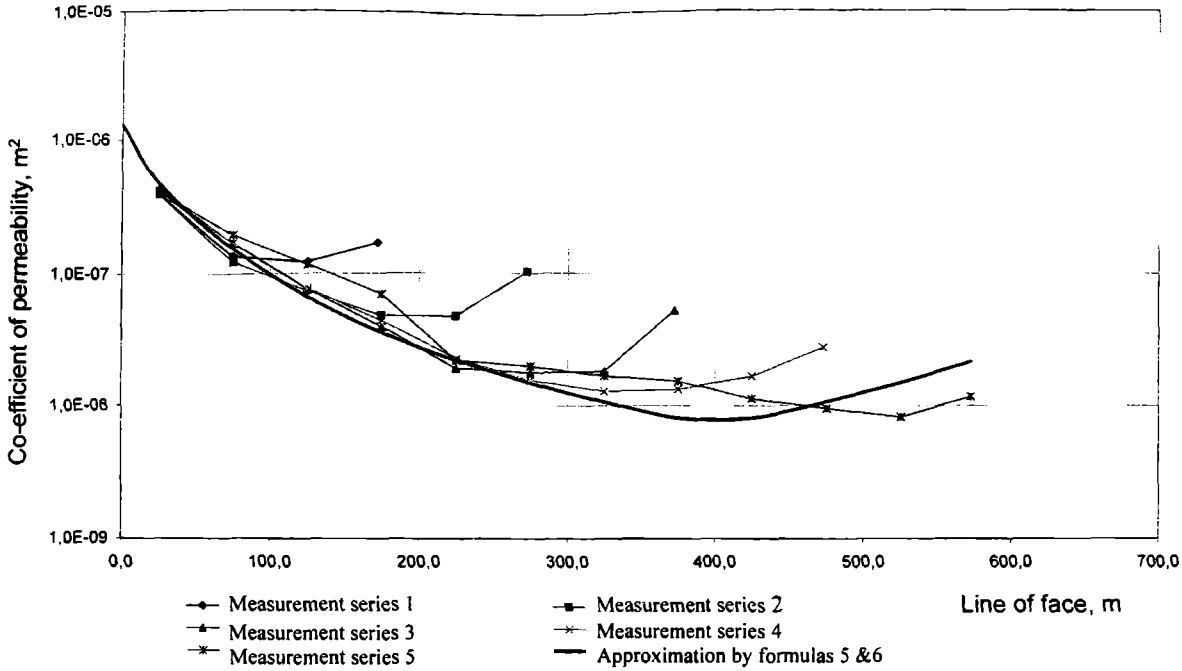


Fig.1. Changes in goaf permeability co-efficient depending on distance from longwal face 660

excavations adjoining the area under consideration. Therefore these are the conditions of the first kind. Solving equation (4) in a numerical way results in obtaining an area of pressure in gob area. Further on local values of co-ordinates of vector of linear air velocity in the area filtered can be calculated on the basis of Darcy's law:

$$u = -K(x)\frac{\partial p}{\partial x},\ v = -K(x)\frac{\partial p}{\partial y}. \qquad (9)$$

The calculation algorithm suggested was obtained on the basis of the method of finite differences that can be physically interpreted in a clear graphic form (fig.1). The gob area under consideration is covered with a net of calculation nodes, that is points, where discrete values of an area of pressure $p(x, y)$ are calculated. In a general case of a heterogeneous net the distances between adjoining nodes (the so-called steps of numerical integration) can be different. The simplest form of algorithm that is characterised by a determined symmetry of matrix of a system of equations is obtained in the case of homogenous calculation nets when discrete spatial variables are expressed by the following formulae:

$$x_i = (i\text{-}1)\Delta x \ oraz\ y_j = (j\text{-}1)\Delta y,\ (i,j = 1,2,3...). \qquad (10)$$

Fig.2, *a* presents the so-called «differential star», which is equivalent to a discrete equation referring to control volume, determined by the rectangle marked with a broken line. The sides of the rectangle, which *de facto* are areas of mass exchange, are drawn perpendicular to steps of integration in points determining the centres of these steps. Balance of air streams in the two-dimensional case considered (the length of the third edge of the rectangular prism is equal to unity) is recorded just for this segment of space. Because of the stationary character of filtration process (no air is accumulated inside control volume) the total of volumetric air streams flowing in and out of the rectangular prism is equal to zero. Therefore the following is obtained:

$$Q_{x1} - Q_{x2} + Q_{y1} - Q_{y2} = 0, \qquad (11)$$

where particular volumetric streams are expressed by formulae that are a differential interpretation of Darcy's law:

$$Q_{x1} = \frac{F_x K_{x1}\left(p_{i-1,j} - p_{i,j}\right)}{\left(x_i - x_{i-1}\right)}, \qquad (12)$$

$$Q_{x2} = \frac{F_x K_{x2}\left(p_{i,j} - p_{i-1,j}\right)}{\left(x_{i+1} - x_i\right)}, \qquad (13)$$

$$Q_{y1} = \frac{F_y K_{y1}(p_{i,j-1} - p_{i,j})}{(y_{i-1} - y_j)}, \quad (14)$$

$$Q_{y2} = \frac{F_y K_{y2}(p_{i,j} - p_{i,j+1})}{(y_{j+1} - y_j)}. \quad (15)$$

The values of filtration co-efficient «*K*» are determined halfway through the steps of integration and the differences in indexes are the result of the heterogeneous character of this value inside gob. The values of an area of mass exchange are respectively as follows:

$$F_x = \frac{(x_{i+1} - x_{i-1})b}{2} \text{ oraz } F_y = \frac{(y_{j+1} - y_{j-1})b}{2} \quad (16)$$

By inserting definitions of streams (12÷15) to balance equation (11), after transformations, the final form of a single balance equation, which is equivalent to central node «*i, j*».

$$A_{x1}p_{i-1,j} + A_{x2}p_{i+1,j} + A_{y1}p_{i,j+1} +$$

$$+ A_{y2}p_{i,j+1} - Bp_{i,j} = 0, \quad (17)$$

where co-efficients *A* are the following functions of discrete variables *i, j*

$$A_{x1} = K_{x1}F_x(x_i - x_{i-1}), \quad (18)$$

$$A_{x2} = K_{x2}F_x(x_{i+1} - x_i), \quad (19)$$

$$A_{y1} = K_{y1}F_y(y_j - y_{j-1}), \quad (20)$$

$$A_{y2} = K_{y2}F_y(y_{j+1} - y_j), \quad (21)$$

and

$$B = A_{x1} + A_{x2} + A_{y1} + A_{y2}. \quad (22)$$

Inserting boundary conditions is a separate problem. Taking numerical steps is particularly simple in the case of the conditions of the first kind. In the case of nodes of a net adjoining the boundary on which the values of pressure are defined (according to the definition of the condition mentioned) these values are inserted directly to a discrete equation in the same way reducing the number of unknowns in this equation. In the case of the boundary condition of the second order in the general form:

$$\frac{\partial p}{\partial n} = 0 \quad (23)$$

Fig.2, *a*, *b*, *c* present the way of balance treatment of boundary and boundary corner nodes. As it can be seen in the numerical stars presented both control values and areas of mass exchange perpendicular to the boundary are smaller than in the case of interior nodes. For node «*i, j*» presented in fig.2, *b* an equation of balance of air streams takes the following form:

$$-Q_{x2} + Q_{y1} - Q_{y2} = 0. \quad (24)$$

However in the case of the corner (fig.1) only the following can be presented:

$$-Q_{x2} - Q_{y2} = 0 \quad (25)$$

Areas of mass exchange are equal to:

- in the case (fig 2, *a*)

$$F_x = \frac{(y_{j+1} - y_{j-1})b}{2}, \; F_y = \frac{x_2 b}{2},$$

- in the case (fig 2, *b*)

$$F_x = \frac{y_2 b}{2}, \; F_y = \frac{y_1 b}{2}.$$

Air streams present in equations (24, 25) are defined on the basis of formulae (12-15), consequently obtaining equations in the form of (17), where some of co-efficients A are equal to zero. It results from the fact that there is no process of mass flow in the areas marked with a solid line adjoining the boundary.

It can be proved that discrete equations identical to (17) are obtained as a result of replacing derivatives in a filtration equation by adequate differential quotients; therefore it is a result of using a classic method of finite differences. It is proved [1, 7] that the schemes used are convergent and stable irrespectively of how condensed a numerical net is. It means that the numerical values of pressures in particular nodes of net approach precise values (coming from an analytical solution) if lengths of steps of integration approach zero, that is the condensation of a net is bigger. However the conclusion presented above is completely theoretical. In practice, as computer calculations are not accurate enough (the so-called «error of cutting off») and speed

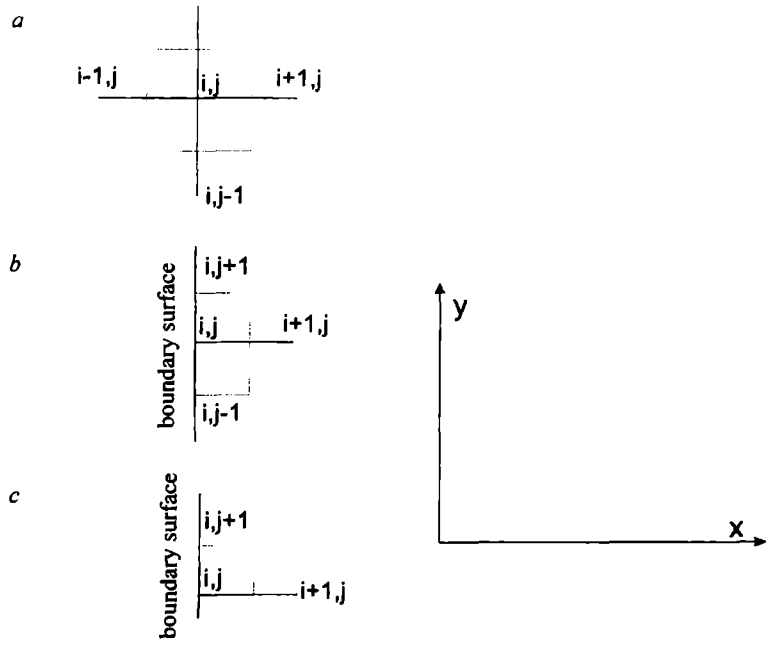


Fig.2. Graphic interpretation of discrete balance equations: *a* – in the case of inside nodes; *b* – in the case of boundary nodes ($\frac{\partial p}{\partial n} = 0$); *c* – in the case of corner boundary nodes ($\frac{\partial p}{\partial n} = 0$)

of convergence of an iterative process is slowing down, an excessive increase in the number of nodes can even lead to a fall in the effective accuracy of a numerical solution. If a net gets more condensed there is also a considerable increase in the time of a computer's work.

Solving a set of differential equations

As a result of presenting algebraic equations in form (17) for all the nodes of a numerical net a set of equations, which in the case of a linear differential equation also has a linear character, is obtained. If boundary conditions of the first kind are defined on the boundary of domain equations (17) are only presented for its interior nodes as on the boundaries the values of the function searched are defined *a priori*.

A set of differential equations (17) can be solved by means of precise methods (Gauss's Method of Elimination, Cholewski's Method) or by iterative methods (approximated). Due to the structure of the matrix of this set (pentagonal for a two-dimensional case and heptagonal for a three-dimensional case) using precise methods is not advised as it is connected with an excessive occupancy of a computer's operating store. Therefore one- or multi-iterative point methods are used. Gauss – Seidel's relaxation method (Beckenbach 1956), (Patankar 1980) is an example of a one-point iterative method. However it is not effective enough due to a relatively slow numerical concurrence (especially in the case of nets containing a large number of nodes). The procedure used most frequently is a multi-point iteration, which enables improving the value of a searched function along the whole line containing nodes (from the boundary to the opposite boundary). The improvement happens in two stages; in the first stage lines parallel to axis OX are served and in the second one – the ones parallel to axis OY. The sequence of steps to be taken in order to put the procedure mentioned above into practice can be expressed in the following way:

1. Assume *a priori* the values of area searched (in the case under consideration – of pressure) in particular nodes of a net treating them as the first approximation.

2. Treating the values of function in nodes on horizontals as unknowns, solve a set of linear equations for each of these lines using the values of functions in adjoining nodes along axis OY obtained from the previous iteration.

3. The steps described in point 2 should be repeated for verticals using the values of function in adjoining nodes along axis OX obtained in stage 2.

4. Check the absolute value of the maximum difference of function on a net obtained in the two subsequent iterations. If it is smaller than the positive value assumed, which shows how accurate a numerical solution is, stop your calculations.

The procedure described, which is called Alternating Directions Method, was formed by Peaceman – Ratchford [1]. In the case of matrix with a predominating main diagonal it is convergent, which in the case of differential equations describing the transport of mass, momentum and energy is always fulfilled.

A set of equations leading to simultaneous calculation of the values of function in nodes belonging to a particular line is solved on the basis of algorithm TDMA (Tridiagonal Matrix Algorithm) suggested by Thomas (Beckenbach 1956), (Patankar 1980), (Roache 1978). This procedure, which is a special form of Gauss's method of elimination, is assigned for linear sets characterised by a tridiagonal structure of matrix. It means that non-zero matrix elements are located only on its main diagonal and on diagonals located close to the diagonal mentioned above. The remaining matrix elements are equal to zero.

The algorithm mentioned above is very convenient when computer technology is used, it occupies little operating store and is characterised by a small increase in a rounding error.

Calculating air streams flowing into gob area

Air stream flowing into gob is calculated on the basis of the following integral formula:

$$Q_L = h\int_0^L v_n d\xi, \qquad (26)$$

In order to calculate the value of the integral defined by formula (26) at the beginning the values of velocity co-efficients u and v are calculated by approximating spatial derivatives of pressure (formula (9)) by frontal differential quotients. Further on definite integral (26) is numerically solved by means of a well-known method of trapezoids.

Calculation example of air velocity in goaf

Calculation programme prepared on the basis of the presented mathematical model allows for the determination of the steady state of air velocity distribution in goaf.

It is important to know the distribution of air flow velocity in goaf depending on a kind of roof rock when a prevention method for fire fighting is selected. Therefore, the calculation example is presented below. Calculations were done for different longwall ventilation systems (U-advance longwall, U-retreat longwall, Y-retreat longwall) located in identical geological conditions, which are characterized by the same bed separation resistance of roof, the same loss of pressure in a ventilated logwall area and the same geometrical parameters (longwall length 200 m, length of longwall panel 500 m, longwall height 2,5 m).

Nomenclature:

$K = \frac{k(x)}{\mu}$ – filtration co-efficient of a porous medium,

v – filtration velocity,

p – presure,

μ – co-efficient of absolute viscosity of air,

$k(x)$ – co-efficient of permeability,

m – medium porosity,

ρ – air density,

l – total line of face (legth of longwall panel),

r_0, a – empirical co-efficients dependent on mining and geological conditions of caving,

k_0 – co-efficient of caving permeability behind a longwall face,

x – distance from a longwall face,

R_{rrs} – bed separation resistance of roof rocks,

$v\{u,v\}$ – vector of velocity,

n – normal to the sides of an excavation, numerical values of pressures in boundary nodes are calculated,

b – signifies the flow along the length of 1 m, (b = 1 m).

h – height of airflow zone,

L – length of excavation,

$\xi \in [x,y]$ – co-ordinate parallel to axis of an excavation,

v_n – velocity co-efficient parallel to goaf boundaries.

Summary

The mathematical model (presented above) of airflow in the zone of caving, while variable co-efficient of gob permeability is taken into consideration, and also a numerical method of solving it, allowed for developing a computer programme aiming at determination of the distribution of velocity and pressure in a caving zone. The presented example of the distribution of air velocity in gob for the most typical ventilation systems (U – advancing mining, U – retreat mining and Y – retreat mining) allows for the determination of ventilation intensity. The intensity of goaf ventilation can help to select a fire prevention method.

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