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MATHEMATICAL MODEL OF MINE VENTILATION PROCESS INTERRUPTED BY A ROCK BURST

O MODELU MATEMATYCZNYM PROCESU WENTYLACJI KOPALNI ZAKŁÓCONEGO TĄPNIĘCIEM GÓROTWORU

In this article presented are considerations regarding the impact of shock or rock burst on performance of mine ventilation networks. A practical approach being applied to control such ventilation systems is to use a method of forecasting of the venting (aeration) process of mine ventilation network, with application of computer simulation of the occurring phenomena. The new issue that has not been taken into consideration until now in application of forecasting method of the air and methane mixture's spreading in mine excavation network, is a mathematic description of phenomena caused by rock burst, as well as impact of a sudden inflow of methane on the air and methane mixture's spreading and methane concentration distribution. Presented here is a mathematical model, with consideration of a phenomenon called after-blow, as well as transportation of the air and methane mixture after the shock or rock burst.

Key words: mine ventilation, rock burst, mathematical model

W artykule przedstawiono rozważania związane z wpływem tąpnięcia górotworu na rozpływ mieszaniny powietrza i metanu w sieci wentylacyjnej kopalni. W kopalniach gazowych tąpaniom towarzyszy silny wypływ lub wyrzut metanu (Budryk 1952). Można tu wyróżnić następujące zjawiska związane z emisją metanu:

- wydzielanie się metanu wolnego i sorbowanego z okruchów zniszczonego pokładu węgla i przemieszczonego do wyrobiska,
- filtracyjny przepływ metanu do wyrobiska przez nowo formowaną w procesie reologicznym strefę odprężenia i przez górotwór poza tą strefą.

Stosowaną w praktyce metodą kontroli systemu wentylacji jest zastosowanie prognozowania procesu przewietrzania kopalnianej sieci wentylacyjnej z wykorzystaniem komputerowej symulacji zachodzących zjawisk. Nowym zagadnieniem, dotychczas nie uwzględnianym przy stosowaniu tej metody, jest prognozowanie rozpływów mieszaniny powietrza i metanu w sieci wyrobisk po wystąpieniu tąpnięcia górotworu. Proces wentylacyjny, który realizuje się w takim systemie ma charakter

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bardzo złożony, przy czym rozpatrujemy proces składający się z powiązanych ze sobą zjawisk, takich jak dopływ znacznej ilości metanu w krótkim czasie wywołany tąpnięciem górotworu oraz transport przepływającej mieszaniny powietrza i metanu w złożonej sieci wentylacyjnej.

Rozważania teoretyczne poparte obserwacjami praktycznymi (Parysiewicz 1966) pozwalają na wyróżnienie zjawiska rozchodzenia się w sieci wentylacyjnej fali ciśnienia i prędkości, wywołanej gwałtownym zmniejszeniem się objętości strefy tąpnięcia (tzw. podmuch). W tym okresie istotne znaczenie mają procesy narastania ciśnienia, a strefa podwyższonego stężenia metanu ogranicza się tylko do rejonu wstrząsu lub tąpnięcia. Następnie, po ustaniu wstrząsu lub tąpnięcia górotworu, rozważa się przepływ mieszaniny powietrza i metanu w wyrobiskach górniczych. W tym okresie istotne znaczenie mają procesy emisji oraz transportu metanu w sieci wyrobisk, przy czym pojawiają się znaczne wartości depresji naturalnej, mającej wpływ na kierunki przepływu mieszaniny.

W związku z powyższym w artykule przedstawiono matematyczny model zjawisk wywołanych tąpnięciem, zachodzących w sieci wentylacyjnej. Wyróżniono zjawiska:

- podmuchu, który opisano układem równań ciągłości, ruchu i stanu mieszaniny dla płynu nieściśliwego dla strefy tąpnięcia (7), (8), (9), i dla pozostałych wyrobisk (10), (11), (12).,
- przepływ mieszaniny powietrza i metanu w wyrobiskach po zakończeniu wstrząsu tub tąpnięcia, który opisano układem równań ciągłości, ruchu i stanu mieszaniny dla płynu nieściśliwego i stanu ustalonego (24), (26), (32), (39),
- zmiany stężenia metanu w wyrobiskach wywołane dopływem metanu oraz transportu wzdłuż dróg wentylacyjnych, gdzie uwzględniono:
  - dopływ metanu wywołany tąpnięciem,
  - w równaniu transportu metanu wzdłuż wyrobiska poza strefą tąpnięcia uwzględniono zjawisko dyfuzji.

Przedstawiony matematyczny model zostanie wykorzystany w dalszych pracach prowadzących do opracowania profesjonalnego programu komputerowego do symulacji rozpatrywanych zjawisk.

Słowa kluczowe: wentylacja kopalń, tąpnięcie górotworu, model matematyczny

1. Introduction

In gas mines, the rock bursts are being accompanied with abrupt outflows or ejections of methane (Budryk 1952). One may distinguish the following effects related to the methane emission:

- release of free or sorpted methane from coal chips or side walls into the working,
- filtering-type flow of methane into mine working through the stress relieved zone newly formed in rheological process, and through the rock mass.

Determination of non-stationary distribution of the air and methane mixture in conditions described as emergency or disaster still remains a difficult computational task, in spite of the considerable progress achieved in computer sciences. Ventilation process being realised in such system, is of a very complex nature, and we would like to point out that the process being analysed encompasses a number of cross-related phenomena, such as:

- influx of a large volume of methane in a short period of time, caused by shock or rock burst,
- transport of the flowing air and methane mixture in a complex ventilation network.

The new issue that has not been taken into consideration until now in application of forecasting method of the air and methane mixture's spreading in mine excavation networks, is a mathematic description of methane emission after rock burst, and the impact of a methane inflow on the air and methane mixture's spreading and methane concentration distribution. There is research being carried out on this subject matter, and considerations resulting in formulating of the mathematical model of methane emission has been presented in a publication (Dziurzyński, Krach 2000).

In this article presented shall be considerations leading to description of the phenomena occurring in a ventilation network after shock or rock burst, together with the particular elements that comprise the mathematical model formulated in this regard.

2. Impact of rock bursts on mine ventilation

A rock burst causes serious disturbances in performance of mine ventilation network (Fig. 1).

Those disturbances can be categorised as being of short and long duration. The short-duration ventilation disturbance is a phenomenon of pressure and velocity wave propagation throughout ventilation network, caused by a sudden decrease in volume of the rock burst zone. In his publication the author (Parysiewicz 1966) writes about

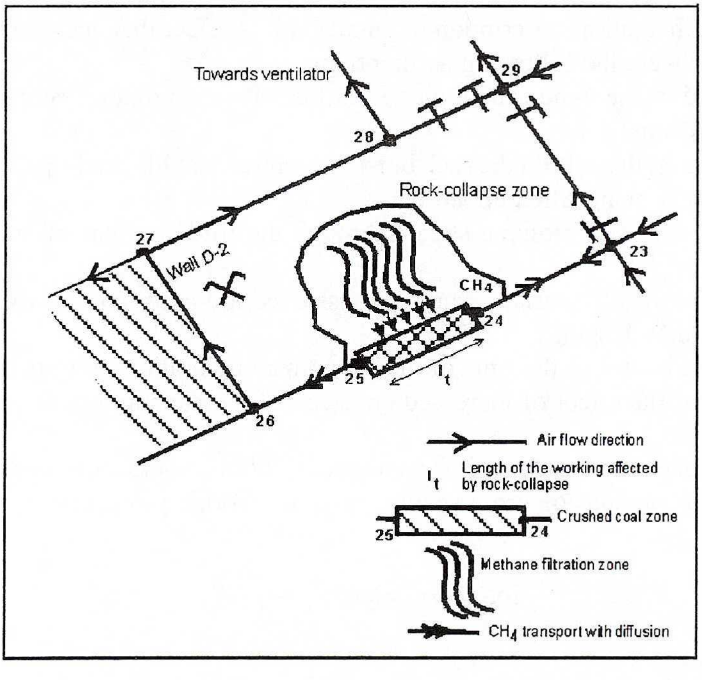

Fig. 1. Scheme of the D-2 Wall workings and rock burst zone

Rys. 1. Schemat wyrobisk rejonu ściany D-2 oraz strefy tąpnięcia górotworu powerful after-blow, accompanying the vast rock burst, that causes damages of ventilation stoppings and turns over trucks carrying mine output. The long-duration ventilation disturbance is the increased resistance of mine working, filled-up (entombed) as a result of rock burst, as well as the increased release of methane from the rock burst that results in significant increase of methane concentration in those parts of mine workings, where the air flow discharge has been considerably diminished as a result of the resistance increase. Theoretical considerations supported by practical observations (Parysiewicz 1966) allow for the following distinction of phenomena:

- effect of pressure and velocity wave propagation throughout ventilation network, caused by a sudden decrease in volume of the rock burst zone (so-called after--blow). Of the particular importance in this time period are processes of pressure increase, and the zone of increased methane concentration is limited to the area of shock or rock burst,
- the air and methane mixture flow in mine workings after shock or rock burst cessation. Of the particular importance in this time period are processes of emission and transport of methane in workings network, at this time one can observe occurrence of the natural depression of considerable values that affects the mixture flow routes.

2.1. After-blow effect

For the mathematical description of an after-blow effect that accompanies the rock burst, adopted were the following assumptions:

- assumed is one-dimensional model for the whole ventilation network, including the rock burst zone;
- assumed is, that within the rock burst zone a free, not blocked-up cross-section of working is being filled up slowly;
- disregarded is air volume stream through the filled-up part of cross-section of working;
- for branches of ventilation network assumed are constant cross-sections along each branch length;
- assumed is, that in the time of the phenomenon duration, it is still acceptable to disregard the effect of increased emission of methane and its impact on the air density.

Mass balance for the elementary volume *S(t)dx* of rock burst zone, where *S(t)* is time-related variable of cross-section of mine working and can be presented as follows:

$$\frac{d}{dt}[\rho S(t)dx] = (\rho Q)\big|_x - (\rho Q)\big|_{x+dx} \tag{1}$$

where:

ρ — air density,
Q — air volume stream.

In the balance given above, according to the initial assumptions, disregarded was methane inflow to the volume being under consideration.

Out of the equation (1) results equation of mass continuity in a form as follows:

$$\frac{\partial}{\partial t}(\rho S)+\frac{\partial}{\partial x}(\rho Q)=0 \tag{2}$$

Momentum balance for the volume in question, with disregarded air viscosity, has a form as follows:

$$\frac{d}{dt}[\rho Q dx]=\left[\frac{\rho}{S}Q^2+Sp\right]_x-\left[\frac{\rho}{S}Q^2+Sp\right]_{x+dx} \tag{3}$$

where:

p — air pressure,

according to the assumption, disregarded were gravitational forces.

Assuming that the area of active cross-section of working S is a function of time exclusively, i.e. area of active cross-section S varies evenly throughout the whole length of working zone being subject to rock burst, on the basis of (3) one may write the movement equation for compressible, not viscous fluid:

$$\frac{\partial}{\partial t}(\rho Q)+\frac{1}{S}\frac{\partial}{\partial x}(\rho Q^2)+S\frac{\partial}{\partial x}p=0 \tag{4}$$

The above equation should be complemented with losses in relation to the mine working's unit of length of cross-section area S, given with the following equation:

$$w=\frac{\lambda\rho}{2DS}Q|Q| \tag{5}$$

where:

λ — non-dimensional resistance coefficient,

ρ — air viscosity,

D — hydraulic diameter,

v — average velocity of the air in cross-section S,

Q — air volume stream through this cross-section.

Necessary is also an equation that describe relation between the air density and pressure, i.e. equation of gas state. Assuming isothermal approximation, one gets as follows:

$$\frac{p}{p_o}=\frac{\rho}{\rho_o} \tag{6}$$

Taking into consideration in (4) the relations (3) and (5), one may formulate a system of equations for the mine working zone being subject to rock burst:

$$\frac{\partial \rho}{\partial t}+\frac{1}{S(t)}\frac{\partial}{\partial x}(\rho Q)+\frac{\rho}{S(t)}\frac{\partial}{\partial t}S(t)=0 \tag{7}$$

$$\frac{\partial Q}{\partial t}+\frac{Q}{S(t)}\frac{\partial Q}{\partial x}+\frac{\lambda}{2D(t)S(t)}Q|Q|+\frac{S(t)}{\rho}\frac{\partial p}{\partial x}-\frac{Q}{S(t)}\frac{\partial S(t)}{\partial t}=0 \tag{8}$$

$$\rho=\rho_o\frac{p}{p_o} \tag{9}$$

Variability in time of the cross-section active area and hydraulic diameter of working zone filled up during rock burst one can describe as follows, approximately:

$$\left.\begin{aligned}\frac{S(t)-S_1}{S_2-S_1}&=\frac{t}{t_T}\\ \frac{D(t)-D_1}{D_2-D_1}&=\frac{t}{t_T}\end{aligned}\right\}\quad \text{for } 0\le t\le t_T \tag{10}$$

$$\left.\begin{aligned}S(t)&=S_2\\ D(t)&=D_2\end{aligned}\right\}\quad \text{for } t>t_T$$

where:

- $S(t)$, $D(t)$ — area and hydraulic diameter of a free, not filled-up cross-section of working being subject to rock burst,
- S_1, D_1 — area and hydraulic diameter of mine working cross-section before rock burst,
- S_2, D_2 — area and hydraulic diameter of mine working cross-section after rock burst,
- t_T — rock burst duration period.

For workings situated outside rock burst zone one may assume the constant value of cross-section area, but one cannot disregard gravitational forces related to the workings slope:

$$\frac{\partial \rho}{\partial t}+\frac{1}{S}\frac{\partial}{\partial x}(\rho Q)=0 \tag{11}$$

$$\frac{\partial Q}{\partial t}+\frac{Q}{S}\frac{\partial Q}{\partial x}+\frac{\lambda}{2DS}Q|Q|+\frac{S}{\rho}\frac{\partial p}{\partial x}+SG\frac{\partial z}{\partial s}=0 \tag{12}$$

$$\rho=\rho_o\frac{p}{p_o} \tag{13}$$

For the workings network the above equations are conjugated in nodes with the mass steams and momentum balances.

Mass steams balance for the node number k:

$$\sum_{i=1}^{N}\left(\frac{|\varepsilon_{ki}|+\varepsilon_{ki}}{2}\rho_{Li}Q_{Li}-\frac{|\varepsilon_{ki}|-\varepsilon_{ki}}{2}\rho_{0i}Q_{0i}\right)=0 \tag{14}$$

Momentum balance for the node number k:

$$\sum_{i=1}^{N}\frac{|\varepsilon_{ki}|+\varepsilon_{ki}}{2}l_{SL_i}\left(\frac{\rho_{Li}Q_{Li}}{S_i}S_i p_{Li}\right)-\frac{|\varepsilon_{ki}|-\varepsilon_{ki}}{2}l_{S0_i}\left(\frac{\rho_{0i}Q_{0i}}{S_i}S_i p_{0i}\right)=0 \tag{15}$$

In the above relations assumed were the following denotations:

N — number of branches,
i — sequence number of branch,
$\varepsilon_{k,i}$ — element of the node-branch coincidence matrix,
S_i — area of cross-section surface of the i-th branch,
l_{SL_i}, l_{S0_i} — vectors normal to surface S_i at the end and at the beginning of branch,
ρ_{Li}, Q_{Li}, p_{Li} — the air viscosity, volume stream and pressure at the end of the i-th branch,
ρ_{0i}, Q_{0i}, p_{0i} — the air viscosity, volume stream and pressure at the beginning of the i-th branch.

The initial condition is distribution of $Q(s)$ and $p(s)$ in ventilation network before rock burst. For the ventilation network being under consideration, routes and distributions of the air pressure and volume streams can be determined only by way of numerical calculation.

2.2. Changes in methane concentration in workings after rock burst

Changes in methane concentration in mine workings occur noticeably slower than variations of the air stream volume, therefore in this case justified is description of the air stream volume distribution in ventilation network with the steady movement equation. The further analysis shall be carried out on the basis of workings system and zone being subject to orogene shock, called rock burst zone, that is demonstrated as a scheme in Fig. 1. The rock burst zone encompasses crushed coal and the area through which methane filters into working. The air and methane mixture in a mine working is described with the equations of state, movement and continuity, that according to the adopted assumptions is given in a form (Pawiński, Roszkowski, Strzemiński 1995):

- movement equation for stationary state:

$$\frac{\partial p}{\partial s} + g\rho\frac{dz}{ds} + w + j_{lok}\delta(s - s_n) = h_w\delta(s - s_w) \tag{16}$$

- continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(v\rho)}{\partial s} = q \tag{17}$$

- state equation:

$$\rho = \rho(C) \tag{18}$$

where:

s — means a spatial coordinate measured along the mine working axis,
t — time [sec],
z — height coordinate, directed upwards [m],
$v(s,t)$ — mixture flow velocity [m/sec],
$p(s,t)$ — absolute pressure [Pa],
$\rho = \rho(C)$ — the air and methane mixture density [kg/m^3],
$C_m = C_m(s,t)$— mass concentration of methane in mixture, given with the equation:

$$C_m = \frac{\rho_C}{\rho} \tag{19}$$

ρ_C — partial density of methane [kg/m^3],
j_{lok} — pressure losses at the local resistance [Pa],
s_n — coordinate of losses occurrence location,
$\delta(s-s_n)$ — Dirac delta [1/m],
h_w — concentration produced by a ventilator [Pa],
s_w — coordinate of a ventilator situation,
$w = w(s)$ — hydraulic gradient [Pa/m], given with the equation (5),
q — methane influx per mine working volume unit [kg/m^{3}s]

While considering non-compressible flow, one assumed that $\frac{\partial \rho}{\partial p} = 0$, therefore the air and methane mixture density can be expressed as being dependant solely from the methane concentration. According to that, the state equation (18), provided constant values of pressure and temperature for the air and methane mixture, shall be as follows:

$$\rho = \frac{p_o}{T[R_p + (R_{CH_4} - R_p)C_{CH_4}]} \tag{20}$$

whereas:

R_p — gas constant of the air $R_p = 287.11$ [J/kgK],

R_{CH_4} — gas constant of methane $R_{CH_4} = 108.37$ [J/kgK],
$T = \text{const}$ — the air and methane mixture temperature [K],

Mass concentration of methane C_m is related to volume concentration C with the equation:

$$C_m = \frac{\mu_{CH_4} C}{\mu_{CH_4} C + \mu_p (1 - C)} \tag{21}$$

where:

μ_{CH_4}, μ_p — molecular weight of the air and methane.

Taking into consideration that:

$$\mu_{CH_4} = \frac{B}{R_{CH_4}} \quad \text{and} \quad \mu_p = \frac{B}{R_p} \tag{22}$$

where:

B — universal gas constant,

one may obtain equation of the air and methane mixture density dependant on volume concentration:

$$\rho = \frac{\rho_o}{T}\left[\frac{1}{R_p} + \left(\frac{1}{R_{CH_4}} - \frac{1}{R_p}\right) \cdot C\right] \tag{23}$$

and as a result

$$\rho = \rho_p - (\rho_p - \rho_{CH_4}) \cdot C \tag{24}$$

where:

ρ_p, ρ_{CH_4} — air and methane density at the pressure value P_0 and temperature T.

One may denote as $\overline{\rho}$ the air with methane average density in mine working of length equal L

$$\overline{\rho} = \frac{1}{L} \int_0^L \rho(s) ds \tag{25}$$

and integrate the expression (16) at length L, as a result one obtains an equation of the air flow in mine working, in the form as follows:

$$RQ|Q| + g\overline{\rho}(z_2 - z_1) + h_w = p_1 - p_2 \tag{26}$$

where:

R — aerodynamic resistance of mine working,

z_1, z_2 — the beginning and the end of mine working location height,

p_1, p_2 — pressure at the beginning and the end of mine working.

For a network of N-number of ventilation branches and M-number of nodes, the $N - M + 1$ equation system (26) describes the state of air propagation in a network, whereas for stationary values of resistances R and ventilators concentration h_w variations of the air propagation in time occur only as a result of changes in density $\overline{\rho}$ in the network branches.

2.2.1. Mine working filled up with coal after rock burst

For the description of changes in methane concentration within the mine working zone filled up after rock burst, assumed was one-dimensional model of filtration flow through a porous medium with mass inflow.

Methane volume balance for the elementary volume Sds of a medium of porosity equal m and with disregard of diffusion, can be presented as follows:

$$\frac{d}{dt}[C \cdot m \cdot S \cdot ds] = (CQ)|_s - (CQ)|_{s+ds} + q_m dx \tag{27}$$

where:

C — volume concentration of methane,

Q — volume stream of the air and methane mixture,

q_m — volume stream of methane inflow per length unit of the mine working.

Out of the above results another equation that describes changes in volume stream of methane in porous medium:

$$Sm\frac{\partial C}{\partial t} + \frac{\partial}{\partial s}(QC) = q_m \tag{28}$$

Assuming filtration-type of non-compressible fluid according to Darcy law, one can obtain:

$$Q = -S\frac{k}{\mu}\frac{dp}{dx} \tag{29}$$

where:

k — permeability of medium,

μ — dynamic viscosity of methane,

p — gas pressure.

As a result of assumption of non-compressibility, obtained is:

$$\frac{\partial Q}{\partial s} = q_m \tag{30}$$

Hence, taking into consideration the above relationship in equation (29) resulted in:

$$\frac{d^2 p}{ds^2} = -\frac{\mu}{SK} q_m \tag{31}$$

and equation (28) can be now formulated as follows:

$$Sm\frac{\partial C}{\partial t} - S\frac{k}{\mu}\frac{dp}{dx}\frac{\partial C}{\partial x} = q_m (1 - C) \tag{32}$$

The pressure gradient $\frac{dp}{ds}$ can be calculated from the equation (31) assuming the boundary conditions as follows:

$$s = 0 \quad p = p_0$$
$$s = L \quad p = p_L$$

$$\frac{dp}{ds} = \frac{p_L - p_0}{\mathrm{L}} - \frac{\mu}{Sk} q_m \left(s - \frac{L}{2} \right) \tag{33}$$

where:

L — length of filtration zone.

Substitution of the above relationship into (29) and introducing denotation:

$$\frac{\mu L}{Sk} = R_t \tag{34}$$

where:

R_t — the mine working resistance after rock burst;

formulated were the following relationships concerning the air and methane mixture volume streams at the beginning and the end of mine working zone where a rock burst occurred:

$$Q_0 = \frac{p_0 - p_L}{R_t} - \frac{q_m L}{2}$$

$$Q_L = \frac{p_0 - p_L}{R_t} - \frac{q_m L}{2} \tag{35}$$

Out of the above-presented relationships one can draw up a conclusion that in the system of equation of the air distribution in ventilation network the filled-up (entombed) zone can be presented in a form branch described with the following equation:

$$p_0 - p_L = R_t Q_t \tag{36}$$

and its two side influxes of the value equal $\frac{q_m L}{2}$ located at the beginning and the end of the branch , whereas Q_t is the discharge of the flow in a branch filled-up with coal after rock burst.

Mathematical models of methane emission into the mine working that enable determination of volume stream for methane emission q_m from the crushed coal and depressurised zone after rock burst occurrence have been presented in the article (Dziurzyński, Krach 2001).

2.2.2. Mine workings adjacent to the rock burst zone

In order to describe changes in methane concentration in the mine workings neighbouring with the rock burst zone assumed was one-dimensional equation of transport with diffusion:

$$S\frac{\partial C}{\partial t} + \frac{\partial}{\partial s}\left(QC - S\mathcal{D}\frac{\partial C}{\partial s}\right) = q_m \tag{37}$$

where:

S — mine working cross-section,
Q — the air volume stream in mine working,
$\mathcal{D}$ — coefficient of a turbulent,
q_m — volume stream of methane influx to mine working, per length unit of mine working.

Methane influx q_m causes gradual increase in the air volume stream Q in mine working, according to the following equation:

$$Q(s) = Q(0) + \int_0^s q_m(s)ds \tag{38}$$

If one can assume that the following condition given below has been met:

$$\frac{Q_{(0)}}{L} >> q_m$$

where:

L — length of mine working,

- then the equation (26) can be formulated as follows:

$$S\frac{\partial C}{\partial t}+Q\frac{\partial C}{\partial s}-S\mathfrak{D}\frac{\partial^2 C}{\partial s^2}=q_m \tag{39}$$

Summary

In this article presented has been the mathematical model of effects caused by burst of rock that occur in ventilation network. Distinguished have been the following effects:

- after-blow, described with a system of equations of continuity, movement and mixture state for non-compressible fluid for the rock burst zone (7), (8), (9), and for the remaining mine workings (10), (11), (12);
- the air and methane mixture flow in mine workings after the shock or rock burst cessation, being described with a system of equations of continuity, movement and mixture state for non-compressible fluid and stationary state (24), (26), (32), (39);
- changes in methane concentration in mine workings caused by methane inflow and transport along the ventilation routes. In the implemented model one have taken into consideration:
  - methane inflow caused by rock burst,
  - in the equation of methane transport along mine working outside rock burst zone, the effect of diffusion has been taken into consideration.

It is purposeful to continue the research leading to development of a professional program for simulation of the phenomena considered above. Completion of a forecast of the air and methane distribution in emergency conditions after shock occurrence shall facilitate:

- identification of the zone of increased concentration of methane risk,
- identification of the zone with low concentration of methane,
- indication of places for introduction of the additional methane detectors,
- carrying out the analysis of implementing various systems of ventilation for the wall exploitation in conditions of combined risks,
- restoration of the ventilation process course after occurrence of disturbances.

So developed forecast enables making the right conclusion and assessment of activities in the course of real-life action of rescuing people and the mine degasification.

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