Modeling the propagation of air blast waves in mine workings

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Abstract. The article presents a physical and mathematical model of the propagation of air shock waves in the network of coal mine workings after an instant explosion of the methane-air mixture in a given area. An approach to the implementation of a method for solving problems on the propagation of air shock waves in a branched network of mine workings is presented, taking into account arbitrary angles of their conjugation. The results of calculating the propagation of air shock waves in the model networks of mine workings are presented.

1. Introduction.
Coal mines are considered to be dangerous industrial facilities. The especially critical kinds of emergencies are methane and coal dust explosions. The most important factors for explosions are: excessive pressure, high temperature, high speed of air currents and toxic explosion products. Due to these factors explosions often lead to human casualties and millions of dollars in damage [1-3].

Affected area boundaries are determined using several industry-specific methods. In Russia there are three known methods [4-7]. First two are based on empirical data. The third (actively used) method uses gas dynamic equations to calculate the size of the zones affected by the shock waves.

2. Mathematical model.
Mathematical model of aerial shock wave (ASW) spread in a branched network of mine workings is described through the system of non-stationary gas-dynamic equations. Detailed description on this model is shown in [8-13].

Spatial gas-dynamics equations are used in junctions of workings. Junction is presented as a single cubic cell, with adjacent branches of differently-angled sections attached on its sides. In decartian system of x, y, z coordinates the gas-dynamics equations look like this:

\[
\begin{align*}
\frac{\partial p}{\partial t} + \frac{\partial pu}{\partial x} &= 0, \\
\frac{\partial p f}{\partial t} + \frac{\partial p f u}{\partial x} &= 0, \\
\frac{\partial pu}{\partial t} + \frac{\partial (pu^2 + p)}{\partial x} &= -\tau f p \Pi + p \frac{\partial S}{\partial x}, \\
\frac{\partial p ES}{\partial t} + \frac{\partial (pEu + pu)}{\partial x} &= q \Pi, \\
p &= \rho RT
\end{align*}
\]
\[ \frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0, \quad (6) \]
\[ \frac{\partial \rho f}{\partial t} + \frac{\partial \rho f u}{\partial x} + \frac{\partial \rho f v}{\partial y} + \frac{\partial \rho f w}{\partial z} = 0, \quad (7) \]
\[ \frac{\partial \rho u}{\partial t} + \frac{\partial (\rho u^2 + p)}{\partial x} + \frac{\partial \rho uv}{\partial y} + \frac{\partial \rho uw}{\partial z} = 0, \quad (8) \]
\[ \frac{\partial \rho v}{\partial t} + \frac{\partial \rho uv}{\partial x} + \frac{\partial (\rho v^2 + p)}{\partial y} + \frac{\partial \rho vw}{\partial z} = 0, \quad (9) \]
\[ \frac{\partial \rho w}{\partial t} + \frac{\partial \rho uw}{\partial x} + \frac{\partial \rho vw}{\partial y} + \frac{\partial (\rho w^2 + p)}{\partial z} = 0, \quad (10) \]
\[ \frac{\partial \rho E}{\partial t} + \frac{\partial (\rho Eu + pu)}{\partial x} + \frac{\partial (\rho Ev + pv)}{\partial y} + \frac{\partial (\rho Ew + pw)}{\partial z} = 0, \quad E = c_v T + \frac{u^2 + v^2 + w^2}{2}, \quad (11) \]
\[ p = \rho RT. \quad (12) \]

If we assume, that length and parameters of normal atmosphere as well as conditions in the zone of explosion are known, then the following initial conditions are used. For the branches:
\[ p(x,0) = \begin{cases} P_b & x \in EZ, \\ P_0 & x \notin EZ, \end{cases} \quad T(x,0) = \begin{cases} T_b & x \in EZ, \\ T_0 & x \notin EZ, \end{cases} \quad \rho_f(x,0) = \begin{cases} \rho_f & x \in EZ, \\ 0 & x \notin EZ, \end{cases}, \quad u(x,0) = 0, \quad (13) \]
for the junctions:
\[ p(x,y,z,0) = \begin{cases} P_b & \text{inside EZ}, \\ P_0 & \text{outside EZ}, \end{cases} \quad T(x,y,z,0) = \begin{cases} T_b & \text{inside EZ}, \\ T_0 & \text{outside EZ}, \end{cases} \quad \rho_f(x,y,z,0) = \begin{cases} \rho_f & \text{inside EZ}, \\ 0 & \text{outside EZ}, \end{cases}, \quad (14) \]
\[ u(x,y,z,0) = 0, \quad v(x,y,z,0) = 0, \quad w(x,y,z,0) = 0. \]

Boundary conditions for equations (1)-(4) and (6)-(11): If the working is a through-passage, then boundary conditions are determined by solving the Riemann problem.
If the boundary of the working is a dead end, then insulating boundary condition is used:
\[ u \big|_{br} = 0. \quad (15) \]
If the working leads to the surface:
\[ p \big|_{br} = \rho_{am}, \quad p \big|_{br} = \rho_{amt}. \quad (16) \]

In equations (1)-(16) the following designations are used: - time, \( x, y, z \) – decartian system of coordinates axis, \( \rho \) – gas density, \( \rho_f \) – partial density of combustion products, \( u, v, w \) – speed vector components, \( p \) – pressures, \( E \) – full gas temperature, \( T \) – temperature, \( S \) – area of channel cross-section, \( \Pi \) – perimeter of channel cross-section, \( \tau_r \) – force of wall friction, \( q \) – heat flow into the walls, \( R \) – the gas constant, \( c_v \) – specific heat at constant volume. Indexes: \( 0 \) – atmospheric conditions, \( b \) – explosion zone parameters, \( f \) – combustion products, \( EZ \) – methane explosion zone.

To solve system of equations we use S. K. Godunov method [14].

4. Implementation of the numerical calculation algorithm.
The idea behind the algorithm is to decompose the computational domain, under which "cell", "edge" and "boundary" are highlighted [6]. "Cell" – final volume, in which condition parameters are defined by the system of equations (1)-(5) or (6)-(12). "Boundary" – used for connect adjacent cells, imitation of dead-ends and ways to the surface. "Edge" – used for calculating flow of mass, impulse and energy from boundary to cell and vice versa. The way of connecting the described elements is depicted on figure 1.
Taking into account the introduced "cell", "edge" and "boundary" elements of algorithm, algorithm for the calculation can be depicted as following:

1. straight-line sections of mine workings (branches) are divided into several one-dimensional calculated "cells";
2. three-dimensional "cells" in junctions of workings (branches);
3. two "edges" are created for every one-dimensional "cell", six "edges" are created for every three-dimensional "cell" – one for each of its sides;
4. "boundaries" are created, each of which is connected to the two "edges" of the adjacent "cells";
5. initial conditions are set in every "cell";
6. calculation cycle is conducted:
   6.1. time step is determined on the current time layer with Courant–Friedrichs–Lewy condition in mind;
   6.2. Riemann problem is solved on the boundary of every pair of adjacent cells;
   6.3. inside the cells, equations (1)-(5) or (6) – (12) are solved and condition parameters on a new temporal layer are found;
7. the procedure is repeated until the stopping criterion is reached.

5. Advantages of this approach.
The method described above simplifies the introduction of a new mathematical model and modification of computational domain. Modification of computational domain is achieved through potential replacement of the computational domain or boundary. It is possible for the cells of different dimensions to interact with each other. With the help of a boundary it is possible to create a model of an explosion-containing wall, with boundary type being possible to change in case when wall is destroyed. The cell can be easily modernized, if the need to change the mathematical model arises. This is true, as the cell is isolated and self-sufficient. Examples of such modifications are: consideration of water and shale walls, consideration of combustion of localized methane cluster.

6. Verifying the calculation algorithm.
To verify calculations done using the described algorithm, tests that involve solving of model exercises [15] has been conducted. Sample, represented as a circular working, is depicted on figure 2.
Figure 2. Circular working. 1 – 3D cell, 2 – 1D cell, 3 – cell with an open border, 4 – zone of heightened pressure.

Zone of explosion is designated to be in the lower part of the ring, pressure in the zone of explosion – 0.570 MPa. The results of this calculation are depicted on figure 3. It is apparent, that ASW spreads through the ring symmetrically on both sides. At a point of time $t = 0.6$ sec., a new pressure peak is created due to interaction between the pressure waves, that spread towards each other.

Figure 3. Pressure allocation (a) and temperature (b) at different point of time inside the circular channel.

Calculation of shock wave spread inside a network of workings in the treatment area of the coal mine (fig. 4).

Figure 4. Treatment area. 1 – 3D cell, 2 – 1D cell, 3 – cell with an open boundary, 4 – zone of
heightened pressure, L, n, m – branch lengths

Calculation results are depicted on figure 6 in the form of pressure allocation on the paths of shock wave spread, depicted on figure 5 as dashed and dashed-dotted line.

Figure 5. Ill. 4 topology schematic 1 – path №1, 2 – path № 2

On the fig. 6a, b, it is apparent that the shock wave, that spreads along the path № 1 loses its intensity when passing through the points of convergence with the adjacent working. On the path № 2 a spike of pressure can be observed at moment of time 0.9 sec. It is explained by the interaction between the shock waves, traveling inside it from the two points of convergence with the path № 1.

In the process of every calculation the compliance with laws of conservation of mass and full gas energy was controlled inside the workings. Full gas mass and full gas energy inside the workings under the numerical solution is preserved up to 99.95%. Under the symmetrical geometry of the branches and point of explosion, calculated allocation of pressure in the branches during the spread of the shock waves is also

Figure 6. Pressure allocation on paths № 1 and № 2 of the treatment area at different moments of time

Algorithm described in this article can be easily parallelized. This will enable speeding up mass calculations for creation of emergency response plans.

7. Conclusion.
An approach for solving the problems regarding the spread of ASW in a branched network of mine workings has been developed. This approach is based on usage of the S. K. Godunov method and determining the elements of "cell", "edge" and "boundary" elements of the algorithm. Each of the aforementioned elements of the algorithm is responsible for a certain stage of calculations: "edge" is responsible for solving the Riemann problems in terms of gas parameters, "edge" is responsible for determining of components of speed vectors inside the cells, both normal and adjacent to the "edge", "cell" is responsible for numerical solution
of equations, that make up the mathematical model of ASW spread. Proposed decomposition of calculations is aimed at achieving several goals:

- significant reduction of labor costs under the development of mathematical model due to introduction of new physical processes of, for example, accounting for water and shale walls;
- simplification of parallelized calculations;
- simplification of calculations for ASW spread in geometrically complex areas.

Described approach is realized in the shape of a computer program, test calculations have been conducted, model problems have been solved and compliance with the laws of conservation of mass, impulse and energy has been tested.

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