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Considering the settling of dispersed water in the water barrier when calculating the explosion – proof distance at the methane explosion in a mine

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Abstract. Gas dynamics equations are used to simulate the interaction of shock waves with water or rock–dust barriers. The model is enhanced with the presence of dispersed water in the flow and its settling on the walls of the working. An approach to the implementation of the method for solving the problem of the propagation of shock waves in a branched network of mine workings, considering the interaction of shock waves with water barriers has been developed. The approach is based on the use of the numerical method of S.K. Godunov. Examples of solving the problem of the propagation of shock waves from a methane explosion in simulated networks of coal mine workings with water barriers placed in them are given.

1. Introduction

The introduction of modern technologies in the coal industry makes it possible to introduce highly productive actual mining, up to 10–20 thousand tons / day, using mechanized complexes with a high concentration of longwall operations. The use of new complexes implies an increase in the length of the extraction panels, the development of which requires extensive development workings. The high activity of the development works leads to a significant increase in the release of methane from the development faces, which increases the likelihood of the formation of explosive concentrations of methane–air mixtures and the threat of their explosion.

Methane explosions in mines are the most difficult and dangerous types of accident, as they always lead to catastrophic consequences for the miners and losses for the enterprise. As a result of the explosion, shock waves (SW) are formed, fires and rock falls occur.

In most cases, explosions occur in longwalls and adjoining ventilation and conveyor entries, development workings, poorly ventilated dead ends in a worked–out area.

The resulting fire and blockages can lead to a violation of ventilation, which leads to the accumulation of methane and the risk of the second explosion.

All types of damaging factors of explosion are dangerous for miners in the mine during an accident:

- overpressure;
- rarefaction;
- heat;



- the movement rate of air mass;
- concentration of gaseous explosion products.

The impact area of each damaging factor should be minimized.

One of the ways to prevent the propagation of SW generated after the explosion of methane in the active mine workings is to install water barriers [1-4]. The principle of operation of the barriers consists in the preliminary formation of a cloud of dispersed flame-extinguishing substances on the way of the flame front. Dispersion is carried out by a shock wave, which, interacting with the barrier, destroys it and transfers the extinguishing material into a suspended state. When the shock wave interacts with a large mass of water, the SW intensity decreases. The large mass of the barriers also partially reduces the shock wave energy consumed by their destruction. In this case, the pressure at the shock front can decrease by 25–28% [5].

At the same time, the use of existing methods of mathematical modeling, as an alternative to direct experiments, requires clarification [6-8]. One of such points is to take into account the settling of dispersed water on the walls of the mine workings. Considering the settling of aerosols will make it possible to correctly determine the explosion – proof distances when a shock wave passes along the branch with already destroyed barriers.

2. Purpose and objectives

The purpose of this paper is to develop an approach to the implementation of a method for solving problems on the propagation of shock waves in a branched network of mine workings, considering their interaction with water barriers.

To achieve this purpose, we have set the following objectives:

- To enhance the existing model of shock waves interaction with water barriers, considering the settling of dispersed water on the walls of the mine working.
- To investigate the interaction of shock waves from a methane explosion in simulated networks of coal mine workings with water barriers placed in them.
- To give examples of solving the problem of the propagation of shock waves from a methane explosion in simulated networks of coal mine workings with water barriers placed in them.

3. Physical model

Due to the complexity of the physicochemical processes of the explosion of a methane–air mixture in a coal mine, we will use the instant explosion model. For simulating, we will consider the explosion of a certain known volume of methane–air mixture in a mine as a sharp increase in pressure and expansion of reaction products with the separation of SW from its boundary. In the process of SW propagation through mine workings, its intensity decreases due to the involvement of additional air masses in the movement, friction against the walls of the workings, heat exchange and energy losses at junctions and turns.

When the SW reaches the water barrier, it is destroyed, and the water is transferred to a dispersed state and is involved in movement, which consumes part of the SW energy. The distribution of water is uniform throughout the mine working section.

4. Mathematical model

To simulate the interaction of shock waves with water barriers we use a gas–dynamic model of shock wave propagation through the network of mine workings [9, 10, 11] and a motion model of a gas–dust medium [12], which was enhanced by the equations of mass transfer of water drops. Under the assumptions made, the system of equations describing the movement of the gas–droplet mixture in rectilinear mine workings will be written in the form:

$$\begin{aligned}
\frac{\partial \rho S}{\partial t} + \frac{\partial \rho u S}{\partial x} &= -G_3, \quad \frac{\partial \rho_f S}{\partial t} + \frac{\partial \rho_f u S}{\partial x} = 0, \quad \frac{\partial \rho_3 S}{\partial t} + \frac{\partial \rho_3 u S}{\partial x} = -G_3, \\
\frac{\partial \rho u S}{\partial t} + \frac{\partial (\rho u^2 + p) S}{\partial x} &= -\tau_{mp} \Pi + p \frac{\partial S}{\partial x} - G_3 u, \\
\frac{\partial \rho E S}{\partial t} + \frac{\partial (\rho E u + p u) S}{\partial x} &= q \Pi - G_3 \left(c_3 T + \frac{u^2}{2} \right), \\
E &= \varepsilon + \frac{u^2}{2}, \quad \varepsilon = \frac{p(1/\rho - \alpha)}{(K-1)}, \quad p(1/\rho - \alpha) = RT, \quad \rho = \rho_g + \rho_3, \\
R &= c_p(1-\eta) - c_v(1-\eta), \quad K = \frac{c_p(1-\eta) + c_3\eta}{c_v(1-\eta) + c_3\eta}, \quad \eta = \frac{\rho_3}{\rho}, \quad \alpha = \rho_3/(\rho_g \rho_k), \\
\tau_{fric} &= \frac{1}{8} c_f \rho u^2, \quad c_f = 0.0032 + \frac{0.221}{Re^{0.237}}, \quad Re = \frac{\rho u D}{\mu}, \quad D = \frac{4S}{\Pi}, \\
q &= \alpha_T (T_s - T), \quad Nu = 0.022 Re^{0.8} Pr^{0.47} E, \quad Pr = \frac{\mu c}{\lambda_g}, \quad Nu = \frac{\alpha_T D}{\lambda_g}
\end{aligned} \tag{1}$$

where, t – time; x – coordinate; ρ – density of the gas–droplet mixture; ρ_g – gas density; ρ_f – density of combustion products; ρ_3 – bulk density of water aerosol suspended in gas, ρ_k – water density; p – pressure; T – temperature of the gas–droplet mixture; T_s – surface temperature of the mine working; R – gas constant of the gas–droplet mixture; c_3 – specific heat capacity of water; c_v – specific gas heat at constant volume; c_p – specific heat capacity of the gas at constant pressure; u – rate of the gas–droplet mixture; E – total energy of the gas–droplet mixture; ε – internal energy of the gas–droplet mixture; S – channel cross–sectional area; Π – channel perimeter; τ_{fric} – friction force against the channel walls; q – heat flow into the walls; α – own volume of water weighed in one cubic meter of gas–dust mixture (covolume); η – mass fraction of water per unit volume of the gas–droplet mixture; K – effective adiabatic exponent; c_f – resistance coefficient; Re – Reynolds number; D – equivalent cross–sectional diameter of the straight section of the mine working; μ – coefficient of dynamic viscosity. Nu – Nusselt number; Pr – Prandtl number; λ_g – coefficient of gas thermal conductivity; α_T – heat transfer coefficient; c – heat capacity; E – correction factor that takes into account the effect of wall roughness on the heat transfer process. In the system of equations (1) the value G_3 considers settling of drops on the walls of the mine workings, (mass settling rate), summand $G_3 u$ takes into account the loss of impulse from the flow of the gas–drop mixture due to the drops settling, summand $G_3 \left(c_3 T + \frac{u^2}{2} \right)$ takes into account the loss of total energy from the flow of the gas–drop mixture due to the settling of drops. We define G_3 as $G_3 = \Pi \beta \rho_3$ where, β – mass transfer coefficient.

The junctions of mine workings will be assumed to be cubic and the gas flow in them will be described by three–dimensional equations of gas dynamics:

$$\begin{aligned}
\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} &= 0, \\
\frac{\partial \rho_f}{\partial t} + \frac{\partial \rho_f u}{\partial x} + \frac{\partial \rho_f v}{\partial y} + \frac{\partial \rho_f w}{\partial z} &= 0, \\
\frac{\partial \rho_3}{\partial t} + \frac{\partial \rho_3 u}{\partial x} + \frac{\partial \rho_3 v}{\partial y} + \frac{\partial \rho_3 w}{\partial z} &= 0, \\
\frac{\partial \rho u}{\partial t} + \frac{\partial (\rho u^2 + p)}{\partial x} + \frac{\partial \rho uv}{\partial y} + \frac{\partial \rho uw}{\partial z} &= 0, \\
\frac{\partial \rho v}{\partial t} + \frac{\partial \rho uv}{\partial x} + \frac{\partial (\rho v^2 + p)}{\partial y} + \frac{\partial \rho vw}{\partial z} &= 0, \\
\frac{\partial \rho w}{\partial t} + \frac{\partial \rho uw}{\partial x} + \frac{\partial \rho vw}{\partial y} + \frac{\partial (\rho w^2 + p)}{\partial z} &= 0, \\
\frac{\partial \rho E}{\partial t} + \frac{\partial (\rho Eu + pu)}{\partial x} + \frac{\partial (\rho Ev + pv)}{\partial y} + \frac{\partial (\rho Ew + pw)}{\partial z} &= 0, \\
E = \varepsilon + \frac{u^2 + v^2 + w^2}{2}, \quad p \left(\frac{1}{\rho} - \alpha \right) &= RT
\end{aligned} \tag{2}$$

here u – is the rate along the x -axis, v – along the y -axis, w – along the z -axis

As a numerical method for solving systems of equations, one-dimensional and three-dimensional modifications of the S.K. Godunov [13] were taken using the generalized coordinate system [14]. This method is based on solving the problem of the decay of an arbitrary discontinuity in the gas parameters to determine the mass flows, impulse and energy at the boundaries of the computational cells [15].

5. Solution examples

Figure 1 shows a diagram of a development face with an adjacent working. The figure shows the explosion area and a water barrier installed at 250 to 300 m from the dead end. The point at which the characteristics in the shock wave are monitored is in an adjacent entry at a distance of 10 m from the junction.

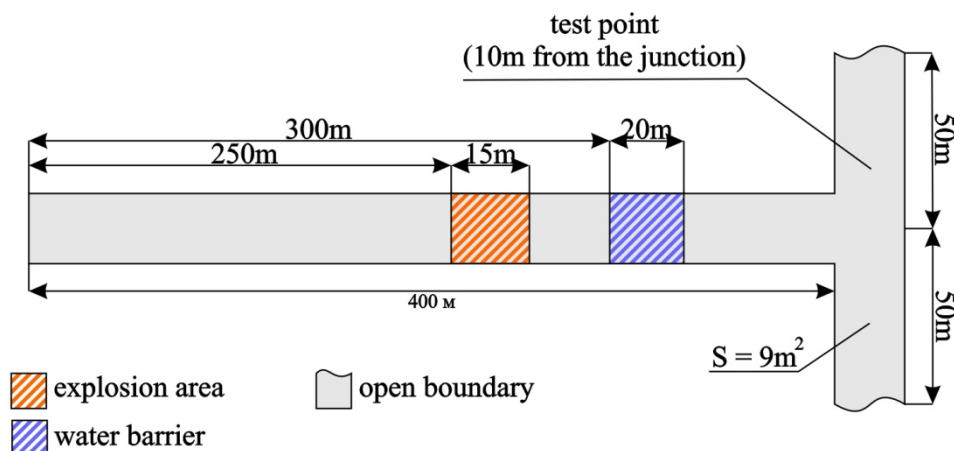


Figure 1. Schematic representation of the computational domain.

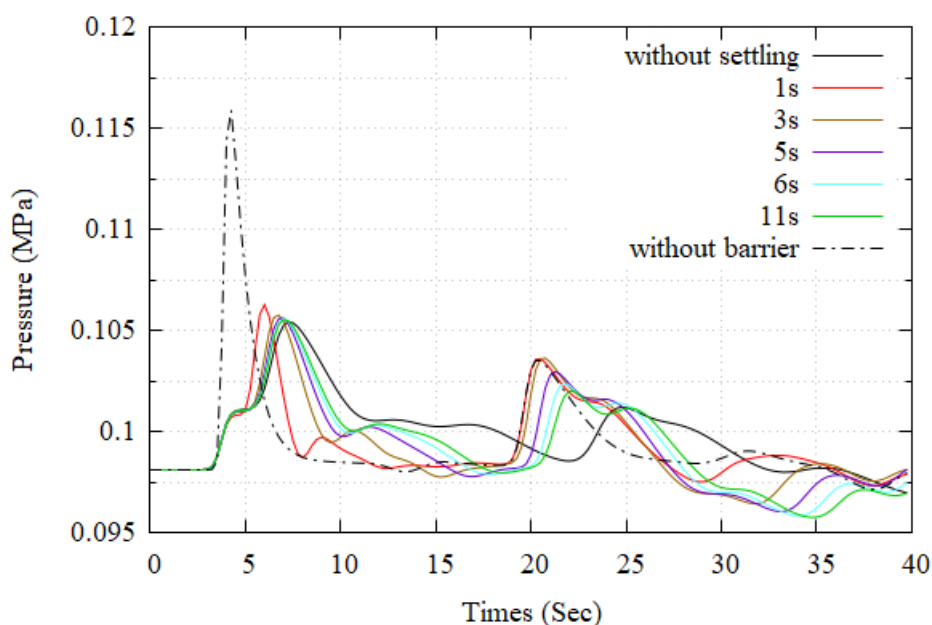
The boundary conditions are set as follows:

- entry bounds dead end: a non-leakage condition is established $u|_{border} = 0$;
- open boundary: density value and atmospheric pressure $p|_{border} = P_{atm}, \rho|_{border} = \rho_{atm}$
- entry bounds junction: the values of mass flows, impulse and energy are used, determined from the solution of the problem of the decay of an arbitrary discontinuity in the gas parameters. $M|_{border} = M(t), I|_{border} = I(t), E|_{border} = E(t)$.

The following initial data are set as the initial calculation data: $P_{atm} = 0.98 \text{ MPa}$; $P_b = 0.4 \text{ MPa}$; $T_{atm} = 20 \text{ }^\circ\text{C}$; $T_b = 921.2 \text{ }^\circ\text{C}$; $\rho_{atm} = 1.1548 \text{ kg/m}^3$; $\rho_3 = 35 \text{ l/m}^3$, where P_b – initial pressure in the explosion area; T_b – initial temperature in the explosion zone; ρ_f – initial density of combustion products; ρ_3 – initial volumetric density of water in the zone of the water barrier. The total estimated time is 40 seconds.

Figure 2 shows the results of six calculations with different characteristic settling times (red 1sec, brown 3sec, blue 5sec, turquoise 7sec, green 11sec). The graphs show the behavior of the characteristics (pressure, rate, temperature) of the shock wave at the control point as a function of time. The dotted line marks the calculation without a water barrier. On the graphs obtained, two peaks can be distinguished, formed when the shock wave passes through the control point. The first peak describes the value of the characteristics of the main wave, the second – reflected from the dead end and arriving at the control point. Due to the long exposure of dispersed water in the calculation without settling, the shock wave is stretched in space with a decrease in its characteristics, while in the calculations with settling the peaks are more pronounced. With an increase in the sedimentation time of a water aerosol, the profile of the shock wave becomes similar to the calculation profile without sedimentation, whereas with a decrease in the sedimentation time, the profile tends to be calculated without a water barrier. From the calculations performed, it follows that when the settling of water aerosol is considered, the explosion-proof distance will be shorter (the dangerous distance will be longer).

Thus, when considering the interaction of SW with water barriers in the calculations, it is necessary to take into account the settling of water aerosol after the interaction of SW with the water barrier.



a)

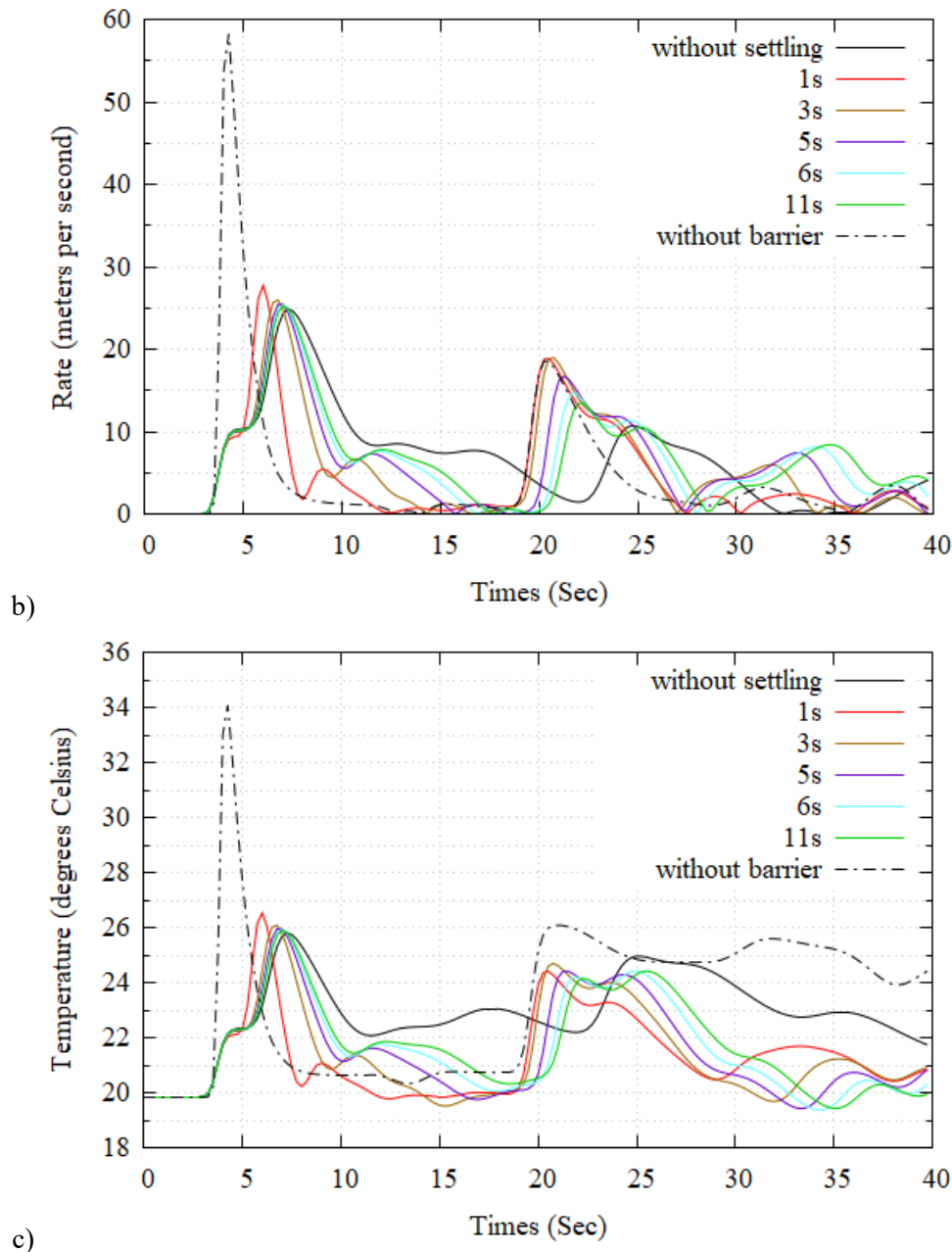


Figure 2. Change in a) pressure, b) rate, c) temperature depending on the time at a control point.

6. Conclusion

The main research results and conclusions obtained in this study are as follows:

- The mathematical model (1) has been enhanced by considering the settling of dispersed water (rock dust) on the walls of the mine working.
- An approach has been developed to implement a method for solving problems on the propagation of shock waves in a branched network of mine workings, considering the interaction of shock waves with water (rock dust) barriers.

- Examples of solving the problem of the propagation of shock waves from a methane explosion in a simulated network of coal mine workings with water barriers placed in them have been given.

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