The study of temperature fields in portogallo congestion in the vicinity of the hearth self-heating

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Abstract. With the increase in the intensity of underground mining, due to the use of modern mining equipment and the use of new technological systems of cleaning works, cases of manifestations of negative factors are becoming more frequent. The main ones are gas-dynamic and thermophysical processes in the atmosphere of mine workings, which significantly reduce productivity and safety in the mining industry. The article deals with the gas-dynamic and thermophysical parameters of shock-wave processes occurring in the atmosphere of mine workings. On the basis of the fundamental laws of conservation of mass, momentum and energy, formulas characterizing changes in pressure, density and temperature in the dust-gas-air mixtures behind the shock front are obtained. When obtaining formulas, it is taken into account that the heat capacity of dust and gas mixtures on different sides of the shock front is different. Built dependency graphs of pressure, density and temperature of mixtures from Mach number and the relationship of indicators of specific heats, Poisson. The analysis on the basis of which a number of regularities in the dust-gas-air flows of mine workings was found.

1. Introduction

With the transition of mining coal seams at deeper horizons, the mining industry is regularly confronted with manifestations of the negative factors that significantly constraining the extraction of coal by underground methods. Some of these factors are of various gas-dynamic phenomena [1 — 3], for example, soufflerie evolution of gas, which, as shown in [2, 3], under certain conditions, can occur at supersonic speed. This leads to the formation of a surge in compaction and a "satellite" flow capable of moving through the mine workings at a hurricane speed, which can cause serious negative consequences.

Other factors include kinetic oxidation processes and heat and mass transfer processes [4] occurring in dust and gas mixtures (PARS) formed during operation of mine equipment. In the presence of ignition sources can occur burning hot water in the regime of a deflagration. So, in work [5] on the basis of the theory of the thermal explosion are determined the critical ignition temperature dust-Laden flue gas micro-heterogeneous mixtures in the atmosphere of mine workings.

In [6, 7] investigated the combustion of micro and fine dust-laden flue gas mixtures and developed an algorithm that allows to determine the temperature of the air mixture anywhere in the combustion zone, and calculate the length of the zone. In [8, 9] revealed some patterns of burnout coarse PGWS in...
the atmosphere of mine workings and the relations between the parameters of the mixture during the flow process of combustion, respectively, in kinetic, diffusive and the intermediate region.

The authors of [10] theoretically and experimentally studied the processes of combustion, but detonation of gas-air and dust-Laden flue gas mixtures at various concentrations and different stoichiometric ratio.

Analyzing the materials of investigations of explosions in the development of mechanized complexes of flat and inclined coal seams, the authors [11] came to the conclusion that the most likely cause of explosions is the ignition of methane-air mixture and subsequent explosions in the developed space, which are initiated by the centers of self-heating of coal. In this case, the burning gas is carried by an explosive wave in the treatment face and in the adjacent workings, causing explosions of coal dust.

In article [12], studies of detonation combustion of a dust-methane-air mixture were carried out, during which it was found that the combustion of the mixture generates disturbances capable of supporting the process of movement of a two-phase mixture, in which the most significant is the convective mechanism of heat transfer associated with the relative motion of the phases and the heat and mass transfer between them.

From the analysis of papers [10–12] we can conclude that in the process deflagrations burning methane burn out quickly, but the resulting discontinuity representing a shock front, are able to spread down through the undisturbed dust-Laden flue gas on-current at supersonic speed. Due to the compression of the mixture by the shock front, it is heated, which causes an exothermic reaction, which together with the shock wave generates a detonation wave, and a subsequent explosion, which in the conditions of the mines is catastrophic.

Thus, it can be argued that the most dangerous phenomena in coal mines, in our opinion, are shock-wave processes, which is manifested in the form of burning and detonation, which refer to accidents with the most serious consequences.

As a rule, the theory of shock-wave processes in gases is based on the model of an ideal gas and three classical conservation laws: mass, pulses and energy. The main purpose of the theory is to establish a connection between the main gas-dynamic and thermodynamic parameters of gas: density, pressure, temperature, entropy, heat content and speed of sound [13–15]. Within the framework of the ideal gas model, solutions to this problem are found for many particular conditions.

However, in some cases, shock and detonation waves occurring in mine workings, are non-classical shock wave and detonation processes. In some cases, this is due to the fact that the surface of the mine is very rough. Therefore, for example, the detonation velocity is no longer a physical-chemical constant of the dust-air mixture.

In other cases, the dust-air flow passing through the shock wave front changes some of its thermal properties, in particular, the heat capacity, which becomes different on different sides of the shock front. In turn, this leads to the fact that the Poisson adiabatic parameters also become different, thereby making an essential feature in the processes of dust-gas mixtures flow behind the shock wave front.

In connection with the above in this article, we determine the basic parameters of dust-gas mixtures behind the shock wave front, provided that the Poisson's adiabatic index changes its value when passing through the shock front. On the basis of the obtained results, we perform the analysis and reveal some regularities of shock-wave processes in dust-gas-air flows.

2. Problem statement and solution
Since the flow of the dust-gas mixture is stationary, the analysis of its state in mining is convenient to perform on the basis of the fundamental laws of conservation: mass, pulses and energy [13–15], expressed respectively by the continuity equation

\[
\rho_2 u_2 = \rho_1 u_1, \tag{1}
\]

equation of pulses
and the energy equation

\[
p_1 + p_1 u_1^2 = p_2 + p_2 u_2^2,
\]

(2)

where \( \rho_1, u_1, p_1, i_1 \) — accordingly, the density, velocity, pressure and enthalpy of the dust-gas mixture before the shock front; \( \rho_2, u_2, p_2, i_2 \) — the same parameters of the mixture, but behind the shock front.

From the equations (1) and (2) we find the relations

\[
u_2^2 = \frac{\rho_2 - \rho_1}{\rho_2} \cdot \frac{\rho_2}{V_2 - V_1}, \quad u_1^2 = \frac{p_2 - p_1}{\rho_2 - \rho_1} \cdot \frac{p_2 - p_1}{V_2 - V_1},
\]

(4)
in which we took into account that the density \( \rho \) and specific volume \( V \) mixtures are related by the ratio \( \rho = 1/V \). Using formulas (4), we find first

\[
u_2^2 - u_1^2 = (p_2 - p_1)(V_1 + V_2),
\]

(5)
and then

\[
u_2 - u_1 = \sqrt{(p_2 - p_1)(V_1 - V_2)}.
\]

(6)

Then, using the formula (5), we give the energy equation (3) to the form

\[i_2 - i_1 = \frac{1}{2}(p_2 - p_1)(V_1 + V_2)
\]

(7)
and given the bond enthalpy \( i \) with internal energy \( E \) [16]

\[i_1 = E_1 + p_1V_1, \quad i_2 = E_2 + p_2V_2,
\]
write

\[i_2 - i_1 = E_2 - E_1 + p_2V_2 - p_1V_1.
\]

(8)
Comparing equality (7) and (8)

\[E_2 - E_1 + p_2V_2 - p_1V_1 = \frac{1}{2}(p_2 - p_1)(V_1 + V_2)
\]
and performing the transformation in the resulting equality, we obtain the following formula

\[E_2 - E_1 = \frac{1}{2}(p_2 + p_1)(V_1 - V_2)
\]

(9)
To find the energy of the mixture at its transition through the shock front, we turn to the Poisson's adiabatic equation, which is represented as [13–15]

\[p = AV^{-k},
\]

(10)
where $A$ — some constant, $k$ — Poisson's adiabatic index, defined as $k = c_p/c_v$, $c_p$, $c_v$ — are the heat capacity of the mixture, respectively, at constant pressure and constant volume.

Since the state of the mixture changes adiabatically before the shock wave front and behind the shock wave front, there is no heat input ($dq = 0$), and so from the first law of thermodynamics [16], we have

$$dE = -pdV = -AV^{k}dV.$$ 

Integrating the resulting equality and believing that $V \in [V_1; V_2]$, get the formula

$$E_2 - E_1 = \frac{p_2V_2}{k_2 - 1} - \frac{p_1V_1}{k_1 - 1},$$

(11)

in which it is taken into account that the adiabatic values $k_1$ and $k_2$ are different, since the temperature of the mixture on both sides of the shock front is different. Therefore, the heat capacity of the mixture will be different: the higher the temperature of the mixture, the lower its heat capacity [16]. Since behind the shock wave front the temperature $T_2$ is higher than the temperature $T_1$ before the front, then $c_p(1) > c_p(2)$, $c_v(1) > c_v(2)$ and therefore $k_1 > k_2$.

Equating the right parts of equations (9) and (11), we obtain equality

$$\frac{p_2V_2}{k_2 - 1} - \frac{p_1V_1}{k_1 - 1} = \frac{1}{2} (p_2 + p_1)(V_1 - V_2),$$

(12)

which in the course of elementary transformations we give to the form

$$2V_1 \left( \frac{p_2 - p_1}{k_2 - 1} \right) = p_2(k_2 + 1) + p_1(k_2 - 1),$$

(13)

and then using the ratio

$$V_1 - V_2 = V_1^2 \frac{p_2 - p_1}{u_1^2},$$

(14)

from (4), convert (13) to the following equality

$$p_2 - p_1 = \frac{2\rho u_1^2}{(k_2 + 1)} \left( \frac{p_2 - p_1}{k_2 - 1} \right).$$

(15)

To exclude the unknown pressure $p_2$ in the right part, we will proceed as follows. First, we add and subtract in the numerator of the right part of the formula (15) the summand $p_1(k_2 - 1)/(k_2 + 1)$, then using equations (1) and (2) we express

$$p_2 = p_1 + \rho [u_1^2 \left( 1 - \frac{p_1}{\rho_1} \right)],$$
and the ratio $\rho_1/\rho_2$ we find from the first formula (4). During the transformation, we will take into account that the square of the sound velocity in the mixture before the shock front is determined by the formula $a^2 = k_1 p_1/\rho_1$.

As a result of the described procedures and after rather cumbersome transformations, we obtain the formula

$$\bar{p}_2 = 1 + \frac{k_1 M_1^2}{k_1 + 1} \left( 1 - \frac{k_2}{k_1} \right) \left( 1 + \sqrt{1 + \delta} \right),$$

(16)

where $\bar{p}_2$ and $M_1$ are, respectively, the dimensionless pressure $\bar{p}_2 = p_2/p_1$ and Mach number $M_1 = u_1/a_1$, a parameter $\delta$, determined by the formula

$$\delta = \frac{2(k_2 + 1)(k_1 - k_2)k_1 M_1^2}{(k_1 - 1)(k_2 M_1^2 - k_2^2)},$$

(17)

is a dimensionless quantity.

3. Analysis of the results

Analyzing the formulas (16) and (17) we note that they take place both in the subsonic flow of the mixture ($M_1 < 1$) and in the supersonic flow ($M_1 > 1$). First of all, we note that if $k_1 = k_2 = k$, then the value $\delta = 0$, whereby the formula (16) is significantly simplified, taking the form

$$\bar{p}_2 = 1 + \frac{2k(M_1^2 - 1)}{k + 1},$$

(18)

it follows that if $M_1 = 1$ and $k_1 = k_2$, then $\bar{p}_2 = 1$, therefore, $p_2 = p_1$ and, therefore, the shock front is not formed.

Knowing the relative pressure $\bar{p}_2$, from the equality (12) find the relative density $\bar{\rho}_2 = \rho_2/\rho_1$ dust and gas mixture behind the shock front

$$\bar{\rho}_2 = \frac{\bar{p}_2 \left( \frac{k_2 + 1}{k_2 - 1} \right) + 1}{\bar{p}_2 + \left( \frac{k_1 + 1}{k_1 - 1} \right)},$$

(19)

where $\bar{p}_2$ determined by the formula (16).

To calculate the temperature of the mixture behind the shock front, we use the Mendeleev – Clapeyron law [13–5]: $p_2 = \rho_2 RT_2$, where $T_2 = p_2/\rho_2 R$, where $R$ — gas constant. Substituting into the obtained formula of the ratio $p_2 = \bar{p}_2 \cdot p_1$, $\rho_2 = \bar{\rho}_2 \cdot \rho_1$, and given that the temperature before the shock front is determined by the formula $T_1 = p_1/\rho_1 R$, find the desired temperature in dimensionless form

$$T_2 = \frac{\bar{p}_2}{\bar{\rho}_2},$$

(20)

where $T_2 = T_2/T_1$ — dimensionless temperature.

Since the heat capacity of $c_p$ is always greater than the heat capacity of $c_v$, then both indicators of Poisson's adiabate $k_1 > 1$, $k_2 > 1$. Next, find the interval of change of the ratio $k_2/k_1$. Let $k_2/k_1 = 0.75$ and $M_1 = 1$. Then the relative density calculated by the formula (22), taking into account the formula (18), will be $\bar{\rho}_2 = 11.4$, in the real world is not observed. From the above we conclude that the ratio of
$k_2/k_1$ should not be very different from the unit. Therefore, in the process of conducting a computational experiment and plotting, we took the interval $k_2/k_1 \in [0.85; 1]$, and Mach number $M_1 \in [1; 2.2]$.

Figure 1, $a$ shows the graphs of the function $\overline{p}_2(M_1)$ for a number of values $k_2/k_1$, which is a nearly parallel, concave curves showing monotonous increase in the relative pressure $\overline{p}_2$ with increasing Mach number $M_1$. Figure 1, $b$ shows graphs of the function показаны графики функции $\overline{p}_2(k_2/k_1)$ for a range of Mach numbers, which is a slightly convex monotone decreasing curves. It follows from the analysis of the graphs that the lower values of $k_2/k_1$ correspond to the higher pressure values $\overline{p}_2$.

Figure 1. Dependences of relative pressure on the Mach number $M_1$ (figure 1, $a$) and on the ratio of Poisson’s adiabate (figure 1, $b$)

Thus, with an increase in the Mach number $M_1$, the relative pressure $\overline{p}_2$ increases substantially, which means an increase in the intensity of the shock front. So, for example, if the Mach number $M_1 = 1.6$, and $k_2/k_1 = 0.85$, the pressure is $\overline{p}_2 = 3.8$, i.e. increases more than four times, compared with the pressure before the front. With the same Mach number and $k_2/k_1 = 1$ ratio, the pressure is total $\overline{p}_2 = 2.8$. Thus, due to the fact that the indicators $k_1$ and $k_2$ are not the same pressure increased by 1.35 times.

Figure 2 shows graphs of functions $\overline{p}_2(M_1)$ and $T_2(M_1)$ for a number of relations $k_2/k_1$, showing that both functions grow monotonically on the segment $M_1 \in [1; 2.2]$, but the graphs $\overline{p}_2(M_1)$ are slightly convex, and the graphs $T_2(M_1)$ — slightly concave.

Figure 2. Dependences of the relative density of the mixture (figure 2, $a$) and the relative temperature $T_2$ (figure 2, $b$) on the Mach number $M_1$. 
However, the main difference between these functions $\bar{\rho}_2(M_1)$ is that the highest values of the function take place at $k_2/k_1 = 0.85$ and decrease with the growth of $k_2/k_1$. Therefore, the smallest values $\bar{\rho}_2(M_1)$ are characteristic for the ratio $k_2/k_1 = 1$, i.e. when the indicators of specific heats of the Poisson are equal.

On the contrary, the function $T_2(M_1)$ has the highest values at $k_2/k_1 = 1$, and decreases with decreasing $k_2/k_1$. Another fundamental feature of the function $T_2(M_1)$ is that if $k_2/k_1 < 1$, it consists of two sections, the first of which $T_2 < 1$, and the second — $T_2 > 1$. The smaller the $k_2/k_1$ ratio, the longer the first section. For example, if $k_2/k_1 = 0.85$, then the function $T_2 < 1$ on the segment $M_1 \in [1; 2]$ (figure 2, b).

But since the temperature $T_2$ is always greater than the temperature $T_1$, the relative temperature $T_2$ should always be greater than one. Therefore, the values of the function $T_2(M_1) < 1$ should be excluded from consideration, so they are shown in dotted lines on the graphs (see figure 2, b).

4. Conclusions

The formulas determining the basic parameters of the dust-gas mixture behind the shock front at different values of the Poisson's adiabate index on opposite sides of the front are obtained. The graphs of relative pressure, density and temperature in the mixture behind the shock front depending on the Mach number and the ratio of Poisson's adiabate $k_2/k_1$ are constructed. Based on the analysis of the results revealed:

- graphs of the dependence of the relative pressure on the Mach number for different ratios of Poisson's adiabate $k_2/k_1$ are almost parallel, concave curves characterizing the monotonic growth of the relative pressure with an increase in the Mach number;
- graphs of the relative pressure dependence on the $k_2/k_1$ ratio for a number of Mach numbers are weakly convex monotonically decreasing curves. In this case, a smaller ratio $k_2/k_1$ correspond to large values of relative pressure;
- graphs of the relative density and relative temperature dependences on the Mach number for a number of $k_2/k_1$ relations show that both dependences increase monotonically;
- highest values of relative pressure and density occur at $k_2/k_1 = 0.85$ and decrease with the growth of $k_2/k_1$. On the contrary, the relative temperature has the highest values at $k_2/k_1 = 1$, which decrease as $k_2/k_1$ decreases.

References

[1] Bolshinskij M I et al 2003 Gas Dynamic Phenomena in Mines (Sevastopol: Veber) p 284
[2] Cherdantsev N V et al 2017 Industrial safety 3 45–52
[3] Cherdantsev S V et al 2017 Sci. Bull. of the Center for Safety in the Coal Ind. 1 26–33
[4] Kantorovich B V 2013 Fundamentals of Theory of Combustion and Gasification of Solid Fuels (Moscow: Kniga po Trebovaniyu) p 601
[5] Cherdantsev S V et al 2018 Giab 1 117–125
[6] Cherdantsev S V et al 2017 Safety in Industry 11 10–15
[7] Cherdantsev S V et al 2018 Journal of Mining Science vol 54 issue 2 339–346
[8] Cherdantsev S V et al 2017 Chemical Physics and Mesoscopy vol 19 4 513–523
[9] Cherdantsev S V et al 2018 Ugol 1 44–49
[10] Vasiliev A A and Vasiliev V A 2016 Sci. Bull. of the Center for Safety in the Coal Ind. 2 8–39
[11] Kurlenya M V and Skritsky V A 2017 Journal of Mining Science vol 53 5 861–867
[12] Levin V A and Tunik Yu V 1987 Fizika Goreniya i Vzryva vol 23 1 3–8
[13] Stanyukovich K P 1971 Unsteady Motion of Continuous Media (Moscow: Nauka) p 856
[14] Physics of explosion 2004 L P Orlenko ed. vol 1 (Moscow: Nauka) p 832
[15] Ovsyannikov L V 2003 Lectures on the Basics of Gas Dynamics (Moscow-Izhevsk: Institute of Computer Research) p 336
[16] Vukalovich M P and Novikov I I 1972 Thermodynamics (Moscow: Mashinostroyeniye) p 672