The analysis of conditions of occurrence of the processes of deflagration and detonation in dust-laden flue gas flows workings

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Abstract. The article discusses the gas-dynamic and thermo-physical conditions of the transition in the processes of deflagration and detonation taking place in the dust-gas-air flows of mine workings near the centers of self-heating. On the basis of the classical laws of conservation of mass, momentum and energy, the formulas of the parameters of the dust-gas air flow crossing the heat supply zone are obtained. The graphs on the basis of which some conditions and regularities of the processes of chemical reaction of dust and air mixtures in the modes of deflagration and detonation are found.

1. Introduction
In recent years, the coal industry is regularly experiencing manifestations of negative factors that significantly constrain the production of coal by underground method. One of these factors is suflar and sudden gas emissions [1, 2]. Other factors include coal dust generated during the operation of mining equipment and coal self-heating centers.

Coal dust in the atmosphere of mine workings forms dust-gas-air mixtures (PARS), capable of chemical reaction [3, 4]. In the presence of ignition sources arising, for example, from the friction of the working parts of machines and tools, we can begin the process of combustion is discussed in [5, 6] with respect to the fine dust and air mixtures, and in [7] to the coarse mixtures.

Hotbeds of self-heating lead to a change in the temperature field of rocks surrounding the treatment plant [8, 9]. Rocks, having a high temperature, in turn, transmit heat to the atmosphere of mining in its local area, which will be called the heat supply zone.

Due to the increased temperature in the heat supply zone, the predisposition of dust and gas mixtures to chemical reaction significantly increases. Thus, the paper [10] shows the influence of self-heating centers on the ignition of methane-air mixture, and the paper [11] reveals the tendency of coal dust to form an explosive mixture in the atmosphere of mine workings.

Here we will discuss some conditions of the processes deflagration and detonation combustion PGS in clearing mines, depending on the gas environment in the first and second areas of excavation (figure 1) and the amount of heat \( q \), entering the atmosphere of production from the heat supply zone, due to the centers of self-heating.

It seems to us that this task is quite urgent, since its solution will allow to identify dangerous and safe conditions for the flow of dust and gas flows in the excavation areas of coal mines.
2. Problem statement and solution

Let the heat be supplied from the hearth of self-heating to some area of the treatment mine workings throughout the whole area (figure 1). The state of the dust-gas mixture will be described by its velocity \( u \), density \( \rho \), pressure \( p \) and temperature \( T \) in Kelvin, which in the first region will be provided with an index 1, and in the second region — an index 2. Find the parameters of the mixture in the region 2, if its parameters in the region 1 are known to us.

The solution of the problem will be built within the following assumptions:

1. we assume that the dust and gas mixtures are homogeneous homogeneous medium, and the heat supply zone is a narrow front, at the transition through which the parameters of the mixture can change abruptly;

2) friction of dust-gas-air mixtures on the walls of the production is neglected and we believe the mixture in its properties, close to the ideal gas with a constant specific heat;

3) the flow of dust and air mixtures in the treatment plant is considered to be stationary and one-dimensional, depending only on the coordinate directed along the production.

Since the flow of the mixture is stationary, the analysis of its state in the treatment production is convenient to perform on the basis of the fundamental laws of conservation: mass, pulses and energy [12–14], expressed respectively by the continuity equation

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

equation of pulses

\[
p_2 + \rho_2 u_2^2 = p_1 + \rho_1 u_1^2, \tag{2}
\]

the energy equation

\[
\frac{u_2^2}{2} + i_2 = \frac{u_1^2}{2} + i_1 + q, \tag{3}
\]

where the enthalpies \( i_1, i_2 \), we can determine the formula [15]

\[
i_1 = \frac{k}{k-1} \frac{p_1}{\rho_1}, \quad i_2 = \frac{k}{k-1} \frac{p_2}{\rho_2}, \tag{4}
\]

in which \( k = c_p/c_v \) is the Poisson's adiabate index and \( c_p, c_v \) are the specific heats of the dust-gas mixture, respectively, at constant pressure and at constant volume. Then everywhere the ratio of specific heats to take \( k = 1.4 \).

By virtue of the formulas (4), the energy equation (3) is rewritten as follows

\[
\frac{u_2^2}{2} + \frac{k}{k-1} \frac{p_2}{\rho_2} = \frac{u_1^2}{2} + \frac{k}{k-1} \frac{p_1}{\rho_1} + q,
\]
where do we find the ratio between the squares of velocities

$$\frac{u_2^2}{u_1^2} = 1 + \frac{1}{u_1^2} \left[ 2q - \frac{2k}{k-1} \left( \frac{P_2}{\rho_2} - \frac{P_1}{\rho_1} \right) \right]. \tag{5}$$

Next, from the continuity and momentum equations we obtain the formula

$$p_2 = p_1 + \rho_1 u_1^2 \left( 1 - \frac{u_2}{u_1} \right), \tag{6}$$

by which, formula (3) is converted to the form

$$\frac{\left( \frac{u_2}{u_1} \right)^2}{\left( \frac{u_1}{u_1} \right)^2} = 1 + \frac{2}{u_1^2} \left[ q - \frac{a_1^2}{k-1} \left( 1 - \frac{u_2}{u_1} \right) \left( M_1^2 \frac{u_2}{u_1} - 1 \right) \right], \tag{7}$$

where $a_1$ is the speed of sound in region 1 determined by the formula [13, 14]

$$a_1 = \sqrt{\frac{k}{\rho_1}}. \tag{8}$$

Note that we can Express the enthalpy of the mixture by the formula [13, 14]

$$i_i = \frac{a_1^2}{k-1} - c_p T_i \tag{9}$$

and so the formula (7) leads to the square equation

$$\frac{u_2}{u_1} = \frac{1}{(k+1)M_1^2} \left[ (M_1^2 - 1) \pm \sqrt{(M_1^2 - 1)^2 - 2(k+1)M_1^2 q} \right], \tag{10}$$

where $M_1 = u_1/a_1$ is the Mach number in the region 1, $q = c_p T_i$ — the number Damkaer, which is a dimensionless quantity supplied of heat.

Further from the continuity equation (1) follows the relation

$$\rho_2 = \frac{(k+1)M_1^2}{\rho_1 (k+1)M_1^2 - \left[ (M_1^2 - 1) \pm \sqrt{(M_1^2 - 1)^2 - 2(k+1)M_1^2 q} \right]}. \tag{11}$$

Transforming the formula (6) can be written as

$$\frac{P_2}{P_1} = 1 + kM_1^2 \left( 1 - \frac{u_2}{u_1} \right)$$

and given (10), we obtain the ratio between pressures
\[
\frac{p_2}{p_1} = 1 + \frac{k}{k+1} \left[ (M_1^2 - 1) + \sqrt{(M_1^2 - 1)^2 - 2(k+1)M_1^2 q} \right].
\] (12)

Finally, we define the Mach number \( M_2 \) in the region 2. To do this, we convert the formula \( M_2 = \frac{u_2}{a_2} \), which determines the Mach number to the form

\[
M_2 = \frac{u_2}{a_2} \cdot \frac{u_1}{a_1} \cdot \frac{a_1}{u_1} = \frac{u_2}{a_1} \cdot M_1
\]

and given the formula (8) we obtain the ratio

\[
M_2 = \frac{u_2}{u_1} \cdot \frac{p_1}{p_2} \cdot M_1,
\]

which, by virtue of formulas (10) and (12) is given to the form

\[
M_2 = \sqrt{\frac{M_1^2 - 1}{k+1} \left[ (M_1^2 - 1) + \sqrt{(M_1^2 - 1)^2 - 2(k+1)M_1^2 q} \right]}.
\] (13)

Formulas (10) — (13), Express the relationships between velocities, densities, pressures, and Mach numbers, in which the Mach number \( M_1 \) is an independent variable and the Damkeler number is a parameter.

For further reasoning, we need to establish a connection between the pressure and the density of the dust-air mixture. For this purpose, we give the formula (6) using equation (1) to the form.

\[
p_2 - p_1 = \frac{\rho_1}{\rho_2} u_1^2 (\rho_2 - \rho_1),
\] (14)

where we get

\[
u_1^2 = \frac{p_2 - p_1}{\rho_2 - \rho_1} \cdot \frac{\rho_2}{\rho_1},
\] (15)

again, using equation (1) we find

\[
u_2^2 = \frac{p_2 - p_1}{\rho_2 - \rho_1} \cdot \frac{\rho_2}{\rho_1}.
\] (16)

Substituting the formulas (15) and (16) into the energy equation (3), we obtain the equation

\[
i_2 - i_1 = q + \frac{1}{2} \frac{(\rho_2 + \rho_1)}{\rho_1 \rho_2} (p_2 - p_1),
\] (17)

which with the help of formulas (4) and (9) we give the form

\[
\frac{2k}{k-1} \left( \frac{p_2}{\rho_1} - 1 \right) = \frac{2qk}{c_p T_1 (k-1)} + \left( 1 + \frac{\rho_1}{\rho_2} \right) \left( \frac{p_2}{\rho_1} - 1 \right),
\]

and after the transformation we get the formula
expressing the relationship between the pressures and densities of the dust-air mixture in different areas of mountain development. If \( \overline{q} = 0 \), then (18) becomes the formula shows that Hugoniot adiabatic \[12–16\].

Given that the densities and specific volumes are related by the relations \( \rho_1 = 1/V_1 \), \( \rho_2 = 1/V_2 \), we give the equation (18) to a more convenient form

\[
\overline{p}_2 = \frac{k + 1}{k - 1} \frac{\rho_1}{\rho_2} + \frac{2k}{k - 1} \overline{q},
\]

(19)

where the relative pressure \( \overline{p}_2 \) and relative specific volume \( \overline{V}_2 \) are determined by the formulas

\[
\overline{p}_2 = p_2 / p_1, \quad \overline{V}_2 = V_2 / V_1.
\]

The formula (19) defines the possible parameters \( \overline{p}_2 \) and \( \overline{V}_2 \) mixtures that can be obtained from some initial thermodynamic state, the pressure \( p_1 \) and the specific volume \( V_1 \) of which are known.

However, we note that the required parameters \( \overline{p}_2 \) and \( \overline{V}_2 \) must satisfy the additional condition that we get from equality (14), transforming it to the form

\[
\frac{p_2 - p_1}{V_1 - V_2} = \rho_1^2 u_1^2.
\]

(21)

Since the value \( \rho_1^2 u_1^2 > 0 \), then the left part of equality (21) is also positive and therefore we have come to inequality

\[
\frac{p_2 - p_1}{V_1 - V_2} > 0,
\]

(22)

which takes place only when

\[
p_2 - p_1 > 0, \quad V_1 - V_2 > 0 \quad \text{or} \quad p_2 - p_1 < 0, \quad V_1 - V_2 < 0.
\]

(23)

The first two inequalities (23) mean the presence of a shock wave, since the pressure behind the shock wave front \( p_2 \) is greater than before the front \( p_1 \), i.e. \( p_2 > p_1 \), and the specific volume \( V_2 \), on the contrary, is less than \( V_1 \). The second two inequalities show the presence of a rarefaction wave, since the inequality implies that \( p_2 < p_1 \), and \( V_2 > V_1 \). Therefore, the combination of values \( \overline{p}_2 \) and \( \overline{V}_2 \) obtained from formula (19) and not satisfying inequality (22) should be excluded from consideration.

According to the formula (19), graphs of the function \( \overline{p}_2(\overline{V}_2) \) characterizing the possible thermodynamic states that can be achieved with a certain supply of the rafts are constructed \( \overline{q} \) (figure 2). On the graphs, dashed lines show the intervals of values \( \overline{p}_2 \) and \( \overline{V}_2 \), which do not satisfy the condition (22) and, therefore, at these intervals, there is a non-stationary flow of the dust-gas-air mixture.
3. Analysis of the results

Analyzing graphs (figure 2), we note, firstly, with the increase in the number Damkaer characterizing the supply of heat, the graphics shifted to the side of the big $\bar{q}$. Second, the larger the number Damkaer, the longer the dotted areas on the charts of $A_iB_i$, values $\bar{p}_2$, $\bar{V}_2$ that do not satisfy the condition (22). Consequently, all graphs for which the number Damkaer $\bar{q} \neq 0$ consist of two branches, separated by dashed lines.

![Figure 2. Graphs of pressure dependences $\bar{p}_2$ on the specific volume $\bar{V}_2$ of dust-gas mixture for Damkaer numbers $\bar{q}$.

To reveal the thermodynamic and mechanical conditions on each of the branches, we transform the formula (21) first to equality

$$\bar{p}_2 = 1 + kM_1^2(1 - \bar{V}_2),$$

expressing the linear relationship of pressure and specific volume, and then to the formula

$$\frac{\bar{p}_2 - 1}{1 - \bar{V}_2} = kM_1^2.$$  

Analysis of the formula (25) allows us to make the following conclusions. On the upper branch of the hyperbola $\bar{p}_2 > 1$, $\bar{V}_2 < 1$ and therefore from (25) it follows that $M_1 > 1$. On the lower branch $\bar{p}_2 < 1$, $\bar{V}_2 > 1$, and therefore $M_1 < 1$.

Thus, we came to the conclusion that the motion of the dust-gas-air mixture decays into a supersonic flow ($M_1 > 1$), and subsonic ($M_1 < 1$).

Continuing the analysis of the graphs (figure 2), we note that at supersonic flow ($M_1 > 1$) the pressure $\bar{p}_2$ and density $\bar{p}_2$ in the dust-gas mixture always increase, and the specific volume $\bar{V}_2$ decreases. On the contrary, at the subsonic flow of the mixture ($M_1 < 1$), the pressure and density...
always decrease, and the specific volume increases. This is the fundamental difference between supersonic and subsonic heat supply.

In general, for a given Mach number $M_1$ to determine the parameters of the mixture should use the formulas (10)—(13), each of which gives two values of the mixture. Based on the foregoing, let us consider the determination of the mixture parameters and perform analysis of her condition for the number Damkaer $\overline{q} = 0.5$. Let’s start with the analysis of the mixture parameters at point $B_3$ (figure 3).

![Figure 3](image)

**Figure 3.** To the analysis of gas-dynamic conditions of various combustion modes dust-laden flue gas mixture in the atmosphere of mine workings

The graph shows that at the point $\overline{V}_2 = 1$, and the pressure we determine by the formula (19)

$$
\overline{p}_{2(B_3)} = \frac{k + 1}{k - 1} + \frac{2k}{k - 1} \cdot \overline{q} = 1 + k \cdot \overline{q}.
$$

(26)

Next, we define the Mach number $M_1$ from equality (10), since $u_2/u_1 = \rho_1/\rho_2 = V_2/V_1 = \overline{V}_2$. Since the relative specific volume $\overline{V}_2 = 1$, then (10) is reduced to equality

$$
1 \pm \sqrt{1 - 2 \left(\frac{k + 1}{k - 1} \cdot \overline{q} \cdot (M_1^2 - 1)^2\right)} = 0,
$$

(27)

which is identically satisfied either at $M_1 \to \infty$ or $M_1 = 0$, and only when in equality (27) there is a minus sign. Since the point $B_3$ is in the supersonic region, the Mach number $M_1$ can not be zero, so $M_1 \to \infty$, which means an infinitely high speed $u_1$. Therefore, at the mixture parameters corresponding to the point $B_3$, the process of deflagration, i.e. slow combustion, cannot occur combustion.
Next, we find the parameters of the mixture at the point $A_3$, in which $\bar{p}_2 = 1$, and the specific volume is found by the formula (19)

$$\bar{V}_2 \big|_{\bar{p}_2=1} = 1 + \bar{q}.$$  \hspace{1cm} (28)

The number $M_1$ is found by the formula (12), which is $\bar{p}_2 = 1$ reduced to equality

$$1 \pm \sqrt{1 - \frac{2(k+1)M_1^2 \cdot \bar{q}}{(M_1^2 - 1)^2}} = 0,$$

coinciding with equality (27), which is true in $M_1 \to \infty$ or $M_1 = 0$ and provided that takes into account a negative sign. Since the point $A_3$ is in the subsonic region, the only value of the Mach number is $M_1 = 0$ and therefore $u_1 \approx 0$. This means that when the parameters of the mixture $\bar{p}_2 = 1$, $\bar{V}_2 = 1 + \bar{q}$, a process of deflagration, i.e. a slow combustion in which the mixture velocity $u_1 \approx 0$.

In the description of the state of the dust-gas mixture, the points $C$ and $J$ (figure 3), which are the points of contact of the line (24) to the graph of the function (19), are of particular importance. We will find the coordinates of these points from the equation

$$\frac{k+1}{k-1} \bar{V}_2 + \frac{2k}{k-1} \cdot \bar{q} = \left[1 + kM_1^2 (1 - \bar{V}_2)\right] \left(\frac{k+1}{k-1} \bar{V}_2 - 1\right),$$  \hspace{1cm} (29)

formed by equating the right-hand sides of formulas (19) and (24). After performing the (29) transformation, we obtain a square equation

$$\bar{V}_2^2 - b \cdot \bar{V}_2 + c = 0,$$  \hspace{1cm} (30)

in which the coefficients $b$ and $c$ are equal

$$b = \frac{2(1 + kM_1^2)}{M_1^2(k+1)}, \quad c = \frac{2(\bar{q}+1) + M_1^2(k-1)}{M_1^2(k+1)},$$

a roots are determined by the formulas

$$\bar{V}_2 = \frac{(1 + kM_1^2)}{M_1^2(k+1)} \pm \sqrt{\left(\frac{1 + kM_1^2}{M_1^2(k+1)}\right)^2 \frac{2(\bar{q}+1) + M_1^2(k-1)}{M_1^2(k+1)}}.$$  \hspace{1cm} (31)

Since the tangent point is defined in a single way, the value $\bar{V}_2$ has a single value if the expression under the radical sign is zero:

$$\frac{(1 + kM_1^2)^2}{M_1^2(k+1)} \left[\frac{2(\bar{q}+1) + M_1^2(k-1)}{M_1^2(k+1)}\right] = 0,$$  \hspace{1cm} (32)

therefore, the desired value is found by the formula

$$\bar{V}_2 = \frac{(1 + kM_1^2)}{M_1^2(k+1)},$$  \hspace{1cm} (33)

and the unknown Mach number $M_1$ is determined from the equation
\[(1 + kM_1^2)^2 - [2(\bar{q} + 1) + M_1^2(k - 1)]M_1^2(k + 1) = 0,\]  
(34)

arising from (32).

The roots of the equation (34) are found by the formula

\[M_1 = \sqrt{1 + \bar{q}(k + 1) \left(1 \pm \sqrt{1 + \frac{2}{\bar{q}(k + 1)}}\right)},\]  
(35)

which, if \(\bar{q} = 0.5\), \(k = 1.4\) equal \(M_{1(C)} = 2.04\); \(M_{1(J)} = 0.49\). Next, the formula (33) determine \(\bar{p}_{2(C)} = 2.843\), \(\bar{p}_{2(J)} = 0.557\). The values obtained are shown in figure 3.

Substituting alternately found values \(M_{1(C)}\) and \(M_{1(J)}\) in the formula (13) and considering it first sign “plus” and then “minus”, we get \(M_2 = 1\). Thus, the dust-air mixture with the parameters \(\bar{q} = 0.5\), \(k = 1.4\), \(M_{1(C)} = 2.04\) и \(M_{1(J)} = 0.49\), corresponding to points \(C\) and \(J\) (figure 3), moves behind the reaction front at a speed equal to the local speed of sound. Points \(C\) and \(J\) are called respectively the upper and lower points of Chapman – Jouge [14].

Find the Mach number \(M_1\) at points \(C_1\) and \(C_2\) in the vicinity of point \(C\) (figure 3). The relative pressures at these points are equal \(\bar{p}_{2(C_1)} = 3.0; \bar{p}_{2(C_2)} = 2.5\). Substituting in formula (12) first \(\bar{p}_{2(C_1)}\), and then \(\bar{p}_{2(C_2)}\), get two equations

\[\bar{p}_{2(C_1)} = 1 + \frac{k}{k + 1} \left[ (M_{1(C)}^2 - 1) + \sqrt{(M_{1(C)}^2 - 1)^2 - 2(k + 1)M_{1(C)}^2\bar{q}} \right],\]  
(36)

\[\bar{p}_{2(C_2)} = 1 + \frac{k}{k + 1} \left[ (M_{1(C)}^2 - 1) - \sqrt{(M_{1(C)}^2 - 1)^2 - 2(k + 1)M_{1(C)}^2\bar{q}} \right],\]  
(37)

each of which has only one real root: \(M_{1(C)} = 2.044\), \(M_{1(C)} = 2.07\). Thus in the equation (36) the plus sign is accepted, and in the equation (37) – minus. Otherwise, these equations have no real roots.

Comparing the results obtained, we note that at point \(C\) the Mach number \(M_1\) is minimal, i.e. \(M_{1(C)} = M_{1,min} = 2.04\) on the supersonic branch of the graph (figure 3), and this is another feature of the mixture parameters at point \(C\).

Find the Mach number \(M_2\) behind the reaction front at \(C_1\) using the formula (13). Substituting the value in it \(M_{1(C)} = 2.044\), get \(M_{2(C)} = 0.954\). For points even higher than \(C_1\), the Mach number \(M_2\) decreases. Thus, the motion of the mixture behind the front of the reaction on the supersonic branch above the point \(C\) is subsonic.

From the above it is easy to understand that before the front of the reaction in the supersonic region there is an adiabatic shock wave, which is able to cause a fast chemical reaction in the form of detonation. The chemical reaction process at point \(C\) can be considered a limiting case.

Substituting the formula (13) value \(M_{1(C)} = 2.07\), get \(M_{2(C)} = 1.133\). For points below \(C_2\), the Mach number \(M_2\) increases. Thus, on the \(B_3C\) segment of the graph behind the reaction front, there is a supersonic velocity. And so on this segment takes place supersonic combustion, which is a non-impact the supply of heat at supersonic speed.

Performing similar calculations at the points \(J_1\) and \(J_2\) in the vicinity of the point \(J\), we find \(M_{1(J)} = 0.455\), \(M_{1(J)} = 0.488\). Therefore, at point \(J\), the Mach number \(M_1\) is the maximum \(M_{1(J)} = M_{1,max} = 0.49\) on the subsonic branch \((M_1 < 1)\) of the graph (figure 3). And the Mach numbers behind the reaction front obtained by the formula (13) are, respectively, equal to \(M_{2(J)} = 0.718\), \(M_{2(J)} = 1.092\) and therefore, the flow of the mixture behind the reaction front at the points \(J_1\)
subsonic, and at the point $J_2$ supersonic. Therefore, in the $JA_3$ area the chemical reaction takes the form of normal combustion (deflagration), which is especially characteristic of the point $A_3$, where $M_1 = 0$, $\bar{p}_2 = 1$. And on the plot below the point $J$, the mixture behind the reaction front is accelerated to supersonic speed. Since $M_1 < 1$, and $M_2 > 1$, then $u_2 > u_1$ and, therefore, in this section of the graph there is a vacuum. As shown in [14] under these conditions, the chemical reaction is practically impossible.

Thus, we discussed possible scenarios of the course of the chemical reactions in the dust-laden flue gas mixture moving in mine workings close to the foci to minimize self-heating of.

4. Conclusions

Analysis of the formulas and graphs showed:

- the greater the number of Damkaer characterizing the heat supply, the longer the areas on the graphs of the relative pressure of the mixture from its specific volume, which are not satisfied with the conditions of the steady flow of mixtures;
- depending on the gas-dynamic conditions of the stationary flow of dust-gas mixtures, there are four variants of the chemical reaction of mixtures:
  a) at the front of the chemical reaction, the Mach number $M_1 > 1$, and behind the front it $M_2 < 1$, which causes the appearance of a strong shock wave and the transition of the reaction to the detonation mode;
  b) at the front and behind the reaction front of the Mach number $M_1 > 1$, $M_2 > 1$ and therefore there is a supersonic combustion of dust-gas mixtures, without the appearance of a shock wave;
  c) at the front and behind the reaction front of the Mach number $M_1 < 1$, $M_2 < 1$ and therefore the reaction proceeds in the form of deflagration, i.e. normal combustion;
  d) at the front of the reaction $M_1 < 1$, and behind the front $M_2 > 1$, whereby behind the front of the reaction there is a vacuum, which excludes the condition of the chemical reaction.

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