ON MODELING OF SHOCK WAVES INTERACTIONS WITH COMBUSTIBLE DUSTY GAS LAYERS

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Abstract

Numerical methods were developed to solve the considered problems. The following results of calculations are presented: Dust entrainment and dispersion from a dense layers behind propagating shock wave; Interaction of dust clouds, Ignition and combustion of resulting dusty/gas mixtures.

Introduction

The physical processes of coal dust/air mixtures motion, ignition and combustion behind propagating shock waves are numerically studied in the paper. These processes take place during explosion in coalmines. Many theoretical and experimental works were devoted to various aspects of arising problems. Nevertheless the large-scale processes were not studied enough. The author's previous results were published in papers [1-4]. It is supposed that dust particles are solid spheres. The perfect gas model is used for gaseous phase and Navier-Stokes description for laminar flow of the gas is adopted. The physical laws of mass and energy conservation, diffusion with chemical reactions and momentum variation for the two phases give us the system of equation of the total model under consideration. The developed numerical methods include implicit and explicit schemes and based on splitting technique. In the paper we focus on two aspects of considered topic: Dust entrainment and dispersion from layers, Ignition and combustion of the formed mixture.

It is well known that the pressure wave induced by gas explosion in the coal mine, disperses coal dust from walls of the mine into the gas stream and forms an explosive dust cloud. In spite of this problem has been intensively investigated by many scientists, there is no complete clearness so far in the question what mechanism is mostly responsible for intensive lift of the particles from the layer. In this paper we make attempt to simulate the particle lift and dispersion by taking into account lifting forces due to particle rotation (Magnus force) and gas phase vorticity, and we show that these effects can essentially affect on the flow pattern after shock wave resulting in fast dust entrainment and dispersion from the dust layers.

Background

The medium considered is supposed to be a mixture of a gas and small solid particles, where both the gas phase and the solid phase consist of a number of components in general case. So, the mass composition of the mixture is described by the gas phase density ρ_1 and the particles phase density ρ_2, there are a number of species in the gas phase, and a number of species in the solid phase.

Conservation of mass for components of the gas and solid phase is used where components of velocity vectors, mass flux due to diffusion in the gas phase, mass source of components due to reactions in the gas and solid phases, and discharging of gases from the particles (so called volatiles) as well as mass exchange between phases are included.

Conservation of momentum for the components is described by the usual manner and we used viscous stress tensor, pressure p, the interphase force, Magnus force**,** Saffman force (near walls). Navier–Stokes model is used for the gas phase.

Equations of energy are also written for the phases. They include total energy, the enthalpy, heat flux vector , viscous dissipation , interface heat flux, and the chemical energy due to burning of particles and volatiles. The equations mensioned above are well known and do not presented here (See, for example, [2,4).

These equations are closed by thermodynamic relations and include internal energy, temperature T, gas constants, specific heats for gas components and the particle specific heat.

The interface interaction is defined by the drag force **F** and convective and radiation heat fluxes Q_T and Q_R. The values of **F** and Q_T are taken in common form as:

$$\mathbf{F} = n\frac{\pi d^2}{8}C_D\rho_1\left|\mathbf{u}_1-\mathbf{u}_2\right|(\mathbf{u}_1-\mathbf{u}_2)\ , \quad Q_T = n\pi d\lambda_1 Nu(T_1-T_2) \tag{1}$$

where **u** is velocity, n the number density of particles, d a diameter, λ_1 the thermal conductivity for the gas phase, and C_D and Nu are calculated by an empirical functions of relative Reynolds number and the Prandtl number:

Except of the drag force **F** there is another that, the Magnus force, which is caused by rotation of particles. It was found that this force is of importance for understanding the mechanism of particles entrainment and dispersion. In what follows we assume that each particle involves in the rotation by gas vorticity and the angle rotation velocity is proportional to the gas vorticity. Under this assumption the Magnus force per one particle can be written as

$$\mathbf{f_M} = K_M \frac{d^3}{8} \rho_1 [(\mathbf{u}_1 - \mathbf{u}_2) \times rot\mathbf{u}_1] \qquad (2)$$

where K_M is a dimensionless coefficient, the value of which can't be derived analytically and should be assessed experimentally. Some estimation carried out by computational experiment shows that this value varies in the limits of several tenths to 100. The Saffman force and gas pressure gradient are also important for the particles lifting process (Saffman [6] Borisov at al [8]). The Saffman force has the form

$$f^* = K_{saf}(u_1 - u_2)\sqrt{\left|\partial u / \partial n\right|}\ x\,\boldsymbol{j} \qquad (3).$$

where ***j*** is unit vector of the wall surface normal ***n.*** It have to be taken into account in shear flow . For the sake of simplification we usually do not include in the model the Saffman force but it is responsible for the dust particles starting motion near a wall .

The radiation part of the interface heat flux Q_R is calculated in a simple way as:

$$Q_R = \sigma_B \varepsilon_1 T_1^4 + q_{1e}$$

where ε_1 (0<ε_1<1) is an empirical coefficient, and q_{1e} is the radiant flux due to external sources (hot walls, sparks, etc).

For the sake of simplicity we use the diffusion approximation for radiation transfer, and split total radiation flux into two parts, one of which is for the gas phase, $\mathbf{q}_{1,R}$, and the other for the particle medium, $\mathbf{q}_{2,R}$. We consider the first under the approximation of Plank for gray body, while for the second, the Rosseland approximation for optically thick case is is used.

The mass interchange terms in the equations are describe by a kinetic model in each concrete case considered, which includes complete set of chemical reactions and physical processes resulted in the mass exchange (ex., devolatilization). In the paper, the gas phase is considered consisting of 3 components: an inert gas, an oxidant, and volatiles extracted from particles. The particle phase cosist of a solid state component and the volatiles lying inside the particles. The mass interchange terms in eqs. are simply defined through the reaction rates $\dot{K}$ and $\dot{R}$ for describing the burning of particles and volatiles, respectively, and the rate of volatiles release in the gas phase from the particles $\dot{W}$. The rates of volatiles burning $\dot{R}$ and W ares described by the Arrenius laws (for the case of laminar flow), while the rate of particle burning $\dot{K}$ is calculated as follows:

$$\dot{K} = A_s (R_s^{-1} + R_d^{-1})^{-1} \qquad (4)$$

where R_s is the surface reaction rate and R_d is the diffusion reaction rate. The parameter A_s is a form factor.

Initial and boundary conditions have to be also formulated for problems considered below.

Numerical algorithms. Numerical approaches have been developed to integrate the equations mentioned above. One is based on the principle of physical and geometrical splitting of spatial differential operators for the equations . This approach was discussed in our works [1-3]. The developed algorithm has the first order of accuracy for time and space variables. It is applied to calculate the problem of ignition and burning of the dusty mixture behind shock waves (problem 3, see below). The other approach includes explicit-implicit time integration of the equations and linearization of spatial discrete operator by using splitting technique[5]. This method is applied to calculate the problem of dust entrainment and dispersion behind a shock wave propagated along a channel . A variant of the Godunov method is also used.

Problem considered

Initiation and propagation of a shock wave is considered in a rectilinear gallery filled with air and small coal particles. The gallery geometry and initial distribution of coal particles are schematically given in Fig. 1. The gallery height *H* is 2.m. Dust is placed in the layers along the gallery

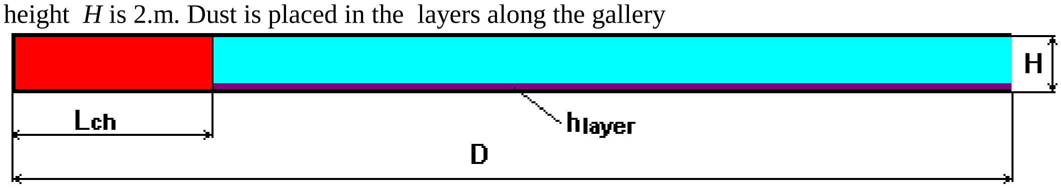

Fig.1 .Scheme of initial geometry and dust distribution along gallery;

The shock wave initiation in this problem: by the detonation wave in the methane/air stoicheametric mixture or by a shock from compressed gas domain , which occupies a zone of 1-3 m near the closed end of the gallery (Fig. 1). The heat flux at walls of the gallery is modelled with the following relation: $q_w = a(T_1 - T_w)$, where T_w is the wall temperature which is equal to 293 K° everywhere in the gallery except of the closed end, the temperature of which may be varied with time. The parameter *a* is varied in calculations in limits from 0 (adiabatic wall) to 10 kg/sec^3/K° .Dust initial parameters are as follows: the diameter d=50 mkm, mass fraction of volatiles α_{vol} = 0.26-45, the average mass density in the layers ρ_{20} = 3.5 - 500 kg/m^3.

Problem 1 The problem concerning shock wave/dusty layer interaction is considered. The shock wave is initiated by a highly compressed volume ($\Delta P = \Delta T_1 = 10$), P=p/p*, T=T1/T*; p*, T* are initial pressure and temperature) placed near the closed end of a rectilinear canal at initial time moment t=0. This shock wave propagates along the canal where dust of small coal particles is congregated on the bottom (or the top) wall of the canal in narrow. layer with the thickness h_{llayer}=0.03H, where H is the thickness of the canal, that is taken equal 2 m. The average particle density in the layer is 0.5 g/cm^3. There are no coal particles in the canal, except of the layers, at t=0. Calculations were carried out with the coefficient K_M =0 (no Magnus force), 20 and 85.
With no Magnus force (K_M =0) calculations show that no any essential dust entrainment and dispersion from the dust layers occurs behind the shock wave. The thickness of the layer is slightly increased. On the other hand, with taking into account the Magnus force, the flow pattern behind the shock wave becomes quite different resulting in fast dust entrainment and dispersion of particles.

Fig2. Interaction of gas flow with dust layer. Density distribution. *Km*=20, bottom case of the layer, h=3cm, density scale in kg/m3, distance along wall in meters, shock waves at 10 m.

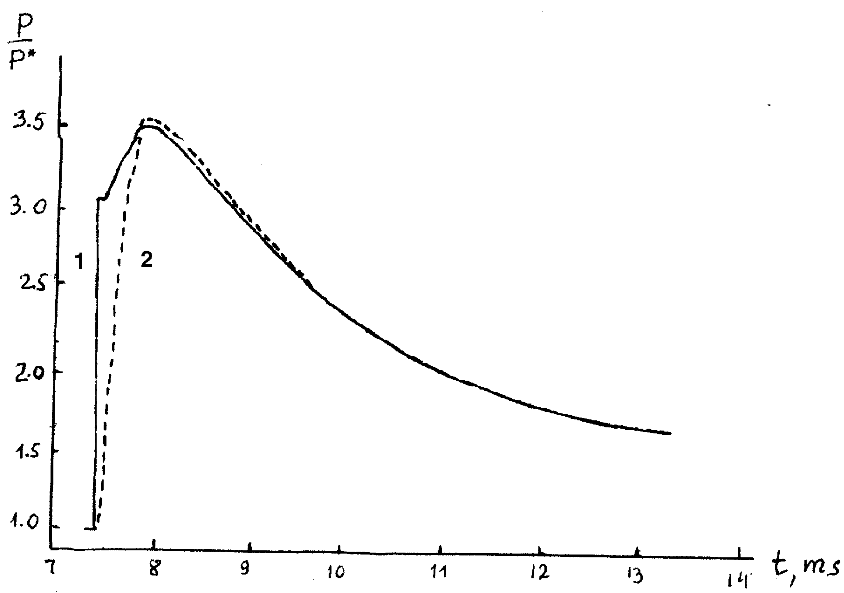

Fig.3 Pressure-time dependence at points for x=7 near the gallery bottom: 1) y=1cm, 2) y=0 cm.

The result of the calculation is shown in Figure2, where isolines of the particle density are given for the distance of the shock of 10m from the closed end. These pictures single out the shape of dispersed dust cloud, which demonstrates that due to Magnus force effect particles in the dust layer can fast disperse from the layer behind shock wave and fill in the whole of the canal.This corresponds to the dust entrainment phenomenon observed in numerous experiments. We note here that smaller number of *Km* and initial dust density in the layer about 0.6-1.0 g/cm3 can be used in the calculations.
Pressure-time relations at distance of *x= 7m* from the close end , inside of layer (*y=0, y=h/2 , h=0.02m*) shown in the Figure3, for the case of H=2m, dust layer density 0.6g/cm3, initial high pressure region length 2m (*o<x<2m*)

with pressure 11bars, Km=20; initial pressure in tube is 1bar. These dependences of pressure on time qualitatively correspond to those for small- scale experiments [7-9].

Problem 2. The case of two layers . There are two layers: at upper and on lower walls with equal initial parametrs (h=3cm).

Distribution of solid phase density and temperature in tube of 1m. heigt are presented in the Figure4, Km=20, initial density of two layers is 500kg per cubic meter for one position of shock wave (11 m).

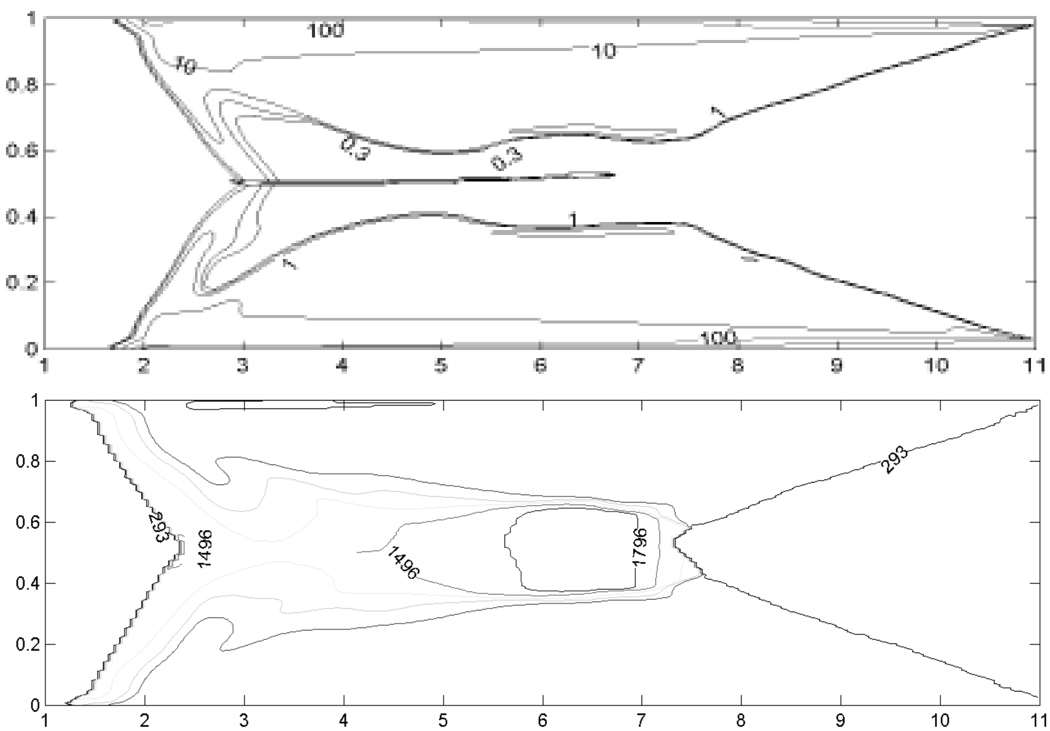

Fig4. Isolines of particles density, kg/m3, and temperature, K. The case of two layers**.**

It is clear from these graphics that ignitions and combustion of volatile and coal particles have to occur .

Problem3.Combustion behind shock wave over dust layer: It is clear that becouse of high temperature, ignition and combustion of volatile (CH_4) and coal particles have to occur . To calculate the combustion process we use laws for reactions which were mentioned above. The isolines of gaseous combustion product density is presented in Figure 5 (light-gray places are combustion regions)

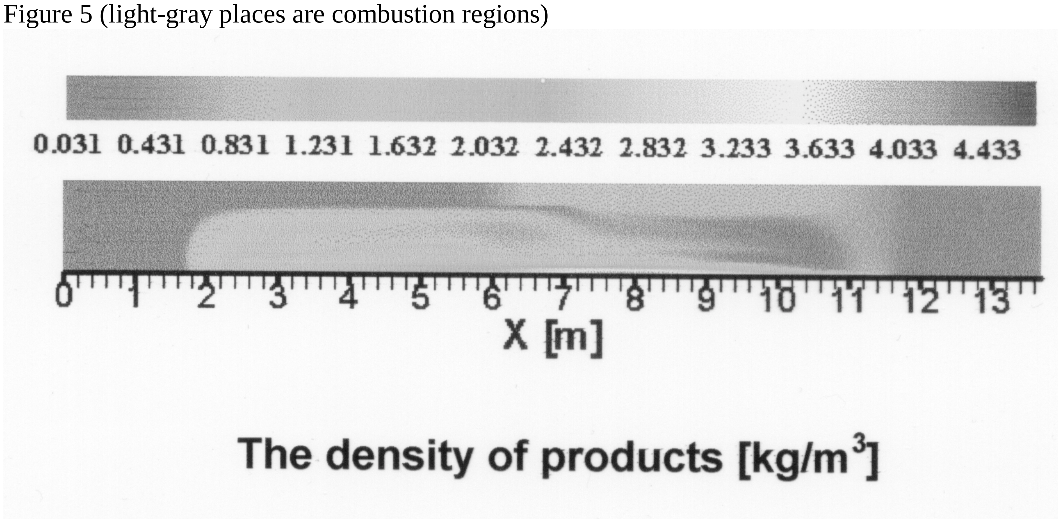

Fig5. Domain of combustion products, density of the products, kg/m3 (H=2m, h=0,06), Lch=2m.

Some details of combuston process are presented below according to the calculations by the variant of Gonunov method developed recently by P.Kosinski. The results of the numerical modeling are given in Figures 6,7.

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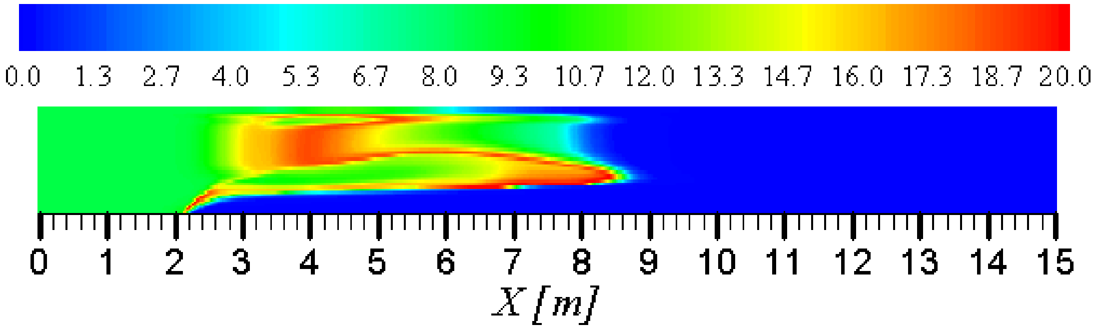

Fig6 Combustion of volatiles-air mixture, Lch=2m, h=0.06 m, Mass fraction of carbon dioxide [%].

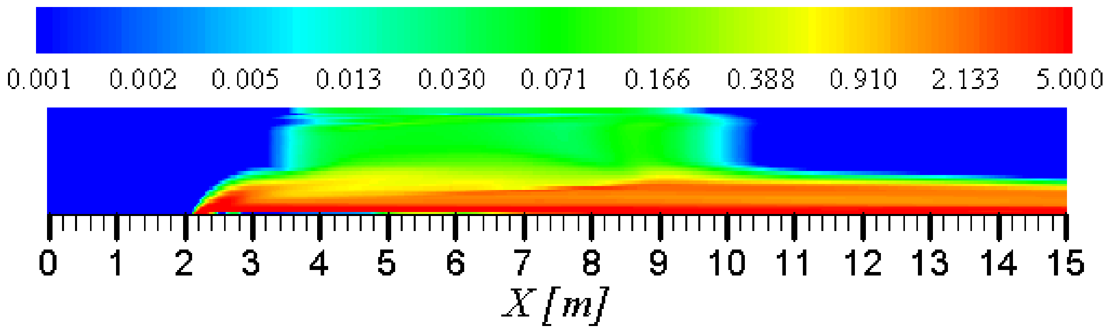

Fig7 Solid phase parameters, Lch=2m; Density of carbon in the particles [kg/m^3], Combustion of carbon.

Conclusions

Numerical methods are derived and applied to several unsteady problems for layers dispersion and interaction behind propagating shock waves. The problem on lifting and dispersing of dust layer as well as dust stream interacting is numerically investigated. The influences of vorticity in gas and particles rotation on the dispersion were figured out. The initiation of combustion by local explosion is numerically studied. The results of calculation of dusty gas combustion behind shock wave are demonstrated. These results qualitativly correspond to experiments in shock tube. Three-dimension calculations and comparisons with apropriate experiments are planned in future investigation.

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