INITIATION OF DETONATION BY SHOCK WAVES IN LONG TUBE WITH THIN DUST LAYERS.

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Introduction.

The processes of dust/air mixtures motion, ignition, combustion and detonation behind propagating shock waves in a tube are studied. These processes take place, for example, in shock tube experiments and some times in coalmines explosions. We focus in the paper on the cases of dust layers on tube walls. Many theoretical and experimental works were devoted to various aspects of arising problems. From the other side detonation in gas/liquid film system was also studied [1]. Nevertheless the processes of layer detonation formation with combustible dust layers are not yet studied. The author's previous results were published in the paper [2]. It is supposed solid particles are spheres with volatiles. The perfect gas model is used for gaseous phase and Navier-Stokes description for the flow of the phase 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 equations of the total model under consideration. Mathematical modeling methods are used for the study. A variant of finite volume method was developed and used for calculations. In the paper we focus on initiating of combustion and transition to detonation. We simulate the particle lift and dispersion by taking into account lifting forces due to particle rotation and gas phase vorticity (Magnus' and Saffman' forces). Volatiles realizing from particles as well as combustion processes with two scales (in time) chemical reactions are analytically and numerically studied. Explosion in long (up to 400 meters) coal mine gallery and shock tube experiments are numerically investigated as examples. Results related to two-dimensional structure of combustion in the duct and to transition of burning to quasi-detonation are discussed. It was found that there is qualitative agreement of the results with experiments [5, 6].

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. Navier-Stokes description for the flow of the gas phase and Euler model with null pressure for the solid phase is adopted. The interface interaction is defined by the drag force **F** and convective and radiation heat fluxs Q_T and Q_R. The values of **F** , Q_T and Q_R are taken in common forms including the number density of particles, diameter, effective (with heat conductivity and radiation heating) thermal conductivity for the gas phase, etc. Except of the drag force there is another force, the Magnus force, which is caused by rotation of particles. It was found that this force is important for the mechanism of particle entrainment and dispersion. The Saffman force and gas pressure gradient are also important for the particles lifting process. They are responsible for the dust particles starting motion near a wall. The Magnus and Saffman forces per one particle can be written as:

$$\mathbf{f}_M = K_M \frac{d^3}{8}\rho_1[(\mathbf{u}_1 - \mathbf{u}_2)\times rot\mathbf{u}_1] \quad , \quad \mathbf{f}_{saf} = K_{saf} d^2(\mu\,\rho_1)^{1/2}\left(\frac{\partial u_{1,1}}{\partial y} \Big/ \sqrt{\left|\frac{\partial u_{1,1}}{\partial y}\right|}\right)(u_{1,1} - u_{2,1})\mathbf{j}$$

where K_M , K_{saf} are a dimensionless coefficients, the values of which can't be derived analytically and should be assessed experimentally. The theoretically estimation shows that the coefficients are in range from 0.3-25.0. We use the diffusion approximation for radiation transfer, and split total radiation flux into two parts, one of which is for the gas phase and the other for the particle medium. The mass flux due to diffusion in the gas phase is defined as usual by proportional to gradient of spicy concentrations. The mass interchange terms in the equations are defined by a kinetic model in each concrete case considered. Initial and boundary conditions have to be also formulated for problems considered below. Numerical algorithms are based on the principle of physical and geometrical splitting of spatial differential operators of used equations. This approach was discussed in our works [2 - 4]. We used also approach based on finite volume method and include explicit-implicit time integration of the spatial differential equations [4]. The fractional time steps way jointly with Gear's scheme were used to include solution of the stiff kinetic equations in the numerical algorithm. This finite-difference method is applied to calculate the problems of dispersion and combustion.

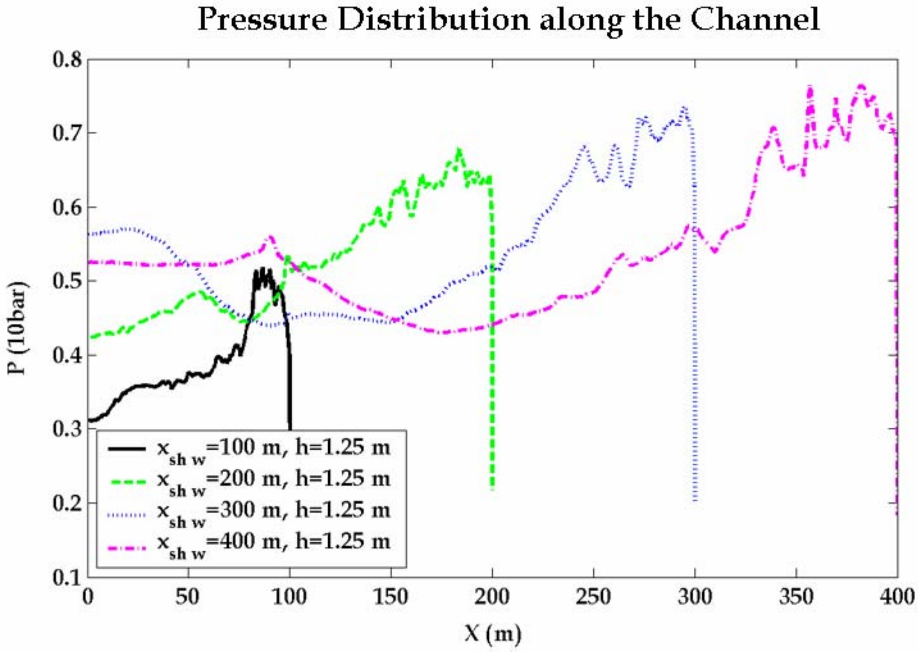
Initiation and development of quasi-detonation.

Bellow we consider the examples of shock waves and combustion initiations and their propagation in a rectilinear (planar) gallery, round long tube and shock tube. They are filled with air and small coal particles on the walls. The thickness of the dust layer h is less or equal 1 cm. The length of tube is L>>H or R. Here H is the gallery height and R is radius of the tube.

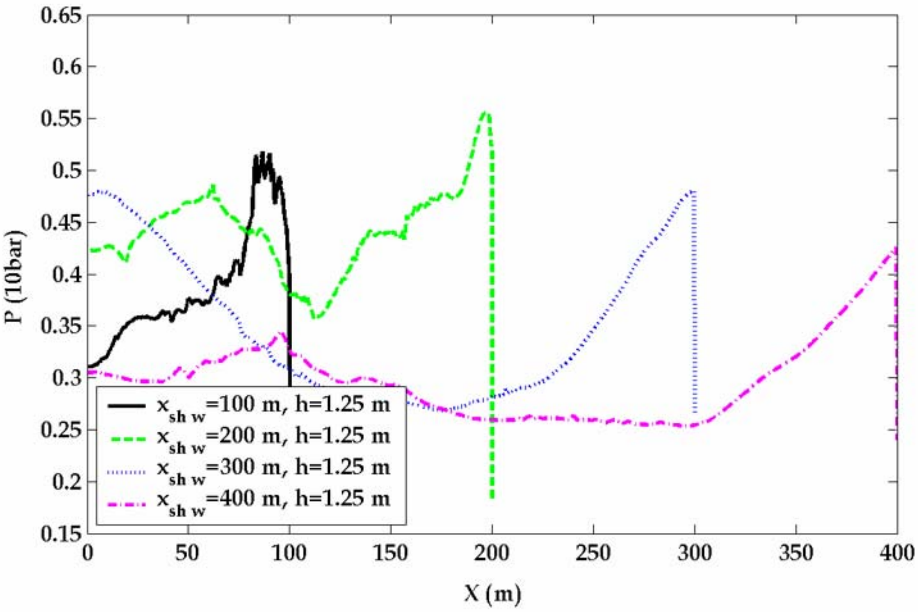
A) First of all, we consider the case of explosion in coal mine gallery, which is simulated by plane tunnel. The gallery height H = 2.5 m. Dust is placed in two layers along the gallery ("top" and "bottom" walls) to the distance of 400 m or less from the closed end of the gallery. The shock wave in tunnel is initiated by the detonation wave in the methane/air stoichiometric mixture, which occupies a zone L_{ch} near the closed end of the gallery. There are two dust layers along the gallery (h_1=h_2=1 cm, H=2.5 m, L_{ch}=6.6 m, h is thickness of layers, L_{ch} - the zone length). We suppose that influence of side walls on the physical processes in middle part of the gallery is not important. Dust initial parameters are as follows: the diameter d=60 mkm, mass fraction of volatiles α_{vol} = 0.37, the average mass density in the layers ρ_2^* = 300 – 500 kg/m^3. These parameters are corresponded by explosions in experimental mine "Barbara". The results of numerical solution are given in Figures 1(a,b), 2.

B) Propagation of shock wave due to detonation of methane-air mixture at closed end of the round tube was considered as the second example. The result of explosion development is presented on the Figure 3. We can see from this figure that distribution of the pressure along the tube behind shock wave for different time moments have non monotonic complicated character. It's due to ignition of volatile and coal particles as well as transfers shock waves propagating between walls. At the distance for shock wave of 300 m there are three peaks of the pressure profile because the coal particles begin intensively burning. Thus it's clear that at this distances we have know any quasi-steady detonation for round tube.

C) The shock tube problem [5] was also considered, but it isn't discussed here.



a



b

Figure 1. Pressure profiles for different leading shock wave positions. a) dust until 400 m, detonation case, b) dust until 110 m, no detonation.

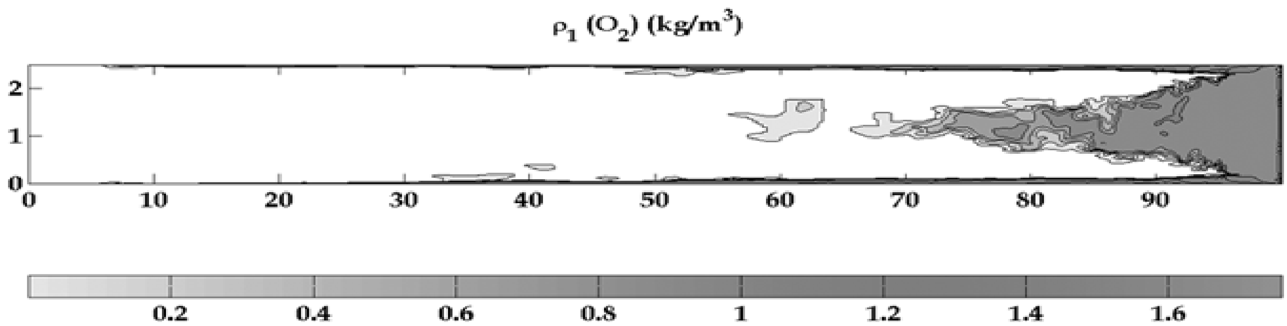


Figure 2. Distribution of the oxygen in the mine. Shock wave position at 100 m.

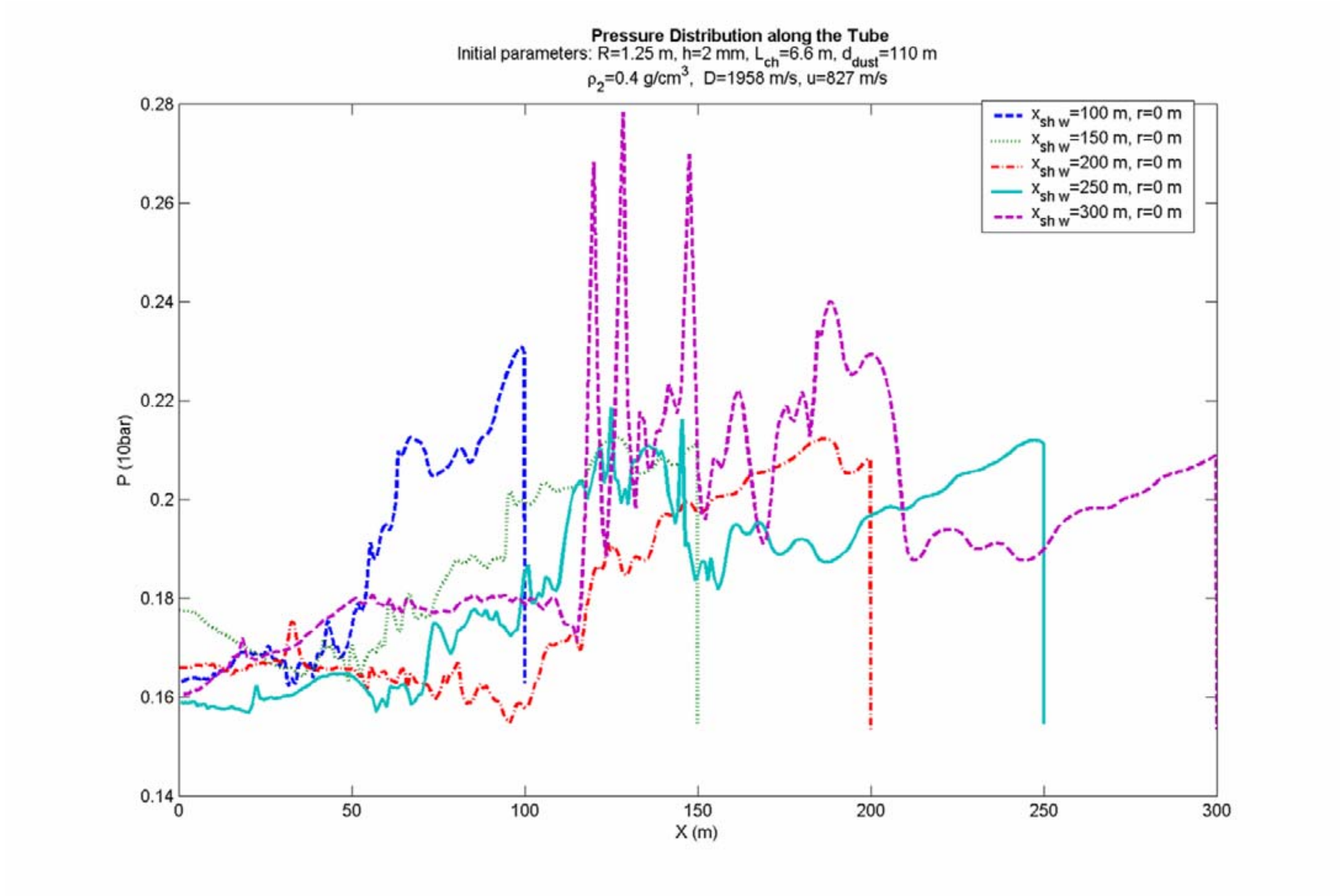


Figure 3. Transition to detonation in round tube. It is stage of coal dust mixture explosion at the shock wave distance up to 300 m from the closed end.

Conclusion.

It was found that transition to detonation is possible for long tube. The length of tube L has to be more than characteristic length of mixture combustion zone plus L_{ch}.

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