Combustible dusty gas flows behind shock waves.

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Abstract

In the paper presented we focus on two aspects of the problem of unsteady processes behind shock waves propagating in a gas-particle combustible mixture. The first concerns questions related to ignition and burning of the mixture behind strong shock waves, where we give some results of numerical investigation the process of the transition to detonation and 2D structure of unsteady detonation in the mixture of coal particles with air. The other emphasis we give to the problem of the dust entrainment and dispersion from the dust layer behind a shock wave. In this paper we make attempt to simulate the particle lift and dispersion by taking into account lifting forces due to particle rotation. Mathematical modelling methods are used for the study. In the model used the moving medium is treated as a two-phase, two-velocity and two-temperature continuum with mechanical and thermal interaction between the phases, and taking into account devolatilization (extract of volatiles from particles), gas-gas and gas-particle exothermic chemical reactions and radiation heat conduction. The special emphasis we give to the problem of the dust entrainment and dispersion from the dust layer behind a shock wave.

Introduction

It is well known that the pressure wave, for example induced by a combustible gas in the coal mine, disperses coal dust from walls of the mine into the gas stream and forms an explosive dust cloud, which may make initial explosion sustained by itself and propagated on a long distance. In spite of this problem has been intensively investigated by many scientists, there is so far no complete clearness as to the question what mechanism is mostly responsible for the intensive lifting of the particles from the layer. In this paper an attempt is made to simulate the particle lift and dispersion by taking into account lifting forces due to particle rotation (Magnus force) and gas phase vorticity (Saffman's force), and to show that these effects can essentially affect on the flow pattern after shock wave resulting in fast dust entrainment and dispersion from the dust layer. 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 generally consist of a number of components. Two approaches have been developed to integrate the equations describing the dusty gas flow. One is based on the principle of physical and geometrical splitting of spatial differential operators. This approach was discussed in our works [1-4]. It is applied to calculate the problem of ignition and burning of the dusty mixture behind strong shock waves propagated in a coal mine gallery. The other approach includes fully implicit time integration of the spatial differential equations. Base features of the method are discussed in [5]. This method is applied to calculate the problem of dust entrainment and dispersion from a dust layer behind a shock wave propagated along a channel.

Background

The physical processes of dusty gases ignition and combustion are numerical studied using different type of flow descriptions. It is supposed that solid particles are rigid spheres, collisions among the particles are neglected and volume of the particles is negligible. The perfect gas model is used for gaseous phase. The moving medium is considered as two-phase, two-velocity, two- temperature continuum including interaction of gas phase and solid phase. One step overall chemical reactions with induction periods are also included into mathematical models . The following models are used [6-9]: a) Navier-Stokes description for laminar flow of the medium; c) K-E approach for turbulent flow case. The paper is devoted to the description of the used models , numerical methods and results of the numerical solutions of combustion problems. The physical laws of mass and energy conservation, diffusion with chemical reactions and momentum variation for the two phases gives us the system of equations of the type [3,4]:

$$\partial U/\partial t = A(U) + B(U) + C(U) + D(U) \tag{1}$$

where U is vector of unknown functions, A is matrix differential operator including gradients for gas phase, B is matrix operator with gradients for solid particles phase, C corresponds to chemical reactions, energy sources and radiation transfer terms of the system, D is algebraic matrix operator containing the members of mechanical, thermal interactions and mass exchanging between phases as well as turbulence sources.

Numerical methods

The developed methods include implicit parts and explicit schemes and based on splitting technique. We use fourth-step splitting for two-dimensional Eulerian equations case and multistep splitting schemes for Navier-Stokes equations and three-dimensional cases. The "large particles" numerical scheme [1,7-9] were used for the construction a numerical algorithm. Sweepings and iterations were worked out for implicit parts of the algorithm. Nonuniform computing mesh was used being adapted for the problem under consideration. Complete splitting schemes of developed numerical algorithms have the first order of accuracy for time and space variables. A scheme of second order of accuracy was also developed [5,11] and used for two-dimensional Navier-Stokes case. This approach include fully implicit time integration of the equations and used finite volume approximations altogether with splitting technique. We use linearization of spatial discrete operator by using splitting of the Jacobian matrix of convective fluxes in the form of Turkel-Jameson, and a majoring diagonal matrix for estimation the Jacobian matrix of diffusion fluxes. The implicit operator such obtained is then resolved by implementing the LU-SGS, 2 factors approximate factorization of Yoon-Jameson generalized to the equation of two-phase flow model.

Problems considered

In the paper we focus on investigation of unsteady processes behind shock waves propagating in a gas-particle combustible mixture. The well-known practical problem is explosion in coal mine. The calculated results for several problems related to coal mine explosion are demonstrated. Among them there are: the initiation of combustion and detonation behind shock waves; the two-dimensional structure of detonation in tubes and Lifting of dust layers behind shock waves. The two-dimensional flow due to a blast is shortly discussed. Coal dust particles with "standard" properties were taken for the calculations. The numerically obtained physical effects are considered. The real cross-section form of the mine gallery and its used two-dimensional model are discussed.

Problem 1. Initiation and propagation of a shock wave is considered in a gallery filled with air and small coal particles. Polish experimental mine "Barbara" configuration is used for modelling. The gallery height is 2.5 m. Dust is placed in the "soft layers" on the distance of 75 m from the closed end of the channel. After this distance the channel is filled in by air only. Two methods of shock wave initiation are considered in this problem. In the first one, the shock is formed due to the detonation wave in the methane–air stoichiometric mixture, which occupies a zone of 3.3 m near the closed end of the gallery. In the second method, this zone is removed, and the initiation is realized by injection (at the end) of supersonic pure gas flow. The parameter characterizing the heat capacity of the gallery wall is varied in calculations in limits from 0 (adiabatic wall) to $10kg/sec^3/K^o$. Dust initial parameters are as follows: the diameter $d = 60\mu m$, mass fraction of volatiles is 0.26, the average mass density in the layer is $3.5 - 5kg/m^3$. Results of numerical calculations are illustrated by distributions of the pressure and gas temperature along the gallery at the middle line for several time moments. They show the influence of the average mass density in the layer, the heat capacity of the gallery wall and injected gas parameters on the burning process development.

Problem 2. The problem concerning shock wave/dusty layer interaction is considered. The shock wave is initiated by a highly compressed gas placed at the initial time moment in a narrow zone near the closed end of a rectilinear canal. This shock wave propagates along the canal where dust of small coal particles with a characteristic size $d = 50\mu m$ is congregated on the bottom and the top wall of the canal in narrow layers with the thickness h=0.03H, where H is the height the canal, that is taken equal 2 m. The average particle density in the layer is $5 - 1000kg/m^3$. The grid used in these calculations is composed of 200 cells in the lengthwise direction stretched to the shock wave, and 100 cells in the transversal direction stretching symmetrically to the bottom and top walls. Due to the symmetry of the problem numerical results are given for the halfpart of the canal only. With no Magnus force calculations show that no essential dust entrainment and dispersion from the dust layers occurs behind the shock wave. The thickness of the layer is increased, and particle motion takes place mostly inside the layer. From the other hand, with taking into account the Magnus force, the flow pattern behind the shock wave becomes quite different resulting in ”explosion-wise” dust entrainment and dispersion particles from the layer. The results clearly single out the shape of dispersed dust cloud, which demonstrates that due to Magnus force effect particles in the dust layer can suddenly disperse from the layer behind shock wave and fill in the whole of the canal. Therefore, this force appears to play an important role in explanation of the dust entrainment phenomenon observed in numerous experiments [11-12]. A pressure gradient and Saffman force have to be also taken into consideration in a boundary layer near the wall. The temperatures are high enough (for the shock Mach number 3 it is about 1500K) to ignite the mixture.

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