Interaction of a shock wave with an array of particlesand effect of particles on the shock wave weakening

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Abstract
Two-phase systems that involve gas-particle or gas-droplet flows are widely used in aerospace and power engineering. The problems of weakening and suppression of detonation during saturation of a gas or liquid flow with the array of solid particles are considered. The tasks, associated with the formation of particles arrays, dust lifting behind a travelling shock wave, ignition of particles in high-speed and high-temperature gas flows are adjoined to safety of space flight. The mathematical models of shock wave interaction with the array of solid particles are discussed, and numerical methods are briefly described. The numerical simulations of interaction between sub- and supersonic flows and an array of particles being in motionless state at the initial time are performed. Calculations are carried out taking into account the influence that the particles cause on the flow of carrier gas. The results obtained show that inert particles significantly weaken the shock waves up to their suppression, which can be used to enhance the explosion safety of spacecrafts.

Keywords
Shock wave; Particle; Particulate flow; Two-way coupling; Suppression

1 Introduction

Research efforts are aimed at determining the conditions of excitation and propagation of detonation waves for the purpose of their initiation, prevention and suppression [1, 2]. The detonation wave is developed as a result of abnormal operation of liquid rocket engines and elements of spacecraft fuel system. On the other hand, it is planned to use the detonation phenomenon in advanced rocket engines operating on a thermodynamic cycle of detonation combustion [3–5]. Interest in the heterogeneous and hybrid detonation is caused by potential of using high-energy metal particles (e.g. aluminium or magnesium) or mixtures of reactive gases with additives of such particles as working media. The tasks, associated with the formation of cloud of particles, dust lifting behind a travelling shock wave, ignition of particles in high-speed and high-temperature gas flows are adjoined to these problems. The use of experimental methods for studying the interaction of shock waves with elements of an aircraft, as well as the occurrence or, on the contrary, the suppression of detonation waves is hampered due to the danger of structures destruction and high speed of the flow, therefore the development of numerical methods is of urgent interest. Computational technologies allow obtaining and visualizing detailed two- and three-dimensional flow patterns, identifying both local features and integral properties of the processes [6–8].

The presence of strong discontinuities and regions with large gradients of flow parameters (shock waves, ignition and combustion fronts, contact discontinuities)requires the application of numerical methods, which allow reproducing the qualitative and quantitative characteristics of the flow with reasonable accuracy.

Supersonic nature of the flows ensures successful application of such schemes as Godunov scheme and schemes with discontinuity capturing for calculating the gas phase [9, 10]. Methods of expansion in terms of physical processes make it possible to perform a separate integration of equations associated with combustion. For turbulent flows the parabolic part of equations is solved by implicit method. In a number of works the Godunov scheme is successfully applied to calculation of discrete phase as well [11]. The equations for gas and particles are written in divergent form with the pressure proportional to the volume concentration of each of the phases. Calculation of both phases using a single finite-difference method is also carried out in [12] (large-particle method), [13] (finite element method) and[14] (MacCormack scheme).Schemes based on flux correction transport (FCT) are used for calculation of both the gas flow [13,14] and the particles motion [15]. Schemes like TVD, based on the use of monotonic operators are used to calculate the gas phase [16].

The equations of gas-particle dynamics for describing the particles motion do not contain the internal pressure, which is why the use of TVD scheme for equations of solid phase motion is limited to degeneration of space dimension of eigenvectors of Jacobi matrix (equations describing the motion of dispersed phase are not hyperbolic). For part of the Jacobian corresponding to discrete phase the eigenvalue $\lambda=u_p$ has the multiplicity of three, and generates two eigenvectors and one attached vector. On the other hand, the equations for particles have the form of vorticity transport equation, therefore to solve them the methods, developed for solving the vorticity equations are used, in particular, the MacCormack scheme and upwind scheme proposed in [17] (Gentry–Martin–Daly scheme).

The developed methods of supersonic gas flows calculation are not always applicable for calculation of the discrete phase (at low volume concentrations of particles, when the volume occupied by the particles is neglected) due to the degeneration of equation system, which determine the evolution of particles. The degeneration is caused by absence of the term, associated with overall mixture pressure in the equations, which describe the dynamics of discrete phase. Different schemes for calculating the particles are finding their application.

To improve the efficiency of calculations movable or adaptive meshes are used allowing to improve the resolution of shock and detonation waves [11, 13], as well as parallel computing [17].Work[17] presents methods of adapting TVD schemes for the calculation of gas mixtures with fine particles (within the context of single-velocity and two-temperature model) and gas mixtures with ultrafine particles (for the mixture equilibrium in terms of velocity and temperature, taking into account the detailed chemical kinetics). The solution of compressible gas equations is implemented on the basis of explicit finite difference scheme of TVD type. Explicit scheme of TVD type provide highly accurate representation of strong discontinuities at standard template, the absence of oscillations behind the front of shock waves in the solution, which are inherent for dispersion difference schemes, and the stability when CFLconditions are met. Application of TVD schemes is justified for detonation flows as well, which are characterized by presence of ignition and combustion fronts (narrow region with a sharp change in flow parameters).

WENO-type finite difference schemes of 3rd and 5th order (WENO-Z scheme) are used in [18, 19] for the simulation of turbulent compressible gas-particle flows (Eulerian–Lagrangian approach is applied). Sampling of main equations is carried out on a uniform grid. For sampling in terms of time Runge–Kutta method of 3rd order is used. The interaction of a shock wave with an array of particles is discussed. Work [9] provides the comparison of calculation results obtained with various difference schemes (Godunov method, WENO scheme), as well as a comparison of data obtained in the context of Eulerian and Lagrangian approaches to description of dispersed phase (during interaction of array of particles with a shock wave, calculations are carried out in one-dimensional formulation of the problem). Accounting for the volume occupied by the particles allows to provide hyperbolicity of equations describing the dynamics and heat exchange of dispersed phase, and to apply the Godunov method to sampling both the equations of gas and on dispersed phase.

For gas mixtures with small reacting particles the scales of velocity relaxation of phases are neglected and one-velocity and two-temperature approximation of heterogeneous media mechanics is assumed [20]. The modified TVD scheme is also successfully applied for calculation of detonation flows in gas suspensions of aluminium particles and coal dust. For the mixture the equations are solved in Eulerian coordinates and equations describing the processes of thermal and chemical relaxation are solved in Lagrangian variables. The length of the velocity and thermal relaxation zones in ultra-fine mixtures appear to be by several orders of magnitude smaller than the characteristic scale of the problem and the scale of change in dispersed phase mass concentration. To describe the processes occurring in the macro scale, a mixture of gas and particles is assumed to be equilibrium in terms of velocity and temperature, but non-equilibrium in terms of chemical composition.

2 Interaction of shock wave with particles

An experimental and numerical study of shock wave propagation in gas-particle mixtures in the presence of pronounced two-phase boundaries (cloud of particle) is performed in [21]. The effect of particle concentration on acceleration of particles behind the shock wave is discussed. With increase in concentration of particulate phase the shocks forming near each particle interact with each other, overlap, and form an aggregate frontal shock. The polydispersity of particulate phase has relatively small effect on the flow pattern in the area (in calculations 8 fractions of particles with diameters ranging from 60 to 130 microns and with increments of 10 microns are used). In gas mixtures with particles the flow pattern is characterized by the influence of velocities and temperatures relaxation processes of two phases, whose characteristic lengths are determined by particle sizes. In flows with high concentration of dispersed phase deviation resistance coefficient from characteristic values of single particle is observed. In low-speed two-phase flows, this effect becomes remarkable when the volume concentration is about 5%, and in supersonic nozzle the flow constraint effects appear at 1% [21].

The results of mathematical modelling of particles lifting behind the shock wave reflected from the end wall, which slide over the layer of particles, are presented in [22]. Particles lift occurs in a vortex that arises in the gas after reflection of the shock wave from the wall. Formation of vortex flow is caused by the emergence of lambda-shaped structure of reflected shock wave due to the gas flow non-uniformity behind the passing shock wave.

The problem of plane shock wave propagation of over a square cavity filled with stagnant gas suspension is solved in [23]. With increase in particles concentration the shock waves in the cavity are attenuated and transformed into compression waves. Particle size has a significant impact on the flow nature and wave structure of the flux inside the cavity. For large particles (about 250 microns) the flow approaches to flow structure of gas mixtures.

Combustion and detonation processed in gas suspensions inside channels with sudden expansion are discussed in [24]. The conditions for passage of detonation wave through the channel cross-section for monopropellant particles of fixed size (particle size is 30 microns) are studied. There is a significant effect of particle concentration on the value of critical relation between pipe diameters to prevent the detonation failure.

A mathematical model based on the two-velocity and two-temperature continuum for description of shockwave and detonation processes in gas mixtures with particles (particle size ranges from 1 to 5 microns) inside channels of complex geometry is proposed in [25]. The propagation of shock and detonation waves in gas suspension of aluminium particles in oxygen inside the channel with sudden expansion is discussed. The diffraction of shock waves in gas-particle mixture on the opposite ledge differs from the corresponding flow in pure gas by lacking self-similarity of the flow and by influence of phase relaxation processes [23, 24]. The results computed show that the formation of zones free of particles and layers with their increased concentration is possible. When the detonation wave exits a narrow part of the canal into its wide part the implementation of various flow scenarios is possible (from partial attenuation to full heterogeneous detonation failure, including the possibility of partial failure followed by initiation).

3 Mathematical model

There are two main approaches to describe the dynamic and heat exchange processes in particle-laden flows [6-9, 26, 27]. The first approach, Eulerian–Lagrangian approach, is based on the continuous-discrete representation of a two-phase mixture. The equations of continuum mechanics for carrier phase are complemented by a system of ordinary differential equations describing the movement path and the change in temperature of each particle [6-8]. In the second approach, Eulerian–Eulerian approach, simulation is carried out within the framework of models of interpenetrating continua mechanics. Both phases are considered as a continuous medium, and are described by the equations arising from the conservation laws of mass, momentum and energy of each phase and component of the gas mixture. Neglecting the volume occupied by the particles, the movement of the gas mixture and the particles is described in the two-speed and two-temperature approximation of heterogeneous media mechanics.

The equations describing motion and heat exchange of phases are complemented by semi-empirical dependencies for drag and heat exchange coefficients of the individual particle. The effect of different representations of drag coefficient on the calculation results of shock-wave processes in particle-laden flows is taken into account [21, 22].

The large-eddy simulation of turbulent two-phase flows is considered in [26, 27]. The motion of dispersed phase is described as part of continuum approach based on application of Liouville theorem to the system of dynamic equations, which describe the behaviour of particles. The influence of sub-grid effects on the particles motion is discussed.

Each approach has its advantages and disadvantages, as well as applications. Lagrangian approach is quite expensive from a computational point of view, requiring the use of a statistically representative particle system. A lower limit of the number of particles is about 6 particles per each cell of Eulerian mesh in each coordinate direction [28], which, in practice, makes it necessary to use the system of $6ND$ particles, where N is the number of cells of Eulerian mesh, and D is the dimension of the problem. For fine grids such requirements to the particles number become excessive. Compared to the Lagrangian approach the Euler approach uses a smaller number of freedom degrees, but its accuracy is substantially dependent on averaging method.

The governing equations of gas represent the conservation equations of mass, momentum and energy in Cartesian coordinates. In Cartesian coordinates (x, y, z), an unsteady three-dimensional flow of a viscous compressible gas is described by the following equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0; \tag{1}$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v}) = -\nabla p - \sum_i \mathbf{F}_{\mathrm{p}i} n_{\mathrm{p}i}; \tag{2}$$

$$\frac{\partial \rho e}{\partial t} + \nabla \cdot [(\rho e + p)\mathbf{v}] = -\sum_i W_{\mathrm{p}i} n_{\mathrm{p}i} - \sum_i Q_{\mathrm{p}i} n_{\mathrm{p}i}.$$

(3)

The equation of state of an ideal gas is

$$p=(\gamma-1)\rho\left[e-\frac{1}{2}\left(v_x^2+v_y^2+v_z^2\right)\right].$$

Here, t is the time, ρ is the density,$\mathbf{v}$ is the velocity,v_x, v_y, and v_z are the velocity components in the coordinate directions x, y and z, p is the pressure, e is the total energy per unit mass, T is the temperature, and γ is the specific heat capacity ratio. The subscript p corresponds to the particles. Summation is performed over all particles of the ith fraction.

The source terms in the right hand sides of equations (2) and (3) take into account the exchange of momentum between the phases, the heat transfer between the gas and the particles, and the work done by the particles on gas. The intensities of momentum and energy exchange between the phases are determined as the product of the number concentration of the particles and the intensity of interphase exchange per one particle ($n_{\mathrm{p}i}$ is the concentration of the particles of the ith fraction per unit volume). The work done by the particles on gas is calculated as $W_\mathrm{p}=\mathbf{F}_\mathrm{p}\cdot\mathbf{v}_\mathrm{p}$.

The particulate phase is simulated through a Lagrangian deterministic tracking model to provide particle trajectories.Particles are assumed to have a spherical shape and they are non-rotating. Particles collisions, breakup and coalescence are neglected. The virtual mass and Basset forces due to their small magnitudes, and the Magnus force due to lack of knowledge about particle angular momentum are neglected. The resulting force acting on a particle is the drag force. The equations describing translational motion and convective heat transfer of a spherical particle are written in the form

$$\frac{d\mathbf{r}_\mathrm{p}}{dt}=\mathbf{v}_\mathrm{p};$$

(4)

$$\frac{d\mathbf{v}_\mathrm{p}}{dt}=\frac{3C_\mathrm{D}\rho}{8\rho_\mathrm{p}r_\mathrm{p}}\left|\mathbf{v}-\mathbf{v}_\mathrm{p}\right|\left(\mathbf{v}-\mathbf{v}_\mathrm{p}\right);$$

(5)

$$c_\mathrm{p}^m m_\mathrm{p}\frac{dT_\mathrm{p}}{dt}=2\pi r_\mathrm{p}\mathrm{Nu}_\mathrm{p}\lambda\left(T-T_\mathrm{p}\right).$$

(6)

To calculate the drag coefficient, the modified Stokes law is used

$$C_\mathrm{D}=\frac{24}{\mathrm{Re}_\mathrm{p}}f_\mathrm{D}(\mathrm{Re}_\mathrm{p}).$$

The function f_D takes into account the correction to the Stokes law for the particle inertia. The particle Reynolds number is

$$\mathrm{Re}_\mathrm{p}=\frac{2r_\mathrm{p}\rho\left|\mathbf{v}-\mathbf{v}_\mathrm{p}\right|}{\mu}.$$

The particle Nusselt number is calculated based on semi-empirical correlation for solid sphere

$$\mathrm{Nu}_\mathrm{p}=2+C\mathrm{Re}_\mathrm{p}^m\mathrm{Pr}^n.$$

The dynamic and thermal particle relaxation times are calculated by the relations

$$\tau_v=\frac{\rho_\mathrm{p}d_\mathrm{p}^2}{18\rho\nu},\quad \tau_t=\frac{\rho_\mathrm{p}c_\mathrm{p}^m d_\mathrm{p}^2}{12\rho c_p a},$$

where $a=\lambda/\rho c_p$ is the thermal diffusivity.

Equations (4)–(6) are integrated along the path of an individual particle and require specification of the initial conditions – the Cartesian coordinates and velocity of a particle at the time $t=0$.

4 Two-way coupling

The effect of viscous forces is only taken into account when the gas interacts with particles. The equation describing the unsteady flow of non-viscous compressible gas is written in the conservative form and takes into account the reverse effect of particles. Characteristic length, characteristic density, characteristic velocity and characteristic temperature are chosen as characteristic scales for variables with dimensions of length, density, velocity and temperature.

To construct the equations describing the motion and heat exchange of particle continuum, the approach for simulation of gas-particle flows proposed in [26] is used, as well as its generalization, developed in [9, 27] for direct numerical simulation of two-phase flows. In continuum approach, the continuity equation, momentum equation and energy equation are obtained from the Lagrangian equations of motion and heat exchange of individual particle. The probability density function, which satisfies the Liouville equation in the phase space is introduced. Spatial filtering operator is determined by the ratio with non-negative kernel, which satisfies the normalization condition. The filter width is selected to be sufficiently small and such that sub-grid fluctuations of gas velocity can be ignored. With a non-negative kernel (top-hat filter, Gaussian filter) the probability density function satisfies the imposed requirements. The problem of closing the equations that describe motion and heat exchange of dispersed phase is discussed in [29] (mesoscopic Eulerian formalism).

Neglecting the inertial effects, the velocity and temperature of the dispersed phase are equal to the corresponding gas parameters. In this case, only equations for particle concentration are solved, and the momentum equation and energy equation are not solved. It is possible to partially account for inertial effects within the context of equilibrium model, in which the local velocity of dispersion phase is expressed as a sum of gas local velocity and acceleration. As an expansion parameter the time of particle dynamic and thermal relaxation (the local acceleration of dispersed phase is equal to the local gas acceleration) is used. The equilibrium model describes a number of inertial effects (preferential acceleration), but it is suitable for describing the motion of quite small particles. To fully take into account the inertial effects, the transport equations are solved, assuming that the contribution of correlation moments is negligible. In this case, the equations of the mathematical model are equivalent to the model proposed in [30], which describes the flow of gas suspension with negligible volume occupied by the particles, and with reasonably large ratio between densities of dispersed and gaseous phases. For gas-particle mixture with mono-dispersed particles the equations of mathematical models coincide with the equations formulated in [31]. Although the inertial effects are taken into account, neglecting the second correlation moments of dispersed phase doesn’t allow to account for a number of important effects (trajectory crossing effect), which play an important role in flows of gas suspension with high inertial particles [32].

To solve the problem of closing several other approaches can be used, including the approach [32] (quadrature-based moment method), which uses an approximation of higher order, but requires the solutions of additional transport equations. In the approach [33] the closure problem solution is based on the use of transport equation of kinetic energy of particles. Work [29] proposes an approach designed for simulating the non-isothermal gas suspension flows. In this approach three additional transport equations for the vector components of thermal flow are solved. In the described models, the concept of dispersed phase viscosity is introduced, and the models produce satisfactory results for low-inertia particles.

5Computational procedure

Accurate simulation of detonations and explosions presents challenges for numerical methods. The finite volume code, solving transient and fully compressible Euler equations, has been developed for numerical simulation. The solver uses the total variation diminishing (TVD) numerical schemes which are suitable for shock capturing.

Non-linear CFD solver works in an explicit time marching fashion, based on a three-step Runge–Kutta stepping procedure and piecewise parabolic method. The governing equations are solved with Chakravarthy–Osher scheme for inviscid fluxes. Convergence to a steady state is accelerated by the use of multigrid techniques, and by the application of block-Jacobi preconditioning for high-speed flows, with a separate low-Mach number preconditioning method for use with low-speed flows. Using the flux vector splitting the Jacobian is represented as $A=R(\Lambda^{+}+\Lambda^{-})R^{-1}$, where the matrices Λ^{+} and Λ^{-} are diagonal matrices with positive and negative eigenvalues on the main diagonal. Components of matrices A^{+} and A^{-} are obtained using values averaged by Roe.

Equations describing motion of particles are solved numerically to obtain the threshold irradiance required to produce breakdown for a given pulse duration, using a Runge–Kutta fourth order technique with adaptive time step.

6 Results and discussion

Subject of consideration is the interaction uniform sub- and supersonic flow of inviscid compressible gas with an array of particles, filling a certain bounded area of space, and being in stable state at the initial time. Calculations are performed in the one-dimensional statement.

Calculations are performed on the interval [–5, 6]. The particles array consists of 8.6×10^{4} particles that are immobile at initial time and evenly fill the interval [0, 0.3]. Computational grid contains 1,000 nodes. Certain computational gas with specific heats ratio equal to 1.4at constant pressure and constant volume is selected as a working medium. The ratio of specific heat is assumed equal to 1. In practice, the dynamic and thermal relaxation times turn out to be close to each other. The calculations assume that $\tau_v=\tau_t=3.5$ (in dimensionless variables relaxation time is corresponded by the Stokes number). The particles material density and the particle mass are equal to $\rho_p=1000$ kg/m^3 and $m_p=10^{-4}$kg (particle diameter is $d_p=5.77\times10^{-3}$ m).

On the left boundary, through which the working gas flows into the computational area the Mach number equal to 0.3is set for subsonic flow (case 1).For the case of supersonic flow (case 2) the parameters on left boundary are obtained from Rankine–Hugoniot relations so that Mach number behind the shock front is equal to 2.8.

At the initial time t=0 the gas is moving at a uniform velocity (ρ=1, p=1 and u=1 in dimensionless variables). The particle velocity is zero, and the particles temperature is assumed equal to gas temperature. The initial concentration of dispersed phase is 2.885×10^{-5}.

Particles of different sizes have different inertia and different velocity lag relative to the gas stream, which affects the process of establishing a quasi-stationary flow. The duration of the quasi-stationary regime in operating chamber is defined by the degree of uneven distribution of impurities concentration and the velocity gap of particles from the gas.

For case 1,the parameters distribution of carrier gas at different moments of time is shown in Figure 1 and Figure 2. In front of array of particles the stream decelerates, which leads to velocity reduction and to increase of gas density, pressure and temperature. At the contact of the incoming stream with particles array the particles, which were at rest at the initial moment of time, begin to accelerate, acquiring non-zero velocity and providing less resistance to gas flow, resulting in increase of carrying flow velocity. Behind the area occupied by the particles occurs the recovery of density, velocity, pressure and temperature to the corresponding values in incoming flow.

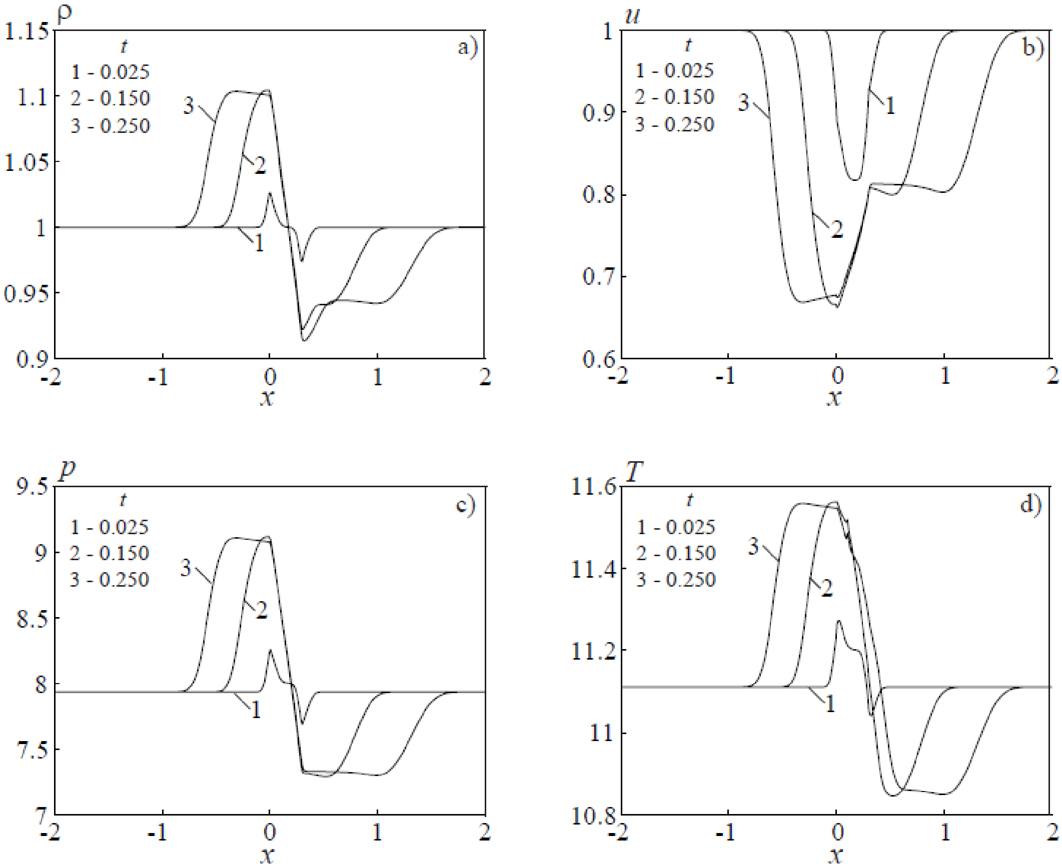

Figure 1. Distributions of density (a), velocity (b) pressure, (c) and temperature (d) of gas for case 1for$t$=0.025 (line 1), t=0.150 (line 2), t=0.250 (line 3)

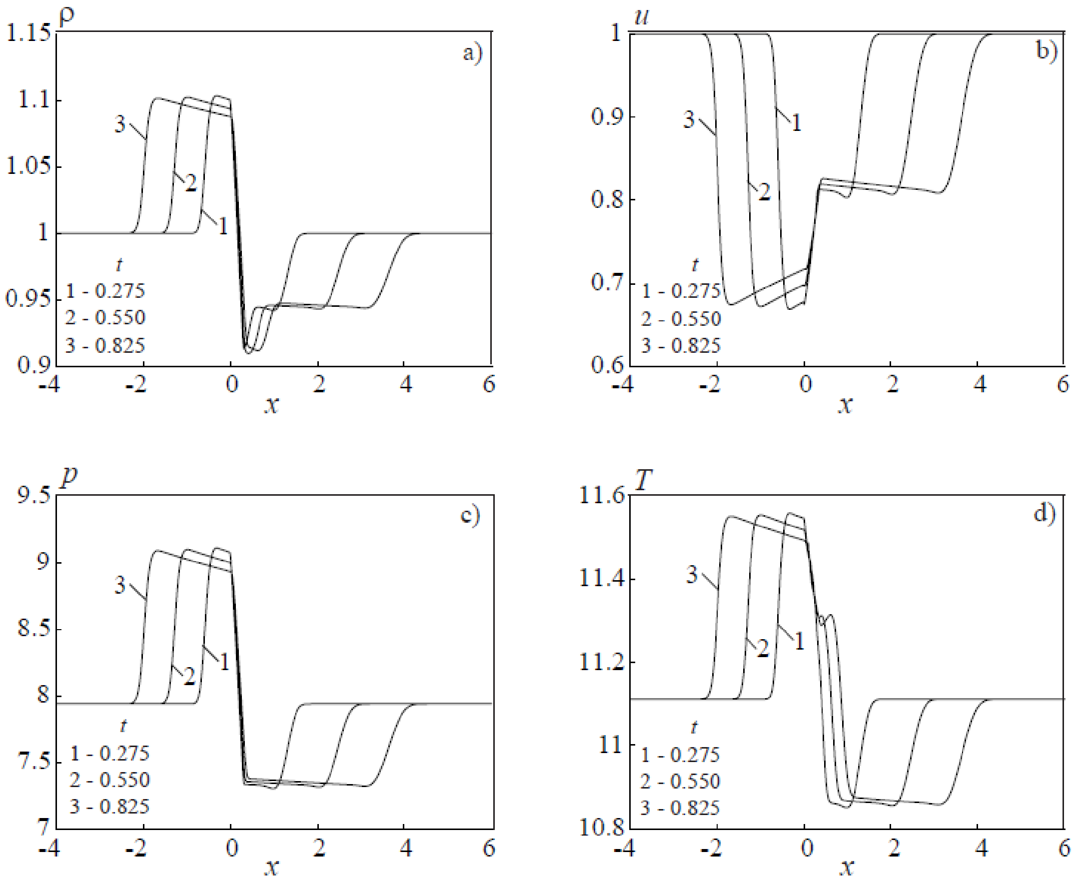

Figure 2. Distributions of density (a), velocity (b) pressure, (c) and temperature (d) of gas for case 1 for t=0.275 (line 1), t=0.550 (line 2), t=0.825 (line 3)

During t=0.275 the particles array doesn't displace noticeably, although the density of the dispersed phase at frontal boundary of the array is slightly higher than at rear boundary. Within the area occupied by the particles the velocity of dispersed phase is distributed unevenly. Near the rear boundary of the array the velocity of dispersed phase increases due to acceleration of carrier gas in this area. The particles located near the frontal boundary of the array have the highest velocity, as they interaction with the gas flow begins at the moment when the gas reaches the area occupied by the particles. The temperature of the dispersed phase remains approximately constant. Uneven distribution of velocity along the array (high velocity at the front boundary and low velocity at rear boundary) leads to a different intensity of heat exchange between the gas and the particles located near front and rear boundaries of the arrays. As a result, there is a slight decrease in temperature of dispersed phase near the rear boundary of the array. Distribution of correlation moments of velocity and correlation moments of velocity and temperature of dispersed phase are qualitatively similar.

For case 2, the distribution of carrier gas parameters at different moments of time is shown in Figure 3 and Figure 4. Interaction of supersonic flow with an array of particles leads to the formation of a shock wave, behind which there is an abrupt decrease the gas velocity to subsonic values and increase its density, pressure and temperature. Behind the shock wave occurs the interaction of the carrier flow and the particles. In the region occupied by the particles the velocity of carrier flow remains approximately constant, while the density pressure and temperature of the gas of the gas decrease. The particles, which are at rest at initial time, are involved in movement by the gas, receiving non-zero velocity and providing less resistance to gas flow. At the rear edge of the array a rarefaction wave is observed, in which acceleration of the flow and decrease in density, pressure and temperature of the gas occurs. Behind the arrays of particles gas parameters do not reach the values they had in undisturbed flow, which is due to energy losses at the shock wave front. In front of expansion wave fan the velocity and pressure of the gas are lower than in the undisturbed flow. Density and temperature of gas behind expansion wave fan undergo minor fluctuations due to the occurrence of the contact discontinuity, which moves down the flow at velocity lesser than velocity of the shock wave induced by array of particles. To the left of the contact discontinuity the gas temperature is higher and its density is lower than the temperature and density of gas to the right of contact discontinuity. Contact discontinuity arises due to the abrupt change in gas density and temperature at the front of shock wave, which moves down the flow.

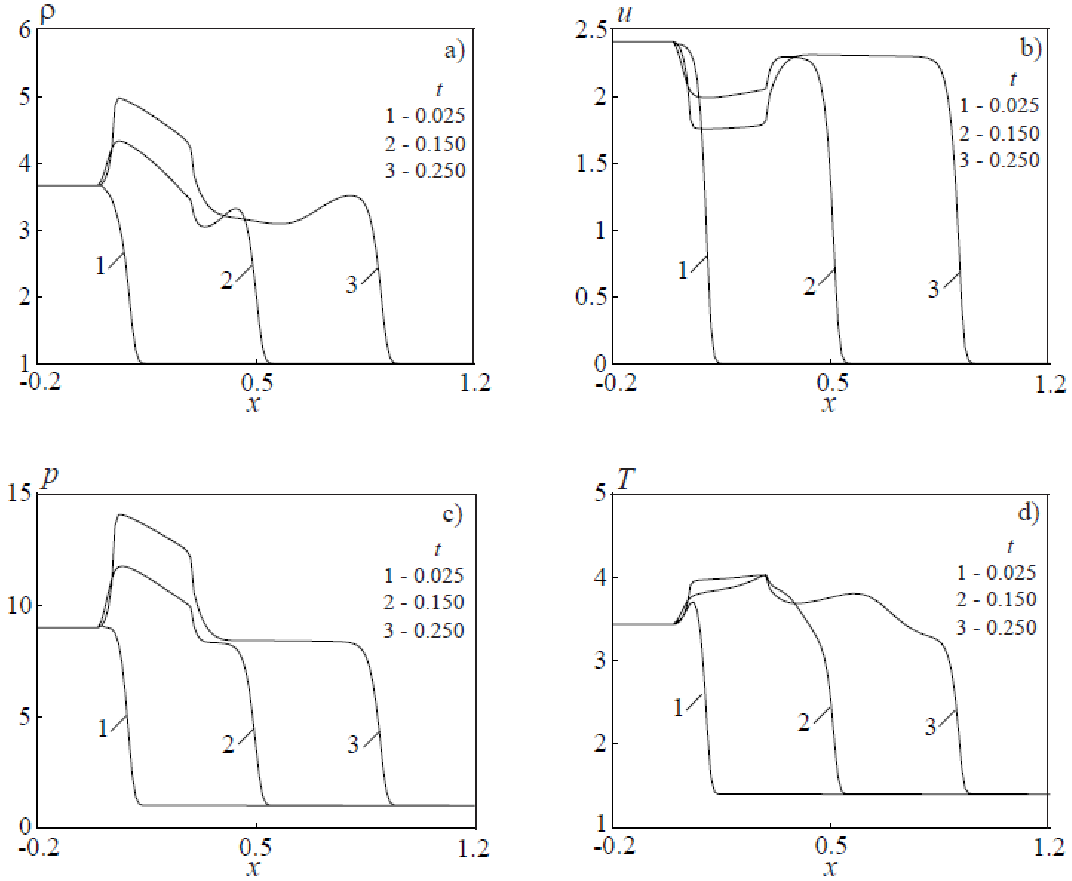

Figure 3. Distributions of density (a), velocity (b) pressure, (c) and temperature (d) for the case 2 for t=0.025 (line 1), t=0.15 (line 2), t=0.25 (line 3)

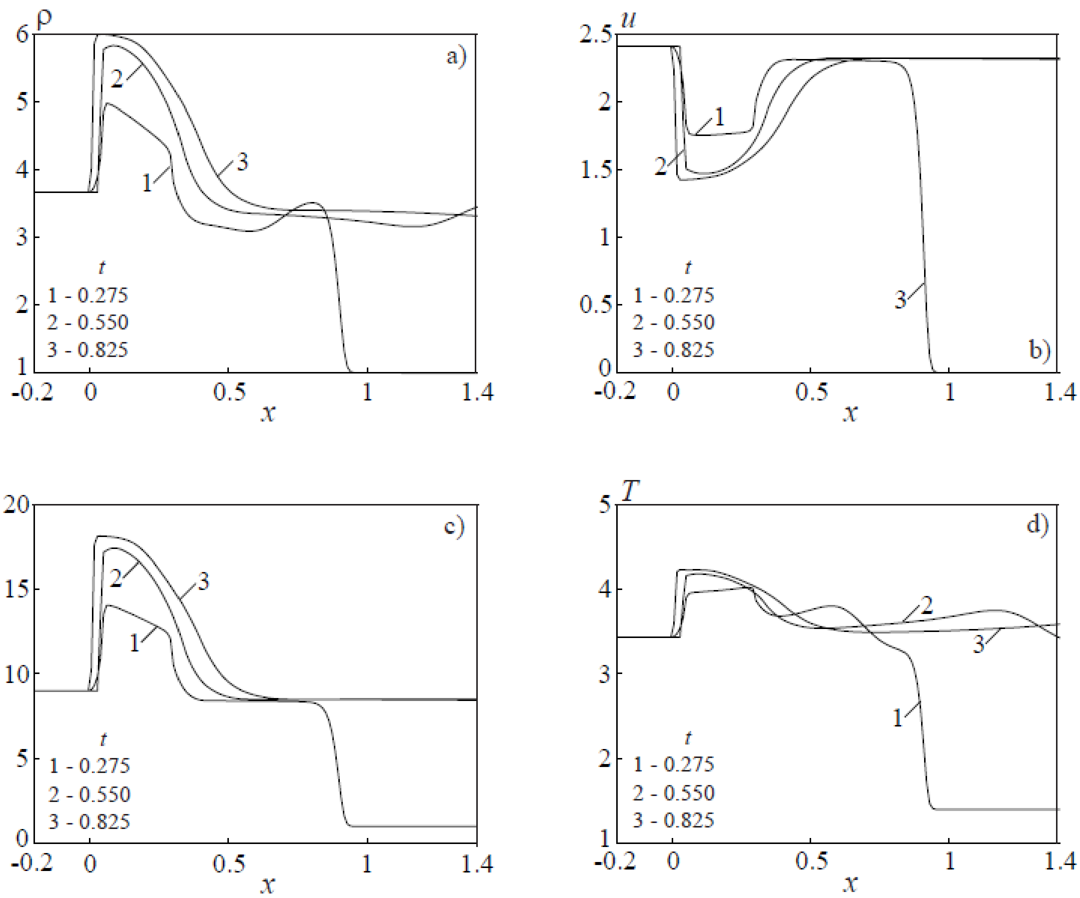

Figure 4. Distributions of density (a), velocity (b) pressure, (c) and temperature (d) for the case 2 for t=0.275 (line 1), t=0.550 (line 2), t=0.825 (line 3)

Comparison of gas parameters distributions at different moments of time shows that the position of shock wave front induced by array of particles remains practically unchanged in space, but the magnitude of shock of flow parameters increases as time passes.

At time t=0.275 velocity of particles near the front boundary of the array exceeds the velocity of those close to its rear boundary. An uneven velocity distribution result in an uneven distribution of dispersed phase density, which, at the front boundary of the array, exceeds the dispersed phase density at the rear boundary. Increasing the gas temperature at the front boundary of the array increases the temperature of dispersed phase. Distribution of velocity correlation moments, velocity and temperature of dispersed phase are qualitatively similar.

7Conclusions

The study provides an analysis of the main existing methods for description of two-phase flows, and analysis of numerical methods for the simulation of particle-laden flows. The mathematical model of gas interaction with the particles, based on the use of Eulerian and Lagrangian approach is developed. Simulation of inviscid compressible gas is based on the use of Euler equations. For sampling of the equation describing the motion and heat exchange of gas and dispersed phases the finite volume method with splitting by the flow vector Roe is used. On the basis of developed mathematical model calculations of interaction of uniform sub- and supersonic flows of non-viscous compressible gas with an array of particles, which are in still state at initial time.

It has been demonstrated that inert particles significantly weaken the shock waves up to their suppression, which can be used to enhance the explosion safety of spacecraft(see, for example, discussion of blast mitigation onboard flying vehicles in [34, 35]). In contrast, high-energy particles of metals (aluminium, magnesium) or mixtures of reactive gases with additions of these particles can be used as working media in rocket engines using hybrid and heterogeneous detonation. In this case, the developed method can be used to calculate the concentration of particles, providing a controlled secure detonation.

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