Shock and Detonation Wave Diffraction in a Variable-Section Duct

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1 Introduction

Diffraction of shock waves is one of fundamental problems in gas dynamics and mechanics of multiphase media. Of especial interest is the shock wave (SW) diffraction at a sudden expansion of a duct. Such a configuration is typical of the ducts of technological devices.

The processes of shock and detonation waves diffraction in gas-particle mixtures are more complex than in gas mixtures. The flow pattern is characterized by an additional influence of the processes of relaxation of velocities and temperatures of both phases whose typical extensions are determined by the particles size. Due to extra geometric scales the flow in the corner neighborhood is not self-similar unlike the gas flow. The data of previous research [1-3] show that the influence of the particle size and mass fraction on the wave processes in regions with complex geometry is considerable. Thus, the analysis of the shock and detonation wave diffraction process in a gas-particle mixture at a sudden cross-sectional expansion of the duct is of interest both from the practical and theoretical viewpoints.

In the present work, we analyze the wave structures arising at a diffraction of shock and detonation waves at a cross-sectional breakdown of a flat duct on the base of numerical modeling of two-dimensional flows. We consider monodispersed mixtures of aluminum particles of diameters 1-5 μm in oxygen. The mathematical model is based on the two-velocity and two-temperature approach of mechanics of heterogeneous media.

The purposes of the work are as follows: development of an adequate numerical technique; numerical modeling of the SW propagation process in gas-particle mixture in the duct with a sudden expansion; investigation of the influence of the mass loading and the particle size on the wave structure; investigation of propagation of heterogeneous detonation waves in the reacting mixture in the duct under consideration.

2 Formulation of the Problem

Consider a flat duct consisting of a narrow part and a wide part which are filled with a homogeneous mixture of gas and fine aluminum particles. Assume that the duct is symmetric with respect to the X axis, therefore, it sufficient to consider its upper part (Fig. 1). A supported planar stationary shock wave or stationary detonation wave with an adjacent rarefaction wave propagates in the duct narrow part in the gas-particle mixture. We investigate the process of a passage of this wave from the narrow part of the duct into its wide part and its further propagation in the duct wide part. In the flow scheme (Fig. 1),: L_1 is the location of wave front at the initial moment of time, L_2 is the length of the duct narrow part, L is the computational region length, H_1 is the transverse size of the duct narrow part, H_2 is the transverse size of the duct wide part.

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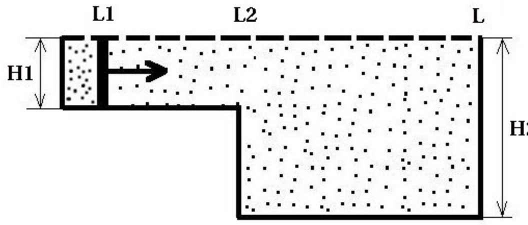

Fig. 1. Flow scheme

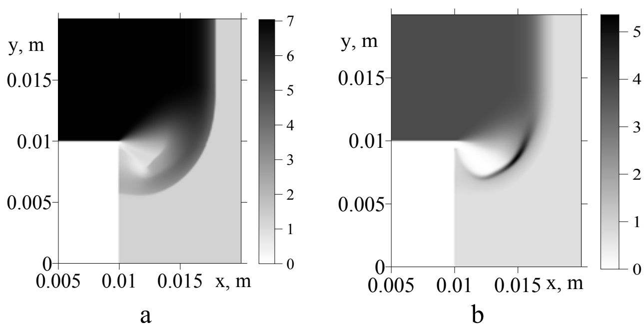

Fig. 2. SW diffraction on the backward-facing step: the gas density field (a), the field of particles density (b), M=3, t=16 μs.

The flows in non-reactive and reactive gas-particle mixtures are governed by the system of Euler equations in the approximation of the velocity and temperature non-equilibrium [4]. To close the model the ideal gas equations of state are used with regard for small values of the volume concentration of particles.

To solve the equations a numerical method which was tested and applied successfully in [4] was taken as the basic method for computation of two-dimensional unsteady detonation flows of gas-particle mixtures of reacting particles. The method includes the Harten TVD scheme for the gaseous phase equations and the Gentry—Martin—Daly upwind difference scheme for the solid phase dynamics. The problem of diffraction of a planar shock wave in a gas on the right angle was considered as a test problem. A fair agreement has been obtained in the structure of a flow realizing on the expansion angle with numerical results obtained by different numerical techniques [5].

3 Characteristic Features of the SW diffraction in gas - inert particle mixtures

A specific feature of the shocked flows in heterogeneous mixtures in comparison with inviscid gas flows is that here the shock waves possess an internal structure caused by the processes of thermal and velocity relaxation of the phases. The typical scales of relaxation processes depend on the particles size, and for monodispersed gas-particle mixtures under consideration they are also comparable with the geometric scales (the duct transverse dimensions). The presence of above relaxation parameters may affect significantly both the SW diffraction pattern at the passage of the backward-facing step and the conditions of the further SW propagation in the duct.

Computational results for the flow forming at the SW diffraction around the expansion right angle for the mixture of particles 1 μm in diameter and a fixed initial loading $\rho_{2,0} = 0.69$ kg/m^3 obtained for the Mach number (M) values from 2 to 3 are presented in Figs. 2 – 4. Figure 2 shows the density fields of the gaseous and dispersed phases for M=3 that is at a supersonic flow around the backward-facing step. Note that the wave pattern is on the whole similar to the flow at the SW diffraction in a non-dusty gas. One can also identify here the vortex, the secondary shock, and the expansion wave whose boundaries separate the regions of different colour intensity in Fig. 2 a. The presence of particles, however, affects considerably the form and dimensions of typical flow structures. An analysis of the particles density patterns (Fig. 2 b) shows that an expansion zone with a very low content of particles (the mean density of particles is less than 0.05 kg/m^3) forms behind the backward-facing step. This is caused by the fact that immediately after the shock wave passes over the backward-facing step the gas changes abruptly the direction of its motion and the particles still continue their motion due to their inertia. Thus, a zone is forming behind the backward-facing step, into which the particles do not come from the flow region upstream. The particles, which were initially in this zone behind the backward-facing step, follow the diffracted shock wave and escape from the given region. The vortex gas flow forming behind the backward-facing step contributes to a further separation of particles.

The accumulation of particles occurs in a layer adhering to the contact surface, which may clearly be seen in Fig. 2 b. Since the discrete phase (as well as the gas phase) velocity in the expansion fan is much higher than behind the diffracted SW (by virtue of its weakening behind the backward-facing step), the particles decelerate in a region behind the contact surface and the secondary shock. A consequence of this is a considerable increase in their concentration (the mean density of particles reaches the value 5.36 kg/m^3). This means that the mean density of particles has increased nearly by an order of magnitude, that is a peculiar kind of the ρ- layer arises, which organizes as a rule behind the SW. We emphasize that in the given case, it arises near the contact discontinuity.

The characteristic lengths of zones of relaxation processes depend on the particles diameter. The influence of particles size on the diffracted SW structure in the mixture is shown in Fig. 3, where the computed results are presented for M=2, $\rho_{2,0} = 0.69$ kg/m^3, t=40 μs for two values of particles diameter: 3 μm and 5 μm. It is seen

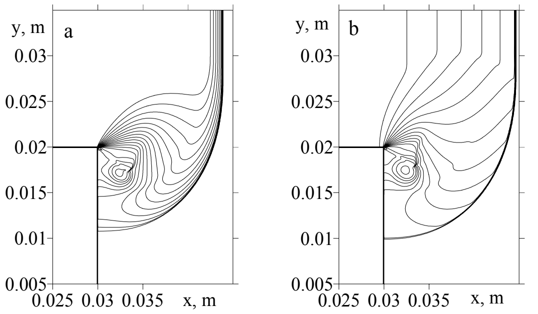

Fig. 3. Particles size influence on the wave pattern. Density contours of gaseous phase. a — d= 3 μm, b — d=5 μm.

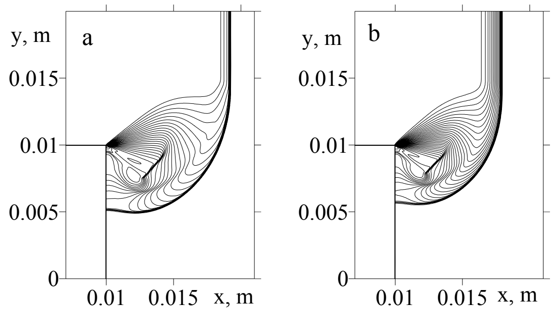

Fig. 4. Influence of the particles loading in the gas-particle mixture on flow pattern, M=3, t=16·μs: a – $\rho_{2,0} = 0.27$ kg/m^3, b - $\rho_{2,0} = 0.69$ kg/m^3

from the comparison of Fig. 3,a and Fig 3,b that an increase in particle diameter leads to a change in the inclination angle of the secondary shock so that the vortex region shape and the expansion fan shape change. For the maximum considered particle diameter (5 μm) the relaxation zone is so large that the flow behind the backward-facing step is practically frozen, that is it approaches the one realizing in a non-dusty gas.

Influence of the particles mass loading on the diffraction pattern is shown in Fig. 4. For a low particles content in the mixture the pattern nearly coincides with the one realizing in gases. It is seen in Figs. 4, a and 4, b that when the particles concentration increases by an order of magnitude and higher the effects manifests themselves, which are related to the influence of relaxation zones: the bending of expansion waves, alteration of flow character between the diffracted SW front and the contact discontinuity and of the flow in vortex zone. Thus, the influence of particles on the flow is substantial already at the values of relative mass concentrations of particles $\xi_2 = \rho_{20}/(\rho_{20} + \rho_{10})$ of the order of 0.1.

4 Detonation diffraction in gas – particle mixture

Some preliminary results of detonation wave dynamics in the duct with a sudden expansion of the cross-section area filled with the mixture of reacting aluminum particles and oxygen are obtained. Propagation of plane overdriven heterogeneous detonation waves for three different points of time is presented in Fig. 5. The decaying wave intensifies due to diffracted and then reflected wave. As with gas mixtures [2, 3] further development of detonation process depends on ratio of the transverse sizes of the duct narrow and wide parts, particle size (Fig.6) and particle loading. We suppose that both an extinction of detonation with subsequent reinforcement caused by diffracted wave reflection at the duct wide part walls, and the detonation breaking with subsequent re-initiation. Analysis of the relaxation processes influence on the conditions of stable detonation process retaining and cellular detonation behaviour in conditions of complex geometry are the subjects of following investigations.

5 Conclusions

- The problem of shock wave propagation in a gas-particle mixture in a flat duct with a cross-sectional jump has been investigated numerically within the framework of a physical-mathematical model of the mechanics of heterogeneous media in the two-velocity and two-temperature approximation.

- It has been found that on the whole, the flow structure in mixture at the SW diffraction on a cross-section discontinuity qualitatively corresponds to a similar flow in gases. The presence of particles, however, affects the shape and dimensions of the forming flow structures.
- The influence of particles mass loading at the values of mass concentrations of the order of 0.1 and higher affects significantly the expansion fan shape, the flow between the diffracted SW front and the contact surface, and the flow in vortex zone.
- The influence of particle size on diffraction pattern is the most pronounced in the time interval when the typical dimensions of structures are comparable with scales of relaxation zones.
- The overdriven plane detonation waves behaviour in gas-particle mixtures in the ducts with a cross-sectional discontinuity also is similar to the same processes in gas.

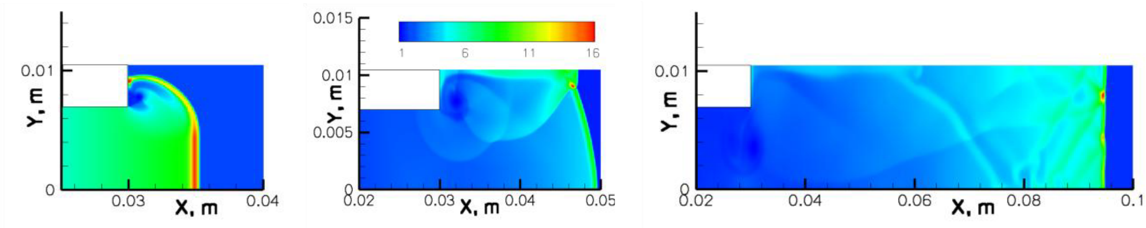

Fig. 5. Development of detonation diffraction, gas density fields, $H_2/H_1=1.5$

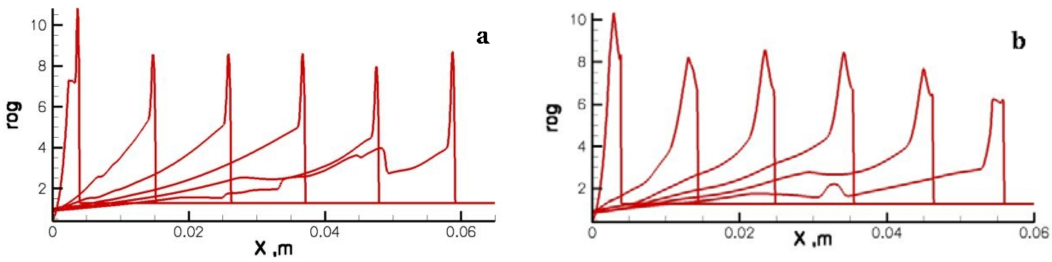

Fig. 6. Gas density profiles, $H_2/H_1=1.5$. a – d=1µm, b – d=3µm

6 Acknowledgements

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