Cellular Detonation Diffraction in Gas - Particle Mixtures

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1 Introduction

The urgency of investigations on heterogeneous detonations in gas suspensions of small solid particles is caused by both problems of hazard, and development of the technologies based on application of detonation processes, in particular, for providing the propulsion in new generation of engines. Therefore, analysis of the specific features of distribution of detonation waves in channels of the technical devices characterized with complex geometry is a subject of interest. The typical configuration is a channel with sudden expansion.

The problems of detonation propagation in channels with an abrupt cross-sectional rupture are well studied for gaseous mixtures. Similar problems of heterogeneous detonation in gas suspensions of solid particles were investigated in very few works. In [1] within the limits of physical and mathematical model of heterogeneous detonation in aluminum particle oxygen suspensions the processes of a planar detonation wave withdrawal from a plane channel into unconfined volume were investigated numerically. Existence of three different regimes of propagation of the heterogeneous detonation, inherent as well to mixtures of reacting gases has been established: subcritical (detonation failure), critical (partial failure with the subsequent reignition), and supercritical (continuous detonation propagation). Essential differences of the flow structure behind the backward step in gaseous mixtures comparing with gas mixtures, in particular, different configurations of the combustion front shape were revealed. These differences are connected with influence of the relaxation processes of phase interactions which scales are determined by the particle sizes. Therefore transition from one regime to another depends not only on geometrical parameters (width of the channel), but also from the sizes of particles. It has been established, that in some cases there is a transition to a cellular detonation mode of the wave propagation.

In [2] similar research was performed taking into account the effects caused by the presence of the walls in a wide part of the channel, and also influence of distribution of particles in their sizes in polydispersed mixtures. Possible scenarios of the flow evolution after the reflection of the diffracted wave from the wall in different regimes of detonation wave propagation described and analyzed in [1] and influence of geometrical parameters and the particles sizes were studied. Formation of the cellular detonations has been shown. Some differences in the flow pictures formed in the channel with an abrupt expansion from cellular detonations formed in plane channels owing to development of small disturbances are revealed.

The present work is an extension of the studies [1, 2] and focuses on investigation of propagation of the cellular detonation in gas suspensions in channels with an abrupt expansion of the cross-section. The purpose of the work is the analysis of cellular detonation diffraction in aluminum particles oxygen

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suspension on the backward step: 1) determination of scenarios of detonation propagation after the passage of the channel cross-sectional breakdown; 2) the analysis of influence of the size of particles of a monodisperse suspension and geometrical parameters of the channel on the flow development in various regimes.

2 Problem Formulation

The problem considers a flat duct with an abrupt expansion of the cross section, filled with a homogeneous stoichiometric mixture of oxygen and fine aluminum particles. The duct is assumed to be symmetric with respect to the x axis; therefore, it is sufficient to consider its upper or bottom part (Fig. 1). A developed cellular detonation wave propagates along the duct in the gas-particle mixture. We investigate passage of this wave from the narrow part of the duct to the wide part. The channel geometry is shown in Fig. 1: L_1 is the initial location of the wave front; L_2 is the length of the narrow part of the duct; L is the length of the computational domain; H_1 is the width the duct narrow part, and H_2 is the width of the wide part.

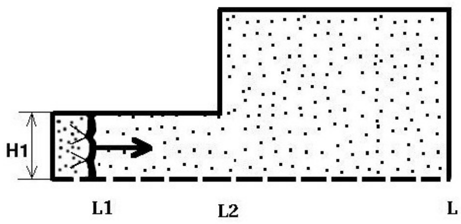

Figure 1.Flow scheme.

We use the same model and numerical technology as in [1, 2]. The mathematical model of detonation of aluminum particles in oxygen was developed in [3, 4] and verified by comparison with experimental data [5]. The model is based upon the concept of a two-velocity two-temperature continuum of the mechanics of heterogeneous media. Aluminum combustion is described as a reduced reaction initiated after the particle achieves a critical temperature (the ignition temperature) that accounts for incomplete particle combustion (due to the oxide film growth). The parameters values (ignition temperature, activation energy, heat release, and chemical reaction velocities) were determined from experimental data, including detonation velocity, ignition zone length and combustion delay. The numerical method includes the Harten TVD scheme for the gaseous phase and the Gentry-Martin-Daly upwind difference scheme for the solid phase dynamics. For convenience of numerical implementation of the two-dimensional TVD scheme for the current geometry, a planar channel of maximum width is used as the computational domain. At each time step, the computation is performed in the entire region. Then the boundary conditions on the walls of both narrow and wide parts of the channel are set as for isothermal slip walls.

The initial cellular detonation flow is obtained from the problem of cellular detonation formation in a plane channel under an action of a SW on a particle cloud with small local density perturbation [6]. The part of the solution including undisturbed flow, the leading SW and the detonation structure with a part of the adjacent rarefaction wave is posed as initial conditions in the calculations. The outflow conditions on the left boundary are applied at a sufficient value of L_1.

3 Characteristic features of the cellular detonation diffraction in gas-particle mixtures

A great number of experimental and theoretical works are devoted to the investigations of problems of gaseous detonation wave extension to an unconfined volume. Some universal law has been established at which the condition of continuous detonation propagation relates with the tube diameter and the number of detonation cells. For most gaseous mixtures critical diameter is about 10-13 cells, however this value can vary depending on the gas composition and some other parameters.

Since the wave structure of a heterogeneous detonation essentially differs from structure of a gas detonation (relations between the lengths of induction and combustion zones, processes of temperature and velocity relaxation between gas and particles) it is of interest to reveal similarity and distinction of corresponding processes in gases and gas- particle mixtures.

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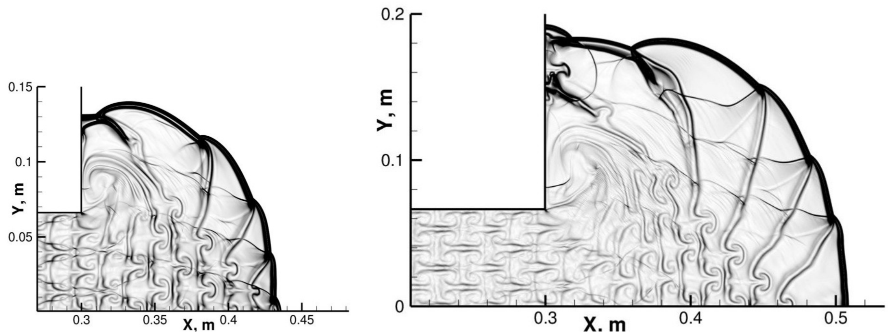

Fig.2. Numerical Schlieren images of gas density. d =2 μm

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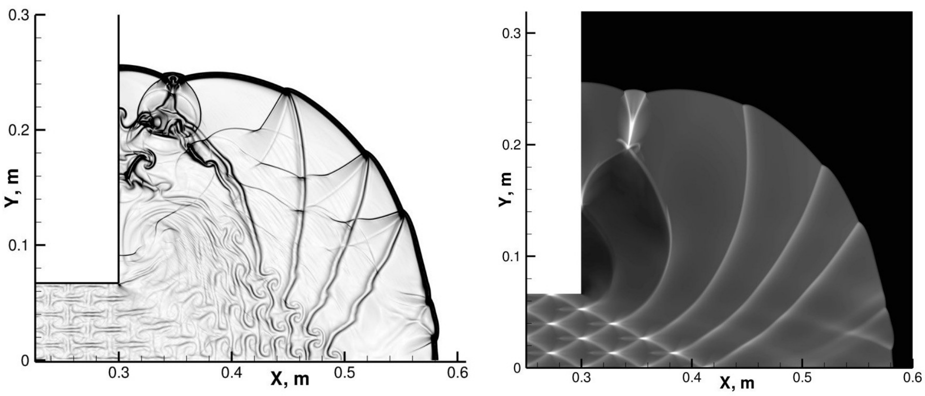

Fig.3. Detonation flow development behind the backward step. Numerical Schlieren image and maximal pressure history. d =2 μm.

The parametric study varying channel width (0.5 -4 detonation cells broadwise), and alumina particle diameter (1.5-3 μm) was carried out. Some results of calculations are shown on Fig. 2 in a monodisperse mixture of particles of diameter d=2 μm for two moments of the time with step of 5 μs. Here H_1=0.07 m, and 2.5 detonation cells occupy the half of the narrow part of the channel. It is obvious that the front expansion leads to an irregularity of cellular structure. Interaction of the rarefaction wave zone behind the backward step with the detonation front leads to separation of the shock wave and the combustion front in a region adjacent to the confining wall. Figure 3 shows numerical Schlieren images of gas density and maximal pressure history for next moment of time. Here the transverse waves reach the confining wall, which bounds the flow, and reflect from it. This leads to a detonation re-initiation in this area, and also brings an additional irregularity in the cellular structure. Thus, the given case concerns a critical regime of the detonation propagation. We should note that on the section of the front adjoining a symmetry axis of the channel, there is an origin of new transverse waves (Fig. 3) that is the result of development of fluctuations on the detonation front.

The detonation cell structure fails behind the backward step with the narrow channel width decreasing or particle diameter increasing. The process is illustrated in Fig.4. The example is shown for 3.5 μm particle mixture and initial channel width H_1=0.07 m (1 detonation cell). The shock wave and the combustion front in a region adjacent to the confining wall are also separated. As it can be seen from Fig.4 there is a layer of unburned particles between the shock wave and the combustion front. Transverse wave propagation along the layer could result in detonation re-initiation.

Thus, as a whole the scenario of detonation propagation in the critical regime corresponds to gaseous detonation flows where one of mechanisms of re-initiation of detonation at diffraction on a backward step is connected with collisions of triple points [7]. In work [8] it was also noticed, that occurrence of the transverse waves can lead to detonation re-initiation even when quantity of the cells on the initial front is less than the critical. Therefore, the mechanisms of the detonation re-initiation in the critical regime of propagation in gases and gas particle suspensions are close.

However it is necessary to notice, that in our calculations of suspensions of aluminum particles in oxygen the quantity of cells at which the re-initiation of the detonation process behind the backward step is possible, is not so much as in gas mixtures. Apparently, it is connected with influence of the velocity and thermal relaxation processes, and this question requires an additional research.

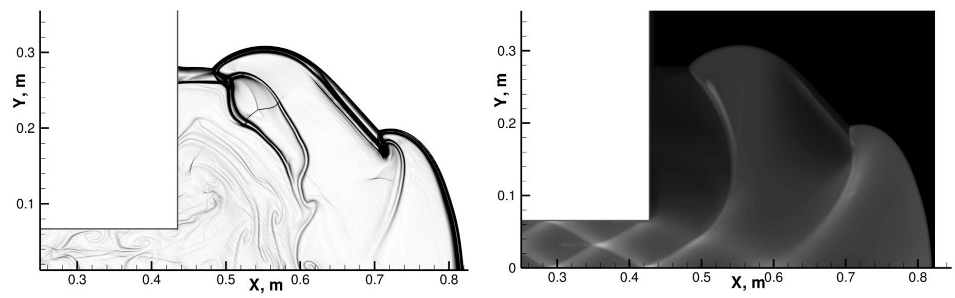

Fig.4. Detonation flow development behind the backward step.. Numerical Schlieren image and maximal pressure history. d=3 μm.

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