Research paper

Heterogeneous detonation propagation in channels with abrupt area expansion

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Abstract

Propagation of heterogeneous detonation in a monodisperse suspension of small aluminum particles in oxygen in a plane channel with abrupt area expansion is investigated numerically. Possible scenarios of the planar or cellular detonation transitions into the wide part of the channel are analyzed. Formation of cellular structure in the wide part of the channel with changing the cell size in the process of propagation is established. In the sustained regimes of propagation the cell size corresponds to the inherent value for a given mixture.

Keywords : particle gas suspensions, detonation, cellular detonation, duct flows, numerical modeling.

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1. Introduction

Investigations on detonations in gas particle mixtures are stimulated by both problems of hazard, and development of the detonation technologies. In industrial dust explosions shock and detonation waves propagate in rooms, conveyers, transporters, channel shafts, etc. Analysis of detonation wave propagations in volumes of complex geometry is a subject of interest. The typical configuration is a channel with sudden expansion.

Problems of detonation propagation in tubes and channels with abrupt area expansions have been investigated for gases (see, for example, Pantow et al[1]). Kutushev and Shorohova[2] studied the influence of particle concentrations on detonation in tube with area expansion filled with gas suspension of monofuel particles. The present work focuses on analysis of transition of planar or cellular detonations in aluminum oxygen suspensions through an abrupt area expansion of flat channels. The purpose of the study is to determine the influence of the channel geometric parameters and particle size on the propagation regimes.

2. Problem formulation and solution methods

The problem considers a plane channel with an abrupt expansion of the cross section, filled with a homogeneous mixture of oxygen and fine aluminum particles. We consider two types of detonation waves : (a) a complex of planar self-sustained detonation wave with an adjacent rarefaction wave and (b) a self-sustained cellular detonation wave. The numerical solution (a) is obtained from the problem of detonation initiation in a cloud of gas-particle suspension under a shock wave action. The developed cellular detonation wave in plane channel (b) is obtained from small disturbances in accordance with the method[3]. We investigate the passage of these waves from the narrow part of the channel to the wide part. The channel transverse sizes are denoted by H_1 and H_2 (Figure 1). The investigation is performed in the frame of the physical and mathematical model developed by Fedorov et al[4] and presented by Fedorov and Khmel[3], Kratova et al[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 in the frame of a reduced chemical kinetic model that allows for incomplete particle burning due to the oxide film growth. The reaction initiates when particles achieve a critical temperature, i.e., the ignition temperature.

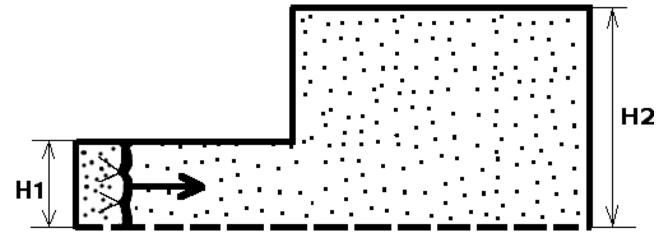

Figure 1 Flow scheme.

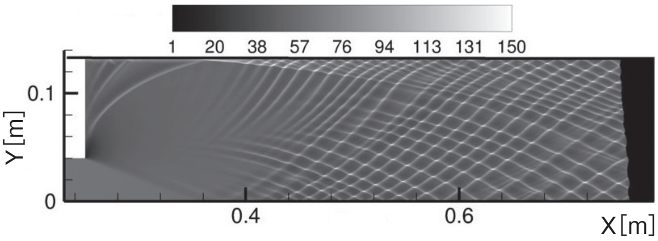

Figure 2 Initial stage of the cellular detonation formation in the supercritical regime, $d = 1\mu$m, $H_1 = 0.04$m, $H_2 = 0.132$m (maximal pressure histories).

3. Transition of a planar detonation wave through an abrupt cross-sectional expansion

Propagation regimes behind the step

Development of the detonation process in the channel with expansion is in many respects caused by initial stage of diffraction of the detonation wave on the backward-facing step and the realized detonation regime. This process was investigated by Kratova et al[5] for the gas-particle mixtures and the following specific features have been established. Three regimes of detonation propagation similar to gaseous detonations are possible: subcritical regime (detonation failure), critical regime (partial failure with subsequent recovery), and supercritical regime (continuous propagation of detonation). In contrast to similar processes in reactive gas media, the transition from one regime to another depends not only on the channel width, but also on the particle size in the gas suspensions.

Influence of the wall on the regime of following detonation propagation

In supercritical and critical regimes presence of the wall of the wide part of the channel does not lead to the regime change. Influence of the transverse wave formed due to the reflection of the diffracted detonation wave from the wall leads to reorganization of system of transverse waves existing at the detonation front. Figure 2 demonstrates the flow development in this regime. The transverse waves formed on the diffracted front are reflected from the wall. The reflected waves are imposed on the existing system of the transverse waves that causes reorganization of the already partially formed cellular structure. Figure 2 shows the trajectories of the triple points in the shadow picture of maximal pressure histories $p_{\max}(x, y) = \max[p(x, y, t)]$. Apparently at the initial stage of cellular detonation formation the trajectories of the triple points are substantially curved, and cells are non-uniform. At the process of following propagation the structure with the cell size inherent in a given mixture is formed.

In critical regimes, the wave front behind the expansion corner is divided into two parts: a detonation wave (in the neighborhood of the symmetry plane) and a shock decoupled from a lagging combustion front (close to the lateral wall). The wave propagation in the transverse direction slows down, and the flow structure in the region behind the backward-facing step is similar to the subcritical case. The detonation part of the front expands, becomes convex, and part of it propagates towards the wall of the backward-facing step. After the transverse wave reflection from the wall, the front propagation acquires supercritical features.

In these regimes the detonation reestablishment may occur in the wave reflected from the wall. Depending on the wall position, reflection can occur either on the part of detonation front, or on the part of shock front with lagging combustion front. Figure 3, a-c demonstrates the case where the detonation part is more developed and reaches the channel wall earlier than the shock. The transverse wave formed as a result of reflection, joining with the combustion front behind the ledge, promotes development of the disturbances related to the Richtmyer-Meshkov instability. Disturbances from the transverse wave generate new small-scale transverse waves at the front (Figure 3b). It leads to development of the cellular detonation (Figure 3c). Comparison of given results with the pictures obtained at initial reflection of the shock part of the front shows identical wave pictures in the front vicinity. Nevertheless, the cellular structure in the case presented in Figure 3 forms earlier than in the Figure 4 case.

Figure 4 demonstrates the detonation restoration in a subcritical regime under the action of the reflected wave. In this case the combustion front lags behind the leading SW on the part of the front adjoining the plane of symmetry (Figure 4a-b). The particles ignite in the reflected transverse wave, and owing to the energy release of particle burning the leading front accelerates (Figure 4b), that promotes reinforcement of the detonation process (Figure 4c-d). There is a formation of a secondary transverse wave, and then transition to the cellular detonation (Figure 4d).

Cellular detonation development

Wave patterns intrinsic to the cellular detonation form over time in all regimes of detonation propagation (Figures 2-4) in the wide part of the channel. When the channel width does not equal a whole number of natural cell size the structure of cellular detonations periodically changes in the propagation process (Figure 5). Here $K = L/H_2$, where L is the distance traveled by the detonation wave after the cross-sectional breakdown. Nikolis et al[6] observed in numerical simulations regular alteration of cellular structure of gaseous detonations during long-duration propagation in a plane channel. Also the transition process of propagation of cellular structure in a channel with an increase in cell size is 1.3 times has been obtained by Benkiewicz and Hayashi[7] in numerical simulation of the cellular heterogeneous detonation in a lean suspension of aluminum particles in oxygen.

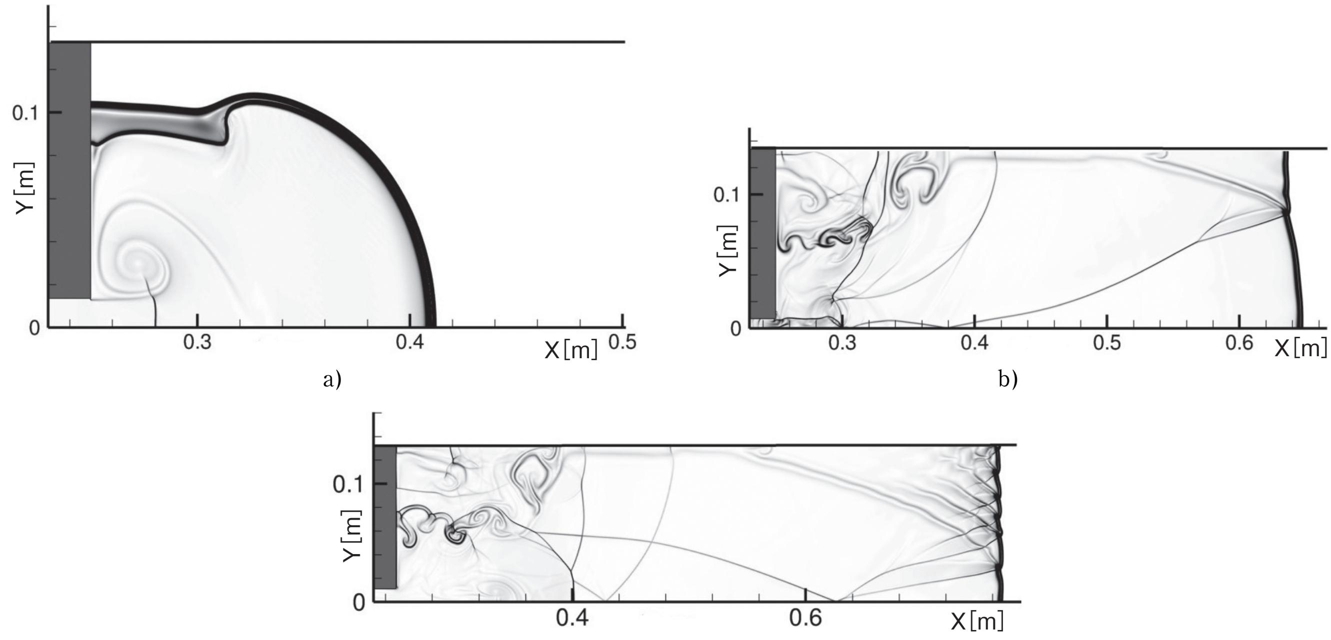

Figure 3 Critical regime with primary reflection of the detonation part of the diffracted front ($d = 2\mu$m, $H_1 = 0.013$m, $H_2 = 0.132$m) : $t = 0.24$ ms (a), 0.4 ms (b), 0.48 ms (c).

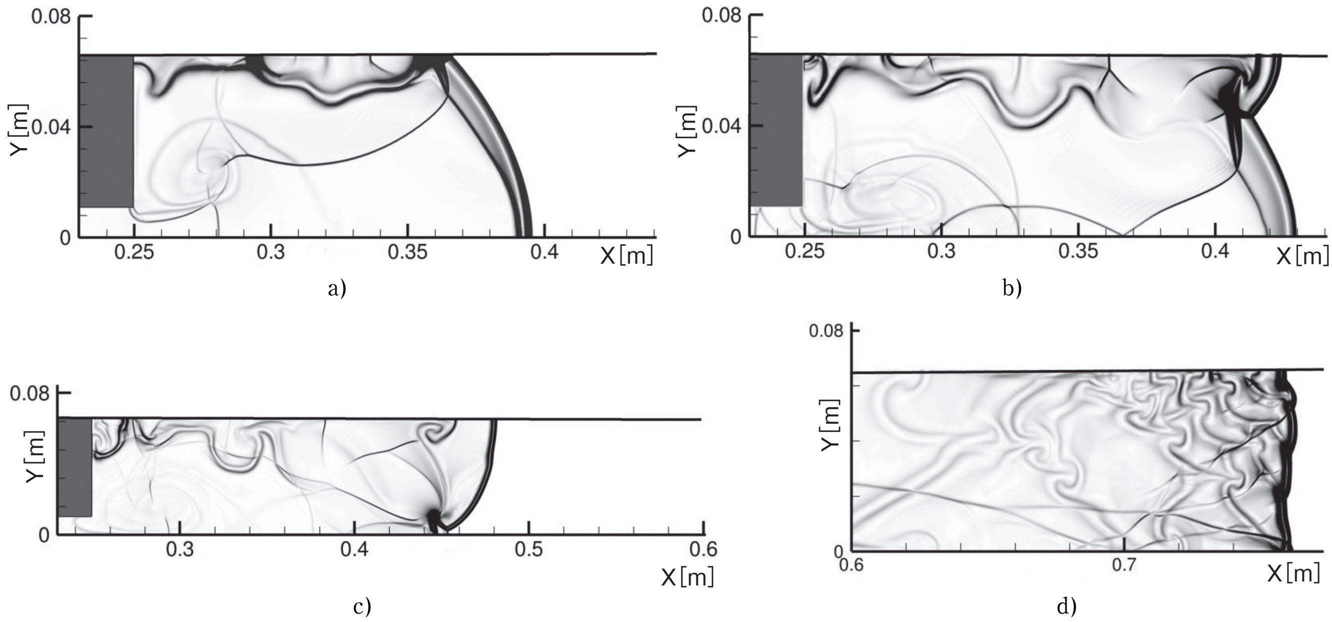

Figure 4 Detonation restoration in a subcritical regime ($d = 2\mu$m, $H_1 = 0.011$m, $H_2 = 0.066$m) : $t = 0.24$ ms (a), 0.28 ms (b), 0.32 ms (c), 0.5 ms (d).

4. Cellular detonation transition through a cross-sectional breakdown

Supercritical and critical regimes of propagation

For the cellular detonation exit into an open space Fedorov et al[8] obtained that critical number of cells in gas suspensions is much smaller than for gas mixtures. This is explained by a more complex structure of waves in the heterogeneous detonation, the presence of inter-phase relaxation processes and the mechanism of particle ignition different from the gas. A flow pattern of cellular detonation transition through the abrupt area expansion is shown in Figure 6. A comparison of Figures 2 and 6 demonstrates that the initial transverse waves insufficiently effect the detonation propagation away from the cross-sectional breakdown.

Reinforcement of detonation in subcritical regimes

In open space the detonation fails only at one transverse wave in the channel[8]. Figures 7-8 show the case of detonation re-ignition. This initial flow is asymmetric in y, therefore, shows both halves of the channel. Here, after the shock wave reflection from the walls two almost symmetrically located opposite transverse waves form, in which the detonation process reestablished fully. After the collision of the transverse waves (in Figure 7a for $x = 0.95$ m) the front propagation in the wide part of the channel takes places in the regime of cellular detonations with one cell per the width. In Figure 7b the structure of detonation waves is visible : a shock wave and the adjacent combustion front, as well as a vortex-like structure behind the front inherent in cellular detonation.

Figure 8 shows the case of detonation failing. Pantow et al[1] obtained that the influence of the walls on gaseous

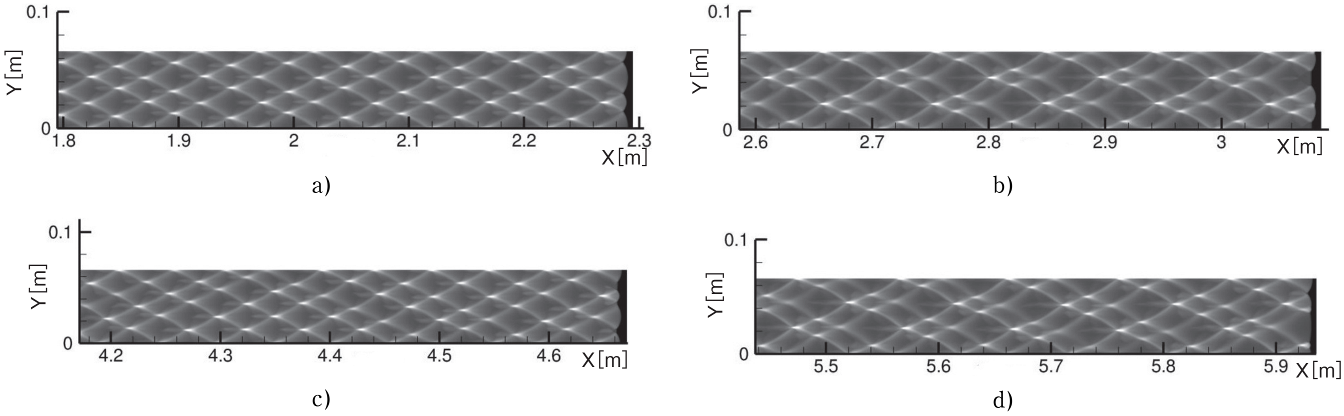

Figure 5 Transformations of the cellular structures during detonation propagation in wide part of the channel ($d = 2\mu$m, $H_1 = 0.012$m, $H_2 = 0.066$m) : $K \sim 30$ (a), 40 (b), 60 (c), 80 (d).

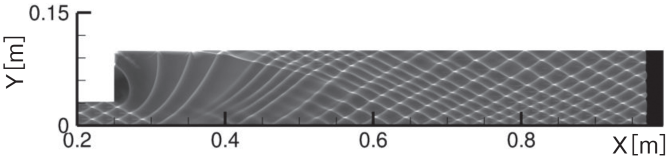

Figure 6 Maximal pressure histories of cellular detonation transition : $d = 1.5\mu$m, $H_1 = 0.033$m, $H_2 = 0.1$m.

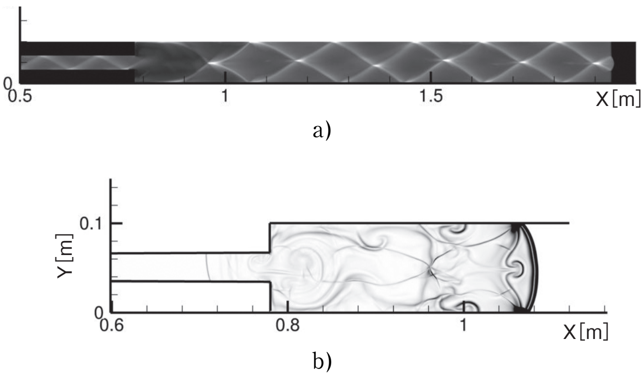

Figure 7 Reestablishment of cellular detonation in a subcritical regime, $d = 3.5\mu$m, $2H_1 = 0.033$m, $2H_2 = 0.1$m : maximal pressure history (a) ; numerical Schlieren, $t = 0.25$ ms (b).

detonation propagation in a plane channel with expansion was limited by $H_2/H_1 < 5$. In our case of 3.5μm particles the detonation continues at $H_2/H_1 \sim 3$ and fails at $H_2/H_1 \geq 4.5$, i.e. at values of the same order. But we should note that H_2/H_1 can not be a universal parameter of detonation transition due to dependence of the critical conditions on particle size[5].

5. Conclusion

Propagation of heterogeneous detonation in gas suspensions of aluminum particles in channels with abrupt expansion is investigated numerically. The following features of propagation of plane and cellular detonations in different regimes are established :

- In the supercritical and critical regime the transverse wave formed by reflection of the diffracted shock wave from the wall leads to the restructuring of the system of transverse waves at the shock wave front. Further propagation of detonation in the wide part of the channel is characterized by the transition to cellular detonations.

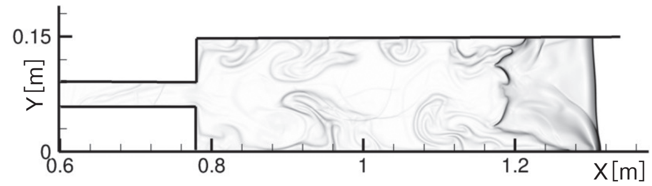

Figure 8 Detonation failing : $d = 3.5\mu$m, $2H_1 = 0.033$m, $2H_2 = 0.15$m, $t = 0.75$ ms.

- In the subcritical modes (with detonation failing at exit into an open space) the detonation re-initiation is possible under an action of the shock wave reflected from the wall. The parameters affecting the possibility of re-initiation, for a given mixture dispersion are the sizes of the narrow and wide parts of the channel.

Acknowledgments

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