# Cellular Detonations in Bidispersed Gas-Particle Mixtures

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## 1 Introduction

The propagation of detonation waves in heterogeneous mixtures can occur in the cellular detonation regime [1-4]. It was shown in [4] numerically and by acoustic analysis methods that in monodispersed gas-particle mixtures the distance between transverse waves (the transverse size of detonation cell) is related to geometric characteristics of the detonation wave structure and depends on particle size. On the basis of processing of data of numerical experiments an approximation formula was obtained for the detonation cell size in stoichiometric gas-particle mixtures of aluminum particles in oxygen

$$\lambda = \lambda_0 (d / d_0)^{\theta}, \qquad (1)$$

where $\theta = 1.6$, $\lambda_0 = 27$ cm, $d_0 = 10$ μm. The results agree with the data obtained numerically in [3] for lean monodispersed gas-particle mixtures with aluminum particles of size 3.5 μm and 1 μm in oxygen.

The actual mixtures are as a rule polydispersed and are characterized by a function of particle distribution over sizes. It is of interest to study the question of the cellular detonation existence in polydispersed gas-particle mixtures and the influence of the mixture fractional composition on the detonation character and the cell size.

The detonation processes in bidispersed oxygen - aluminum particle mixtures were investigated in [5]. The data on the influence of composition on conditions for initiation of planar waves and some preliminary results on the cellular detonation formation were obtained. In the present work, new data are obtained on the saturation parameter influence on the cellular detonation characteristics. Bidispersed stoichiometric gas-particle mixtures of aluminum particles in oxygen are considered. The formation of cellular structures is modeled numerically as a result of shock-wave initiation of detonation in a flat duct and a subsequent development of transverse waves. Results of numerical experiments agree with the estimates of cell size obtained within the framework of the acoustic approach according to the methodology of [6] developed for gas-particle mixtures in [4].

## 2 Formulation of the problem

The physical and mathematical model of non-ideal detonation of a stoichiometric gas-particle mixture of aluminum particles in oxygen has been developed earlier and applied for computation of cellular detonation flows in [4]. The Euler equations for mixture follow from the laws of conservation of mass, momentum, and energy for each phase. The system is completed by the equations of state, the relations expressing the interphase interaction as well as by equations of the reduced chemical kinetics of the Arrhenius type. An incomplete burning is taken into account in the description of the process of aluminum particle combustion, and a temperature criterion for ignition is adopted. A complete description of the model may be found in [4]. The numerical technology is based on the use of a scheme of the TVD class for the gaseous phase and the Gentry-Martin-Daly scheme for the discrete phase.

The initial- and boundary-value problem is posed as a problem of the shock-wave detonation initiation in a cloud of the gas-particle mixture occupying the half-space of a flat duct similarly to [4]. The values of the

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parameters of the initiating explosion shock wave are chosen in such a way that the conditions for detonation initiation in the mixture cloud are ensured. As in [4], a small monotonous perturbation of particle density at the cloud boundary $\rho_{p0}(x,y)=\rho_{st}(1+\beta\cos(\pi y/Y))$ for $X_{cl}\le x\le X_{cl}+\delta X$, $\rho_{p0}(x,y)=\rho_{st}$ for $X_{cl}+\delta X<x<+\infty$ is taken as an initiator of transverse waves. Here $X_{cl}$ is the cloud boundary coordinate, $\delta X$ is the perturbed layer thickness, $Y$ is the duct width, $\beta$ is a small parameter, $\rho_{st}$=1.34 kg/m$^3$ is the particles density in the mixture of stoichiometric composition. The computations were carried out for a duct 0.066 m in width and the gas-particle mixtures consisting of particles with size 3.5 μm, 2 μm, and 1 μm.

The bidispersed mixture composition is characterized by saturation parameter $\eta=\rho_{s0}/(\rho_{s0}+\rho_{l0})$. The subscripts *s* and *l* refer to the fractions of fine and large particles, respectively. The values $\eta=0$ and $\eta=1$ correspond to monodispersed suspensions of fine or large particles.

## 3 Results of Calculations and Acoustic Analysis

As was stated in [4], the cellular detonation develops in monodispersed aluminum particle oxygen suspensions for all values of particle size within the range 1 – 12 μm and is similar to the cellular gaseous detonation. At a divergence of transverse waves, a considerable decay of the front occurs. The pressure at the chemical peak point drops to 40 atm, which amounts to about 70% of the value corresponding to the CJ regime. The collision of transverse waves is similar to explosion (the pressure increases up to values of the order of 140 atm). The numerical maximal pressure history $p_{\max}(x,y)=\max_t[p(x,y,t)]$ is shown in Fig. 1 for mixtures 1 μm and 2 μm.

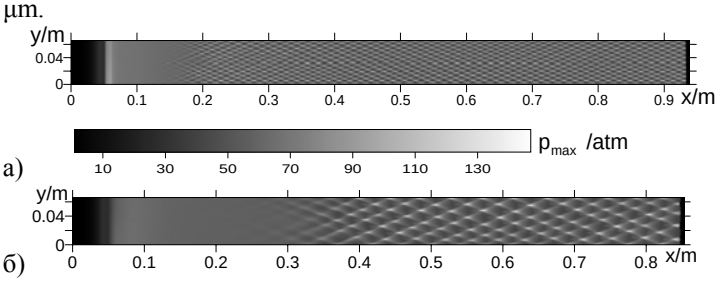


Fig. 1. Cellular detonation formation in monodispersed gas-particle mixtures *d*=1 μm and 2 μm.

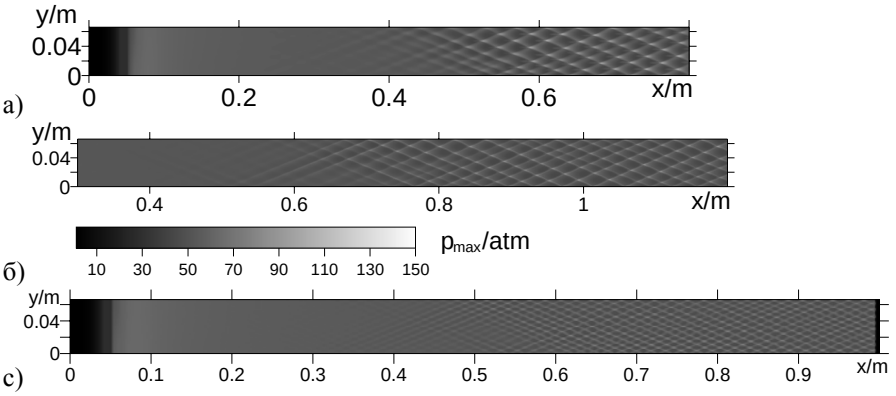


Fig. 2. Cellular detonation in bidispersed gas-particle mixtures 2 μm and 1 μm: $\eta=0.3$ (a), $\eta=0.5$ (b), $\eta=0.7$ (c).

Both the process and the result of cellular detonation formation in bidispersed gas-particle mixtures depend on the mixture composition and differ from monodispersed gas-particle mixtures. The distance between transverse waves (the typical size of a cellular-like structure) depends on the saturation parameter $\eta$ and varies from a

value corresponding to the monodispersed gas-particle mixture of the large fraction (2 cm) to a value corresponding to the fine fraction (0.69 cm) (Fig. 3a).

A longer formation of transverse waves than for $\eta = 0$ and $\eta = 1$ is the general property of cellular detonation in interval $0 < \eta < 1$. For example, in the monodispersed mixture of 1 μm particles a regular system of transverse waves manifests itself by 0.25 m of wave propagation, and of 2 μm by 0.45 m (Fig. 1). In the bidispersed mixture of 2 μm and 1 μm particles this distance increases up to 0.7 m for $\eta$=0.3 and $\eta$=0.7, and up to 1 m for $\eta$=0.5 (Fig. 2). There is, besides, a reduction of the amplitude of pressure oscillations at the chemical peak point (Fig. 3b), which is expressed also by a contrast reduction of Fig. 2 in comparison with Fig. 1, which are presented in the same grayscale. The trajectories of triple points are represented by nearly straight lines (Fig. 2). A relaxation of transverse waves and a reduction of the difference between the maximum and minimum pressure values at the collision of triple points evidence a certain degeneration of cellular detonation.

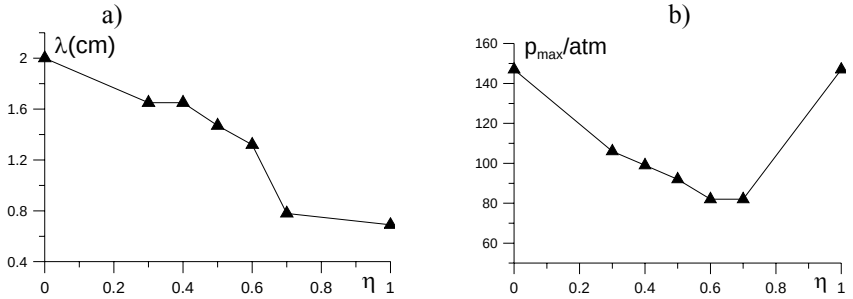


Fig. 3. The saturation influence on cellular detonation parameters in a bidispersed gas-particle mixture of particles 2 μm and 1 μm.

Furthermore, for some mixtures, for example, consisting of particles 3.5 μm and 1 μm, 3 μm and 1 μm, 3 μm and 2 μm, an interval of $\eta$ values (from 0.4 to 0.6) has been revealed within which the transverse waves do not form at all. (Or there is a formation of very weak dispersion transverse waves, Fig. 4a). Despite the initial disturbance presence, the detonation front remains planar (Fig. 4b). Thus, in these cases a complete degeneration of cellular detonation into a planar wave occurs. Outside the above interval of $\eta$ values, transverse waves and cellular-like structures forms, and their properties and character are similar to the ones described above for gas-particle mixtures 1 μm and 2 μm.

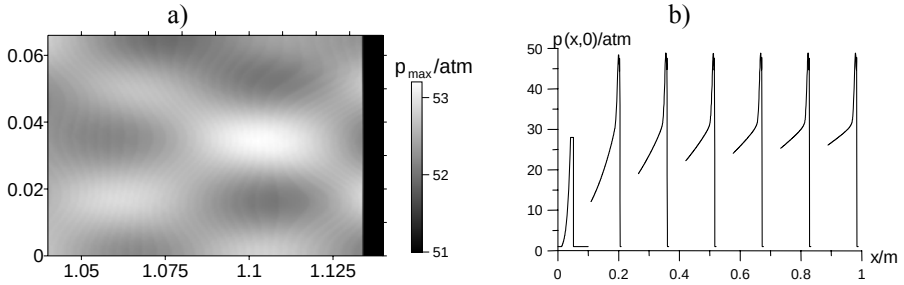


Fig. 4. Complete degeneration of the cellular detonation at $\eta$=0.5: 3.5 μm and 1 μm (a); 3.5 μm and 2 μm (b).

| $\eta$ | $\lambda_m$ | $\lambda_{num}$ | $\lambda_a$ |
|---|---|---|---|
| 0 | 5 cm | 4.4 cm* | 5.6 cm |
| 0.1 | | 4.4 cm* | 7.8 cm |
| 0.3 | | No cells | 16 cm |
| 0.5 | | No cells | Undetermined |
| 0.7 | | 0.94 cm | 0.90 cm |
| 0.9 | | 0.78 cm | 0.84 cm |
| 1.0 | 0.69 cm | 0.70 cm | 0.81 cm |

**Table**. Dependence of the cell size on the composition of a bidispersed gas-particle mixture 1 μm and 3.5 μm

The saturation parameter influence on the cell size and the property of detonation degeneration are confirmed by the data of acoustic analysis of the cell size by methodology of [6, 4]. The Table presents the data of acoustic estimation ( $\lambda_a$ ) in comparison with the data of numerical experiments ( $\lambda_{num}$ ) for the mixture of particles 3.5 μm and 1 μm and with the approximation formula (1) for monodispersed mixtures ( $\lambda_m$ ). Symbol (*) marks relatively narrow computational region [4]. It is seen that planar detonation wave in numerical computations for $\eta$=0.3 and $\eta$=0.5 is confirmed by that for these $\eta$ values, the cell size by the methodology of [6,4] is either not determined or is much higher than the duct width (6.6 cm). For $\eta \geq 0.7$ the "numerical" and the "acoustic" values of the cell size diverge by no more than 15%.

## 4 Conclusions

It is found by the methods of numerical modeling of the cellular detonation formation and acoustic analysis of the detonation structures in gas-particle mixtures of aluminum particles in oxygen that:

- In bidispersed gas-particle mixtures, the process and the result of cellular detonation formation depend on the mixture composition (the relative concentration of particles of each fraction);
- a longer formation of a regular system of transverse waves than in monodispersed mixtures is noted;
- cellular detonation in a bidispersed gas-particle mixtures is characterized by a reduction of the peak pressure values at triple points at their collision and a rectification of the trajectories of triple points;
- a complete degeneration of the cellular detonation into a planar wave takes place in some mixtures at certain saturation values, which is also confirmed by the acoustic analysis results.

Thus, not only the character and size of detonation cell but also the very existence of the cellular detonation in polydispersed gas-particle mixtures depends on the distribution of particles over their sizes.

The given result may be one of the explanations for the fact that in very few experiments on detonation of gas-particle mixtures of reactive particles, one succeeds in observing the cellular-like structures.

## 5 Acknowledgements

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