Analysis of Influence of Inert Particles on Cellular Heterogeneous Detonation Propagation

Fedorov A.V., Kratova Yu.V.
Khristianovich Institute of Theoretical and Applied Mechanics
Novosibirsk, Russia

1 Introduction

One of the means to suppress detonation, which propagates out of control, is the addition of inert particles to an explosive mixture. In what follows, the presence of particles in the reactive mixture can provide different conditions for mixture detonation up to its suppression. The available experimental investigations of detonation suppression by injection of chemically inert particles ahead of the wave front are concerned to a large measure with gaseous detonation. In [1], the state-of-the-art of this problem is described and some new results on simulation of this phenomenon in homogeneous media are presented.

The problem of interaction of heterogeneous detonation with a cloud of inert particles practically has not been investigated. Only in [2], the problem of propagation of a detonation wave in the mixture of gas and monofuel particles and its interaction with the cloud of finite-length inert particles has been studied numerically in one-dimensional approximation. For fixed cloud parameters (cloud length and particle size), it is found the minimal mass fraction of inert particles needed for detonation suppression. At the same time, the influence of the "two-dimensional effect" of flow on detonation wave propagation and suppression has not been considered in these computations. It is therefore of interest to study in detail the interaction of a heterogeneous detonation wave with a cloud of inert particles.

In this research the results of numerical modeling of cellular heterogeneous detonation propagation in a gas solid particle suspension containing of chemically inert particles are presented. The research focuses on transverse detonation wave influence on suppression processes and cellular structure changes during the process.

2 Problem formulation

We consider a flat channel filled with a homogeneous stoichiometric monodisperse mixture of oxygen and fine disperse aluminum particles and partly with alumina inert particle (Al_2O_3) cloud. From left to right in the channel, the cellular detonation wave propagates (Fig. 1). The initial cellular structures were determined from a numerical solution of cellular detonation formation in an extensive channel. The formation of cells was modeled as a consequence of the development of small perturbations on the plane detonation front, these perturbations being induced by small local inhomogeneity of the particle density. The interaction of cellular detonation with an inert particle cloud could lead to different propagation regimes: continued propagation or detonation failure. However, the transverse

Correspondence to: yulia@itam.nsc.ru

wave structure of the cellular detonation makes the wave pattern more complicated by contrast to the plane detonation. The work was aimed at determining the influence of the parameters of an inert Al_2O_3 particles (volume concentration of particles and their size) on the modes of heterogeneous cellular detonation propagation.

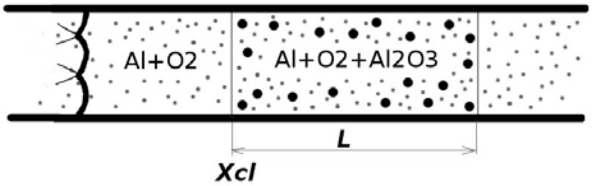

Figure 1. Flow scheme.

All computations were carried out for a mixture of 2 and 3-μm-dia aluminum particles at the stoichiometric concentration ξ_2 = 0.55 (volume concentration $m_2 = 6 \cdot 10^{-4}$). Parameters of the inert alumina were varied within the following range: particle diameter d_3 from 2 to 10 μm, volume concentration m_3 from 10^{-5} to 10^{-3}.

To describe the 2D detonation flows of mixtures of fine aluminum particles and oxygen the physical and mathematical model was used in two-dimensional computations, particular, in [3]. The model is based on principles of the mechanics of multi-velocity multi-temperature continua and verified versus known experimental data. The present work uses the model of a bi-disperse heterogeneous medium approach, one fraction of which is reactive (subscript i = 2) and the other, unlike the one from [4] is inert (i = 3).The numerical method based on the application of the TVD scheme for gas and of the Gentry–Martin–Daly scheme for particles was used [5].

3 Results

It has been shown that the continuous detonation propagation through a large–size inert particle (~10 μm) cloud is possible. The detonation continues to propagate in the cellular regime with reduced peak parameters (Fig. 2). The inert particles presence in the mixture resulted also in the cell structure alteration due to additional relaxation processes. The schlieren images (Fig. 3) allow to compare the wave patterns before and after the interaction with a inert particle cloud. In Fig.3 (right) one can see a detachment of the combustion front from the shock, diffuseness and drop in the image contrast behind the shock. The number of cells remains the same.

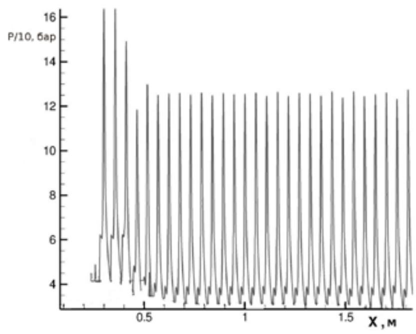

Figure 2. Maximum pressure envelope: Non–reactive particles: diameter d_3=10 μm, volume concentration $m_3 = 6 \cdot 10^{-4}$.

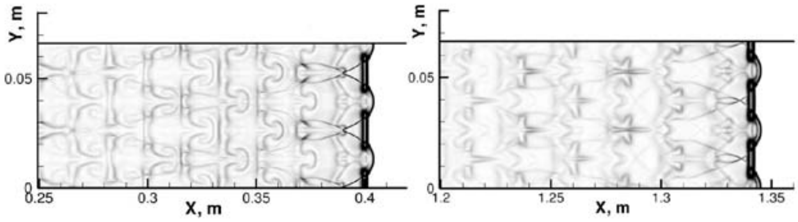

Figure 3. Comparison of wave pattern before (Left) and after (Right) the interaction of detonation with non–reactive particle cloud. Numerical Schlieren images of gas density. Non–reactive particles: diameter d_3=10 μm, volume concentration $m_3=6\cdot10^{-4}$.

The inert particles reallocate behind the shock front and can form ρ - layers at a distance of half–length cell (Fig. 4, top). If the inert cloud volume concentration is not so high, the inert particles collect along the longitude lines connecting triple points (Fig. 4, bottom). The particle distributions imitate the cells and save their forms far away from the shock front. In [6] the effect of particle-to-particle collisions on the process was analyzed for the same problem.

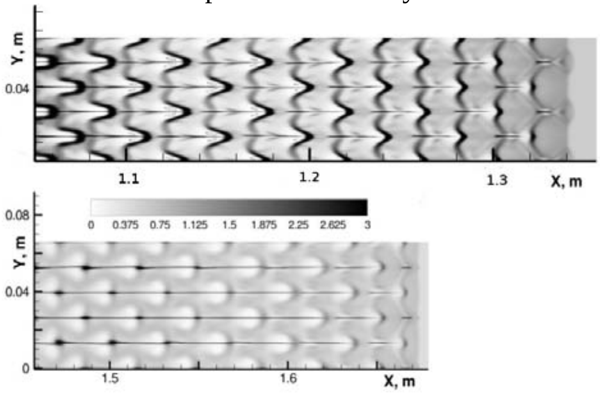

Figure 4. Inert particle density fields. Top: m_3=6 10^{-4}, d_3 =10 μm; bottom: $m_3=10^{-4}$, d_3 =4 μm.

The decrease in the inert particle diameter down to 2 μm results in lowering of the wave velocity to 750 m/s. Figure 5 shows the gas temperature and maximal pressure fields illustrating a detonation suppression process. It is evident that shock detachment takes place already at x=0.5 m (in 0.1 m after the initial cloud position). The cellular detonation wave degenerates into a shock one.

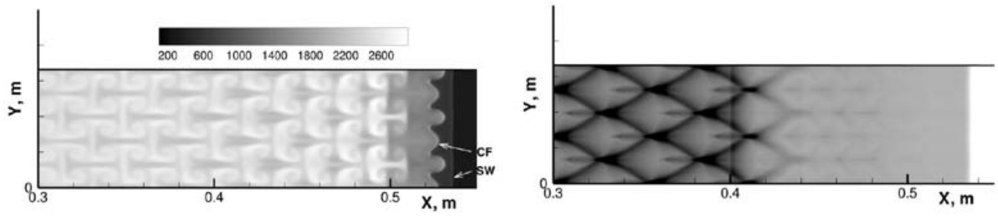

Figure 5. Detonation suppression. Left: gas temperature; Right: maximal pressure history; (CF – combustion front, SW – shock wave). Reactive particle diameter d_2= 2 μm, inert particles: diameter d_3=2 μm, volume concentration $m_3=6\cdot10^{-4}$.

It is also of interest to estimate a critical cloud length (the cloud length that is sufficient to suppress a detonation process) in the case of cellular detonation for defining influence of transversal waves on suppression process. The cloud length varies from 0.1 to 0.4 m.

In the shortest cloud length case the inert particles have not practically any effect on detonation propagation (Fig. 6, top). The wave structure reestablishes very quickly. Increasing the cloud length to 0.15 and 0.2 m results in detonation slowing–down and the essential cell irregularity appeared after the cloud exit (Fig. 6, bottom). Without inert particle exposure the cell regularity re-establishes eventually. In contrast, the cloud of 0.4 m in length leads to complete detonation failure. In Figure 7 the distance between the combustion front and the shock is irreversible large for detonation re-initiation.

Thus, the critical cloud length sufficient to suppress cellular detonation is twice longer than that was obtained for CJ detonation suppression with the same mixture and cloud parameters.

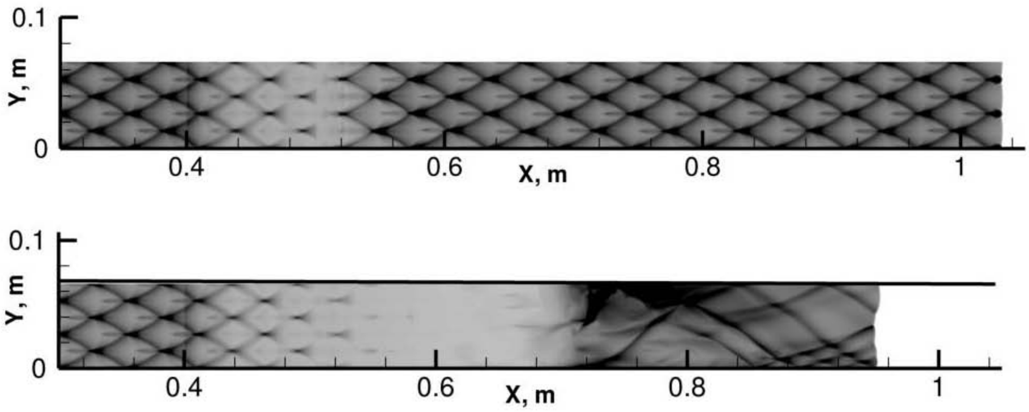

Figure 6. Re-initiation after the interaction with a finite length cloud. Top: L=0.1 m; Bottom: L=0.2 m; the inert cloud parameters: d_3=4 μm, $m_3=6\cdot10^{-4}$.

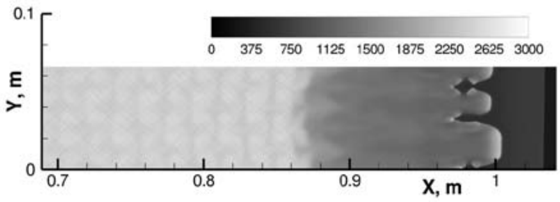

Figure 7. Detonation failure after the interaction with a finite length cloud, L=0.4 m, two sequent time moments; gas temperature. The cloud parameters: d_3=4 μm, $m_3=6\cdot10^{-4}$.

It is known that the formation of a uniform cloud of particles in practical conditions is complicated. Thus, it is of interest to study out the influence of inert particle density non-uniform distribution on suppression processes. Let us consider a mixture of 3 μm-dia aluminum particles. The mixture is characterized by one cell flow that realizes in the channel of 0.66 m width.

The calculations show that the detonation interaction with a uniform cloud of 2 μm-dia inert particles results in detonation failure, on the contrary, the 10 μm-dia particle cloud allows a detonation wave to propagate continuously. Non-uniformity of inert particle distribution can have effect on propagation processes. We consider a semi-infinite cloud with the density distribution function that changes linearly from the 50% initial value at the channel top boundary to the 150% at the bottom one.

In Fig. 8 the gas temperature and maximal pressure history fields are shown. Detonation fails as well as for a uniform cloud does. At the same time the flow asymmetry and a small distance between the shock and combustion front near the top boundary let a possibility of a re-initiation process. In the case of 10 μm-dia particle cloud the non-uniformity first leads to the cell structure degeneration into one transverse wave and then to complete detonation wave destruction (Fig. 9).

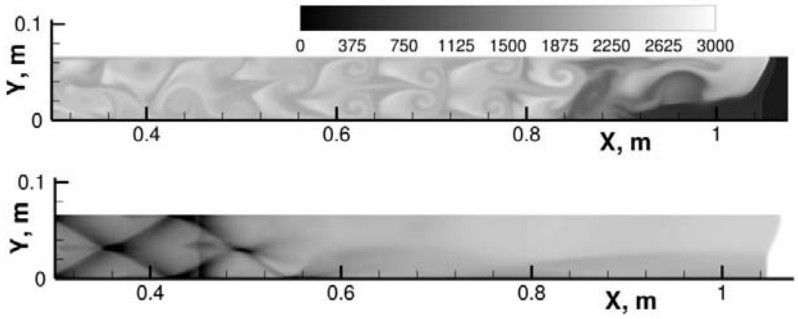

Figure 8. Cloud non-uniformity effect. The cloud parameters: d_3=2 μm, m_3=6·10^{-4}; Top: gas temperature; Bottom: maximal pressure.

The influence of the particle size distribution on the character of cellular structure suppression was also investigated. We consider a bi-disperse inert mixtures consisted of 2 and 10 μm particles. An effect of a half-infinite monodisperse cloud of 2 μm particles on detonation wave propagation results in a complete detonation suppression. In contrast, a 10 μm inert cloud allows a detonation to propagate without a failure. The calculation results show that the scatter of the inert particle size have an effect on a detonation structure. In Fig.10 the maximal pressure history is presented as an example of the mixture consisted of 20% 2 μm and 80% 10 μm. One can see that a change of the cellular structure takes place: after x=1.1 m (0.7 m after the start of the interaction with the cloud) the initial 2.5 cellular cells transform into 1.5 irregular ones.

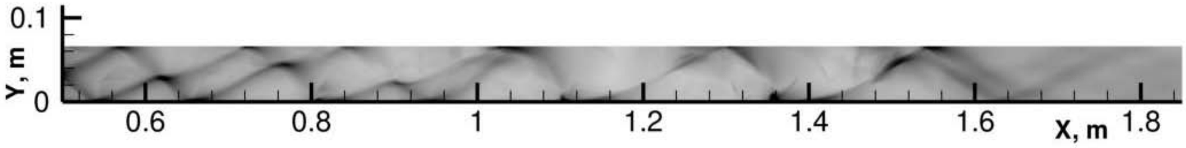

Figure 9. Cloud non-uniformity effect. The cloud parameters: m_3=6·10^{-4}, d_3=10 μm; maximal pressure history.

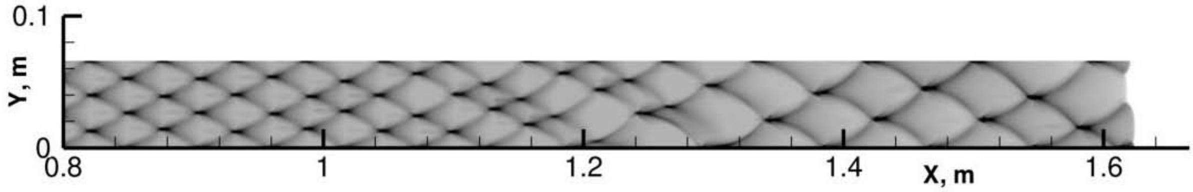

Figure 10. A scatter of the inert particle size effect. The cloud parameters: m_3=6·10^{-4}, d_3: 20% 2 μm and 80% 10 μm; maximal pressure history.

Conclusions

The 2D numerical simulation of cellular detonation propagation in stoichiometric suspension of aluminum particles and oxygen and partly inert particles has been performed. It has been shown that the chemically inert solid particle additives lead to the changes in the detonation characteristics and detonation failure. Three propagation regimes are possible.

The minimal cloud length for detonation quenching has been found, so suppression conditions are determined.

The influence of inert particle dispersion and volume concentration on the detonation suppression has been demonstrated. The effect of non–uniform inert particle distribution across the cloud and the inert particle size distribution on propagation regimes has been considered.

Acknowledgments

The study was supported by the Ministry of Education and Science of Russian Federation, project 14.B37.21.0645 and the Russian Foundation for Basic Research No. 12-07-33064, 13-08-00110.

References

[1] Fedorov A.V., Fomin P.A., Fomin V.M., Tropin D.A., Chen J.-R. (2012) Mathematical Analysis of Detonation Suppression by Inert Particles. Kao Tech Publishing (ISBN 978-986-88423-0-4).

[2] Kutushev A.G., Pichugin O.N. (1993) Numerical investigation of the process of interrupting the detonation wave propagation in monofuel gas suspensions using an inert particle layer. Combustion, Explosion and Shock Waves. 2: 215.

[3] Fedorov A.V. and Khmel' T.A., Numerical Simulation of Formation of Cellular Heterogeneous Detonation of Aluminum Particles in Oxygen (2005) Combustion, Explosion, and Shock Wave. 4: 435.

[4] Fedorov A.V. and Khmel' T.A. Formation and degeneration of cellular detonation in bidisperse gas suspensions of aluminum particles (2008) Combustion, Explosion, and Shock Wave. 3: 343.

[5] Khmel T.A. Numerical modeling of 2D detonation flows of reactive gas-particle mixtures (2004) Mathematical modeling. 6: 73.

[6] Fedorov A.V., Khmel T.A. Description of Shock Wave Processes in Gas Suspensions Using the Molecular-Kinetic Collision Model (2012) Heat Transfer Research. 2: 95.