Detonations in Densely Obstructed Channels

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1 Introduction

Channels with obstacles provide a convenient environment where we can control the flow inside the channel by changing the obstacle configuration and thus have been extensively used for the studies of flame acceleration and detonation propagation. The obstacles mounted in a channel have effects on both hydrodynamic and wave motion of the flow in the channel. Turbulence promotion is one of the effects on hydrodynamic motion. Separated flows over obstacles generates vorticities through Kelvin-Helmholtz instabilities and intensify perturbations in the flow. Obstacles reflect shocks and pressure waves and cause more interaction between shocks and flames triggering Richtmyer-Meshkov instabilities. These effects of obstacles convolute the flame and increase its speed resulting in fast flame acceleration. On the other hand, obstacles also have adverse effects on flame acceleration and detonation propagation. Detonation is quenched by diffraction from obstacles and split into a shock and a flame. Hence, channel height and obstacle configurations determines how the obstacles affects flame acceleration and detonation.

In the past studies[1, 2, 3], we simulated flame acceleration and deflagaration-to-detonation transition in channels with obstacles and observed three different regimes of detonation propagation depending on channel heights. For channel height d narrower than the detonation cell size λ, the choking regime is observed, and detonation cannot propagate over obstacles and becomes fast deflagration. In the quasi-detonation regime for d larger than a few detonation cells, detonation is extinguished by diffraction and split into a shock and a flame, but the shock colliding with obstacles reinitiates the detonation. Extinction and reinitiation of detonation repeatedly occur in this regime. For larger channel heights, detonation propagates virtually without being affected by obstacles. These three regimes are also observed in experiments[4, 5, 6], and have been considered to depend on the channel height.

In this study, we simulate detonation in densely obstructed channels. We use the obstacle spacing much smaller than that used in the literature and study the effect of obstacle spacing on detonation.

2 Numerical Method and Configuration

The governing equations are the two-dimensional, compressible, Navier-Stokes equations including the convection of unburned material, chemical reaction and energy release, molecular diffusion, thermal conduction, and viscosity. The equation of state is that of the ideal gas. An adaptive mesh refinement method[7] is used for discretization, and the mesh is dynamically refined at flames, shocks, and detonations. The scheme for the convective terms is a second-order Godunov method.

The reaction model is based on one-step Arrhenius kinetics including the parameters of the preexponential constant and the activation energy. These input parameters are calibrated to reproduce the laminar flame speed, the flame thickness, the detonation velocity, and the detonation cell size for the stoichiometric H_2-air mixture at 1 atm and 293 K. The detonation cell size of the mixture is 1–2 cm.

The computational configuration is shown in Fig. 1. The obstacles are evenly mounted on the channel wall with spacing S throughout the whole channel. The channel height is d, and the obstacle height d' is $4/d$, which corresponds to the blockage ratio of 1/2. In staggered configuration, obstacles on the top wall are shifted by $S/2$. The channel is filled with a stoichiometric H_2-air mixture at 1 atm and 293 K. and the flow is initially at rest. The minimum mesh size is $\Delta x = 1/512$ cm, which corresponds to 10 cells in the half-reaction thickness of a ZND detonation.

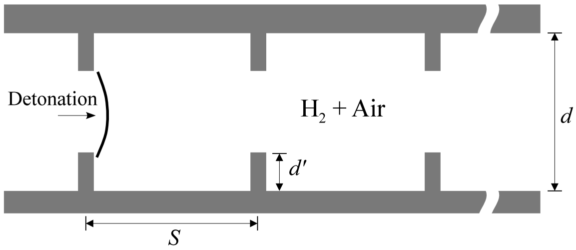

Figure 1: The computational configuration of a channel with obstacles. The height of the channel is d. The obstacles are placed with the spacing of S along the whole channel.

3 Result and Discussions

The channel height used in this study is $d = 4$ cm, which falls in the quasi-detonation regime by the criterion based on channel heights[6]. In our previous computation with this channel height and obstacle spacing of $S = d$[1], we observed quasi-detonation in accordance with this criterion.

Here, we consider shorter obstacle spacing. A computational result for the obstacle spacing $S = d/4 = 1$ cm is shown in Fig. 2. The obstacles are mounted in staggered configuration. The time sequence of the temperature contours in Fig. 2a–f shows detonation propagation in the channel. When the detonation passes the obstacle denoted by "A" at t=2.480 ms (Fig. 2a), it partially decouples into a shock and a flame near the obstacle because of expansion behind the obstacle. The detonation, however, reaches the next obstacle "B" by t=2.483 ms (Fig. 2b) before being fully extinguished. Thus, the center part of the detonation propagates without being affected by the obstacles, and its propagation speed is almost steady and about the CJ value.

The decoupled shock between the obstalces "A" and "B" reinitiates detonation when it collides with the top of the obstalces "B" (Fig. 2b). Then, the detonation spreads in the pocket of the unburned gas between the obstacles and propagates towards the channel wall (Fig. 2c). Figures 2d-e show that the detonation reflected from the channel wall propagates back to the center of the channel as retonation. When this retonation goes out of the pocket, it merges into the secondary shock behind the detonation as shown in Fig. 2f. Bychkov et.al.[8] reported that jet flows from the pockets between obstacles contribute flame acceleration in low Mach number regimes. Here, for detonations in an obstructed channel, detonation and retonation in the pockets create the strong secondary shock following the leading detonation.

This secondary shock is composed of the shocks emitted from the pockets of the obstacles. The structure of the secondary shock is more clearly depicted by the pressure contour plot in Fig. 2g. The emitted shocks cylindrically propagate from the pockets of the obstacles towards the center of the channel, and they overlap as transverse waves forming the secondary shock. The structure of the secondary shock is similar to the multi-head structure of detonation. The transverse shocks are emitted at the interval of Δt, the time period that the leading detonation takes to go across the obstacle spacing, and thus the "cell" size λ' of the secondary shock can be written as $\lambda' = c_s \Delta t$, where c_s is the speed of the transverse shock. The detonation and the retonation in the pocket travel $2d'$ after the reinitiation at the top of an obstacle, where d' is the obstacle height. Thus, the secondary shock is about $S + 2d'$ behind the leading detonation and propagates with the same speed. In the present computation with $d' = S$, the distance between the detonation and the secondary shock is about $3S$, three obstacle spacings, which agrees with the result observed in Fig. 2g. The pressure profile along the center line of the channel at t=2.495 ms is also shown in Fig. 2g. The secondary shock is at x=110.2 cm and is followed by the overlapped transverse shocks whose pressure profiles are similar to that of a cylindrical shock. The pressure increase of the secondary shock in this case is about 1 MPa.

4 Summary

Numerical simulations of detonation in a densely obstructed channel show that the obstacle spacing as well as the channel height affects the propagation regime of detonation. For the channel height we used in this study, the quasi-detonation regime was observed for wider obstacle spacing. For shorter obstacle spacing, however, detonation propagates at CJ velocity virtually without being affected by obstacles, since it reaches the next obstacle before being extinguished by diffraction. It is also found that the detonation is followed by a secondary shock, which is composed of transverse shocks generated by local explosion in unburned gas between the obstacles left behind the detonation.

Acknowledgements
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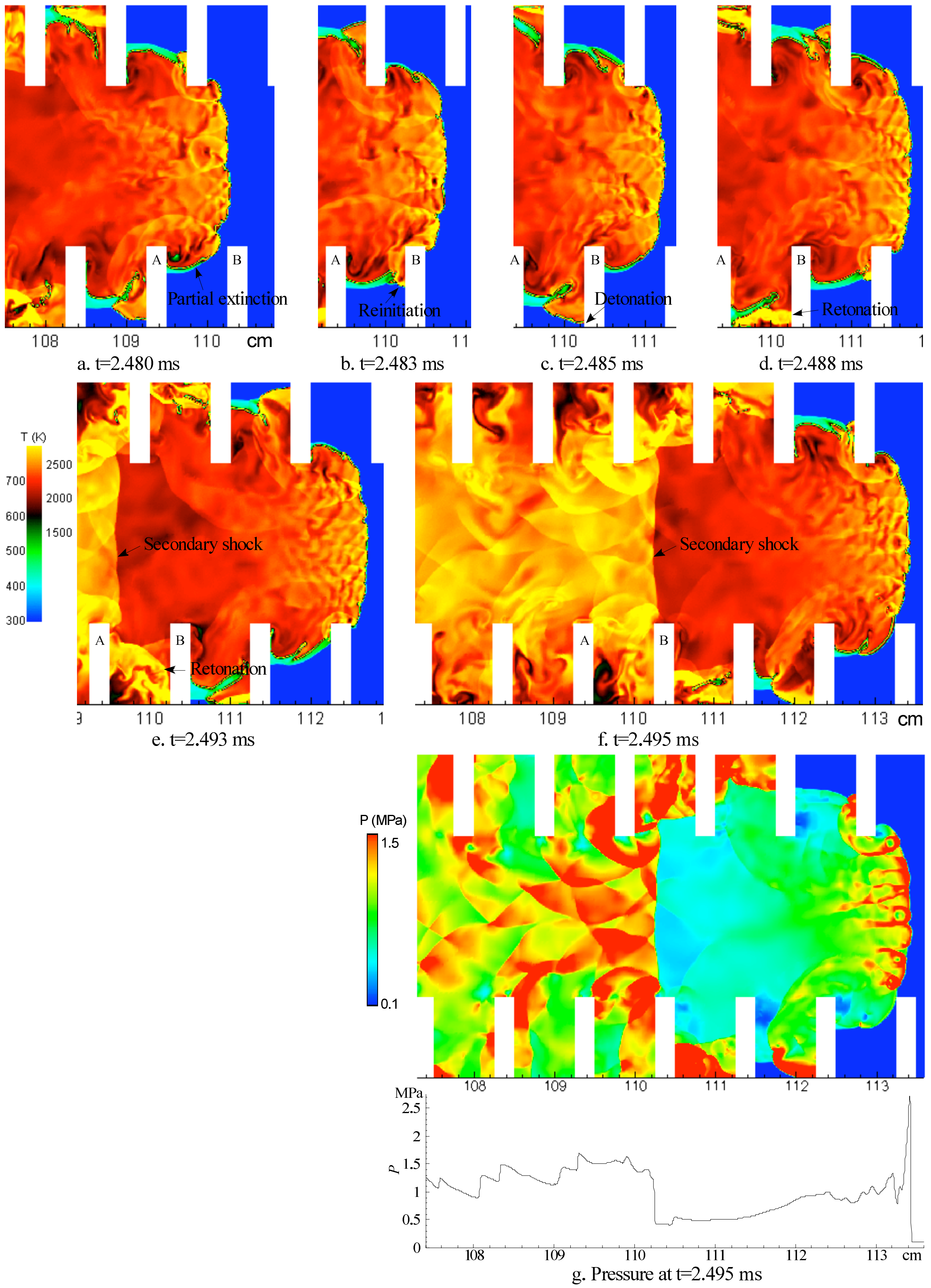

Figure 2: (a)–(f). Temperature contour plots and (g) pressure contour and profile along the center line for channel height d=4 cm and obstacle spacing $S = d/4$. Times in milliseconds are shown below each figure.