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Study of the direct initiation of spherical detonations

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Summary An analysis of the direct initiation of gaseous detonations in spherical geometry is presented, for a Mach number close to unity (small heat release). In this limit, the evolution is described by a Burgers equation, modified by a reaction and a curvature term. The solutions of this equation are presented in a pulsating detonation case.

INTRODUCTION

The direct initiation of a spherical detonation has attracted a lot of attention, starting with the suggestion of Zeldovich that a successful initiation requires that the time to reach the Chapman Jouguet (CJ) velocity is larger than the reaction time. This criterion leads to a critical radius of the order of the detonation thickness of the planar CJ detonation. It was shown experimentally that this critical radius is much too small. A quasi-steady analysis by He and Clavin [1] (see also [2]), using a square wave model, showed that the curvature of the detonation leads to a turning point representative of a curvature-induced quenching; the spherical CJ velocity has a C-shaped curve (see Figure 1) and the quasi-steady solutions exist above a critical radius much larger than the detonation thickness. However the quasi-steady approximation is not fully satisfactory and cannot reproduce the behavior of DNS trajectories, especially near criticality [1],[2],[3]. A theoretical model with an inner structure more realistic than the square wave model, will be used to assess the role of the unsteady effects, in the case of successful initiations or failures.

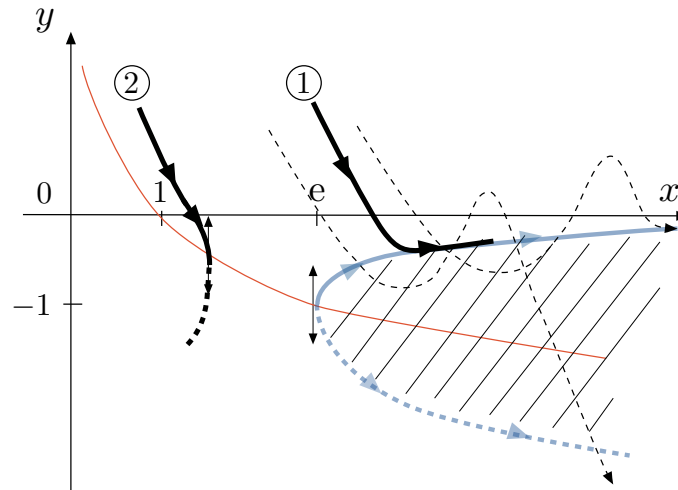


Figure 1: Sketch of the trajectories, x is proportional to the radius, y is proportional to the difference between the detonation velocity and the plane CJ velocity. Dotted lines represent schematically unsteady trajectories obtained by DNS. Solid lines are the quasi-steady trajectories.

MODEL AND RESULTS

In the limit of a small heat release, the full Euler equations reduce to a Burgers equation, modified by a reaction term and curvature term [5, 6]. This inner detonation structure has to be matched to a rarefaction wave. Sufficiently close to the Chapman-Jouguet solution, this Burgers equation can also be transformed in an integral equation [5], of the type recently used in the plane case by the authors in [7].

We present here solutions of the reactive Burgers equation with curvature [6]. For a small heat release, this equation can be written:

$$\frac{\partial \mu}{\partial \tau} + \left(\mu - \frac{y}{b} \right) \frac{\partial \mu}{\partial \xi} = \frac{1}{2} \omega(\xi, y(\tau)) - \frac{(1 + \mu)}{\tilde{r}_f(\tau)}, \quad (1)$$

$$\xi = 0 : \quad \mu = 1 + 2y(\tau)/b. \quad (2)$$

where μ is a reduced flow velocity in the laboratory frame, ω is the reaction term, the last term in the right hand side of (1) is a curvature term. Using the boundary condition at the shock (2), the reduced detonation velocity y can be obtained ($y = 0$ corresponds to the Chapman Jouguet velocity). An example of numerical integrations of this equation for different initial radii is shown in Figure 2.

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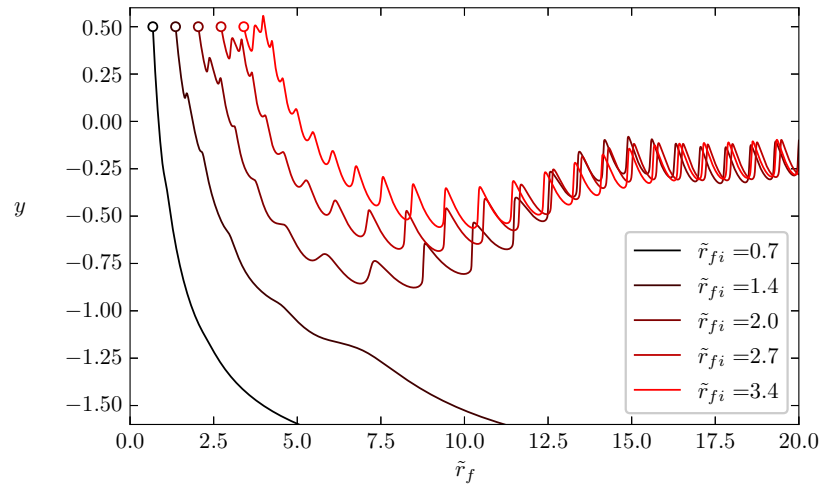


Figure 2: Examples of numerical integration of the reactive Burgers equation for a weakly unstable detonation $b = 2$. The failure occurs for initial radius small enough $\tilde{r}_{fi} < 1.5$ because of chemical-kinetics quenching.

CONCLUSIONS

For detonations close to the CJ velocity, it has been possible to simplify the full system of equations describing the spherical detonation to get a Burgers equation with reaction and curvature terms. Concerning the trajectories of the lead shock in direct initiation, the limit of small heat release is in qualitative agreement with direct numerical simulations, except for the overshoot during the re-acceleration phase which is sometimes observed in DNS.

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