Computation of the mean hydrodynamic structure of detonation with losses

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In the ideal ZND model, the reaction zone length matches the distance from the leading shock to the sonic plane. When losses are taken into account, this is no longer the case and the chemical reaction is not fully completed at the sonic plane location. The thermicity condition thus incorporates the losses which balances the heat release. Detonations are also known to develop a multidimensional cellular structure, of which the regularity can be related to the activation energy, all other thermodynamic parameters being fixed. There is thus a need of include these dynamics aspects of the detonation propagation into a dedicated length scale.

This then lead to the definition of the hydrodynamic thickness, which can be seen as the generalization of the length of the ZND subsonic reaction zone. It corresponds to the distance between the mean location of the leading shock and that of the mean sonic plane.

From the computational point of view, we can rely on Favre-averaging flow-fields, obtained by computations of the reactive compressible flows [1]. We can then analyze the influence of the hydrodynamic instabilities and irregularity of the detonation process, which change according to the value of the activation energy on the hydrodynamic thickness and the corresponding average structure.

From 1D unsteady computations [2,3], we can see that the activation energy threshold leading to the onset of longitudinal instabilities is lowered by the losses. Moreover, they increase the fluctuations, which act as a further source of losses and thus lead to a higher velocity deficit. As the mixture is more unstable, a clear departure from the laminar structure can be observed and the length of the hydrodynamic thickness becomes several times the laminar counterpart. The analysis could be performed in the instantaneous shock-attached frame. Indeed, averaging an oscillatory moving shock in the coordinates attached to mean shock velocity can result in a smooth profile for the mean shock spike, which is then rather difficult to analyze as a shock. This analysis focuses on what sees the leading shock, consequently could be considered as “biased”. In addition, it can be inferred from a hyperbolic analysis of the mean equations that the mean sound speed is augmented with a turbulent sound speed.

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However, the generalization of the latter formalism to a 2D context is not straightforward. In Ref. 1, the authors compute the hydrodynamic mean structure in the ideal case, without losses. The hydrodynamic thickness is consistent with experimental findings, of the order of some cell sizes. Ref. 4 deals with 2D detonations with losses, induced by a yielding confinement. The analysis was performed on one line of the flow field and then compared to the Wood-Kirkwood model. There is an increase of the chemical length and the hydrodynamic thickness as a function of the activation energy. The mean sonic location is delayed by the mechanical and thermal fluctuations far from the end of the main heat-release reaction zone. The end of the mean subsonic reaction zone thus corresponds to the stabilization of the production of these fluctuations and the presence of a small heat-release zone.

When losses are involved in the case of mildly unstable detonations, on contrast to what is featured by the generalized ZND model, the hydrodynamic thickness slightly increases, certainly because of the increase of the fluctuations. Moreover, the scaling of the detonation velocity deficit as function of the mean curvature breaks down, even if the half-reaction length and corresponding cell size remain roughly identical.

In addition, there is a need to obtain the whole multidimensional mean structure, which would be the mean analog of the multidimensional laminar detonation structure [5], based on the equations written in the instantaneous shock-attached frame [6].

We also found that the aforementioned evaluation is quite different from that of experiments. In the latter case, the hydrodynamic thickness is inferred from the decay of the pressure fluctuations downstream of the leading shock [7,8]. How these two approaches bring about coherent results remain an issue.

Numerical simulations show that averaging the chemical source term leads to a lower effective activation energy [2,9], suggesting that the fluctuations remove part of the thermal sensitivity of the mixture. A question thus arises of what would be the transients, i.e. the dynamics of failure if we were to simulate the mean equations, along with the different closure terms to be modelled.

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