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Detonation Wave Propagation, Diffraction, and Attenuation in a T-Branched Tube

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Introduction

Numerical study of detonation wave propagation is carried out for a T-branch, one of the general tube connection configurations. A T-branch is considered in this study because a branching tube is a crucial part of the combustion wave ignition (CWI) system. The CWI is a novel concept of rocket ignition system devised for the simultaneous ignition of multiple combustion chambers by delivering combustion waves through several flame tubes.[1] Either deflagration wave or detonation wave may be used for CWI system, the detonation wave seems to be more preferable for ignition in main chamber due to its wave strength and propagation speed. Prediction of detonation wave propagation through a branched tube is an important issue in the study of CWI system, because the branch makes a sudden change of tube area and detonation wave propagating over a branch experiences a flow expansion, which enforces a degeneration of the detonation wave. However, it is not generally predictable whether the detonation wave may still survive after the passage though the branch, and whether the detonation will propagate through a branched tube as a detonation wave or degenerate as deflagration wave. Thus, the objective of present study is to investigate detonation dynamics (including initiation, propagation, and attenuation) in a T-branched tube.

Numerical Formulations and Problem Setup

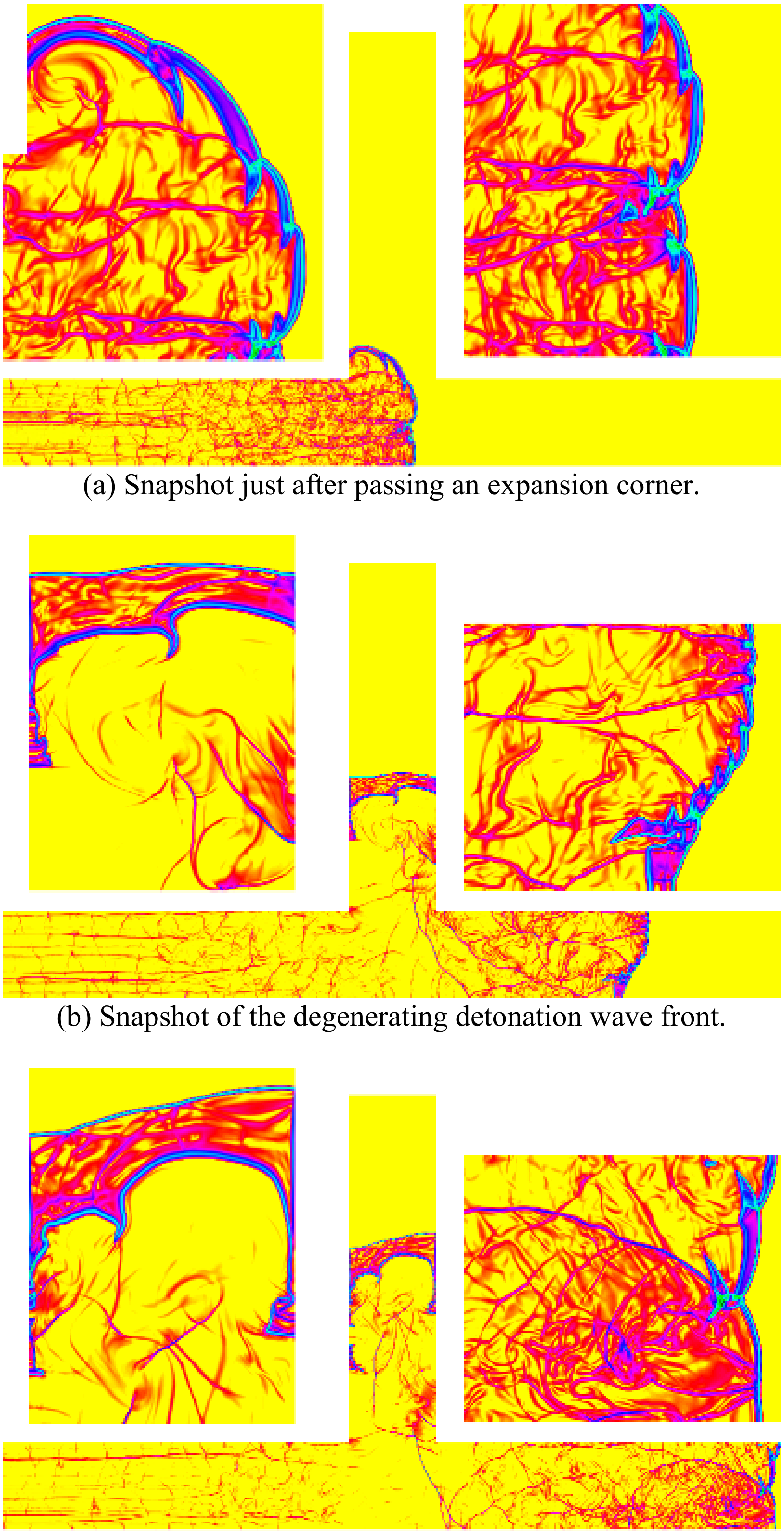
One of the advantages of CWI system is the use of main propellants as ignition material. In the present study mixture of cracked JP-7 and oxygen are considered. Thermally cracked JP-7 fuel is assumed to be composed of four major fuel components: including 50% CH_4, 21% C_2H_6, 24% C_2H_4 and 5% H_2 in mole fraction. An accurate numerical study of detonation phenomena requires correct information about the chemical characteristics of the mixture under consideration. Detonation of complex hydrocarbon mixtures involves dozens of chemical species and hundreds of reaction steps. In practice, however, such a comprehensive approach poses serious challenges in computational resource and turn-around time. Thus a simplified induction parameter (IPM) model was developed to simulate the detonation phenomena of a cracked JP-7 fuel/oxidizer mixture with a reasonable accuracy. The IPM is based on the induction time data obtained using the GRI Mech-3.0 chemical kinetics database [2] and the Chemkin-II package [3]. The resultant induction time data was correlated as a function of temperature T and pressure p in similar way by Oran et al.[4] The induction parameter model (IPM) has been implemented into a two-dimensional fluid dynamics code with variable properties as functions of the induction parameter. Euler equation is used as governing equation for the present study because most of the features in detonation wave propagation phenomena are governed by the coupling between shock wave dynamics and finite-rate chemistry. The code uses second-order implicit method for time integration and Roe's Riemann solver for space discretization with third-order variable extrapolation and minmod TVD limiter. Chemical source term is treated fully implicitly, and sub-iterations are employed to reduce the numerical errors arising from implicit approximations. More details of numerical algorithms had been studied in the previous studies.[5,6]

The T-shaped branch has a configuration where a vertical tube with a length of 4 tube heights is connected at the center of a horizontal tube with a length of 9 tube heights. 3,600×400 grid is used for the horizontal tube and 400×1600 grid is used for the vertical tube. For the initial condition of the detonation wave propagation through the T-branch, a quasi-stationary simulation of two-dimensional detonation wave is carried out for a square computational domain covered by 400×400 grid. Uniform grid is used to maintain the same grid resolution in every direction when the solution is applied for the branched tube configuration. The detonation tube is assumed being filled with JP-7/oxygen mixture at 1 bar and 298.15K. Chapmann-Jouguet (C-J) condition obtained by using CEA code [7] is applied to the entire computational domain except the inflow boundary as an initial condition of the quasi-stationary simulation. The final solution of the quasi-stationary simulation was applied to the T-branch configuration after coordinate transformation. Tube walls are considered as inviscid boundaries. The supersonic inflow condition was fixed and extrapolation was used at the exit boundaries.

Results and Discussions

Flow field solution is plotted in Fig. 1 for several instances. Fig. 1-(a) is the instance just after passing the expansion corner. Detonation wave structure has propagated through a straight tube without big changes in the wave structure, but the shock and the combustion waves decouple due to the diffraction of detonation wave at the expansion corner. A deflagration wave is propagating as decoupled shock and reaction waves through the vertical tube and the distance between the shock and the reaction wave is getting longer. Along the horizontal direction detonation wave is still propagating but the wave front seems to be quite unstable because of the interactions between the expansion waves and reflected shock waves at the corner. In Fig. 1-(b) detonation wave in the horizontal tube is getting unstable and a decoupling of shock and reaction front is shown at the bottom wall. After this instance, there is a local explosion near bottom wall due to the wave interactions. Fig. 1-(c) shows a newly generated detonation wave front interacts with the existing detonation wave front, which is developing as a regular detonation wave. Deflagration wave is still propagates as decoupled waves and the distance between the shock and reaction front is getting longer. It is clearly shown that the propagation speed of detonation wave traveling through the horizontal tube is much larger than the deflagration wave in the vertical tube. Fig 2 is an analogy of smoked foil record during the computation period that shows the detonation wave degeneration and regeneration history.

From this study several facts can be understood. 1) The combustion wave is not propagating directly as a detonation wave through the vertically branched tube. Thus some means enhancing deflagration to detonation transition (DDT) should be devised in the branched tube. 2) There are degeneration and re-initiation of detonation wave in the horizontal main tube, and it takes some distance for a regular detonation wave being developed. Thus there should be a sufficient space between the branches for the stable propagation of the detonation wave. 3) Since the detonation wave is propagating through the horizontal main tube while the deflagration wave in the vertical branch, the time differences of combustion waves in several main branches can be reduced.



(a) Snapshot just after passing an expansion corner.

(b) Snapshot of the degenerating detonation wave front.

(c) Snapshot of the reinitiated detonation wave developing as a regular detonation wave front.

Fig. 1 Density gradient plots of detonation wave propagating in a T-branched flame tube for several instances. As each instance, upward-running wave front is magnified in upper-left image and right-running wave front is magnified in upper-right image.

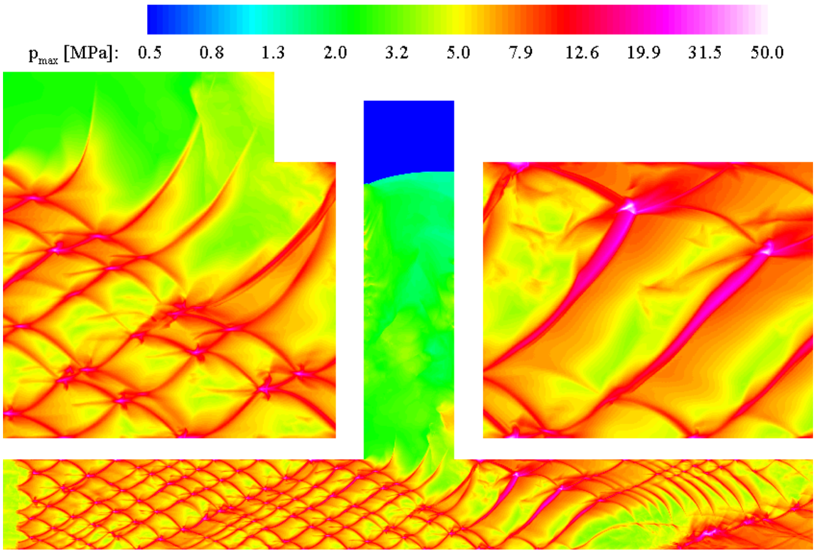


Fig. 2 Numerical smoked-foil record (maximum pressure distribution at each location over an entire computing time) of two-dimensional detonation wave propagating in T-branched flame tube.

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