한국추진공학회 2003년도 춘계학술대회 논문집 pp.221~224 KSPE Spring Annual Meeting 2003

연소파 로켓 점화기의 T형 분기관내 데토네이션파 전파

최정열* · Vigor Yang**

Detonation Wave Propagation Through a T-type Branch Tube in Combustion Wave Rocket Igniter

Jeong-Yeol Choi* · Vigor Yang**

ABSTRACT

A numerical study is carried out for the detonation wave propagation through a T-branch. The T-branch is a crucial part of the combustion wave ignitor, a novel concept of rocket ignition system aimed for the simultaneous ignition of multiple combustion chambers by delivering detonation waves. Euler equation and induction parameter equation are used as governing equations with a reaction term modeled from the chemical kinetics database obtained from a detailed chemistry mechanism. Second-order accurate implicit time integration and third-order space accurate TVD algorithm were used for solution of the coupled equations. Over two-million grid points enabled the capture of the dynamics of the detonation wave propagation including the degeneration and re-initiation phenomena, and some of the design factors were be obtained for the CWI flame tubes.

초 록

T-분기관을 전파하는 데토네이션 파에 대한 수치적 연구가 수행되었다. T-분기관은 데토네이션 파를 이용하여 여러 개의 연소기를 점화시키는 연소파 점화기라는 새로운 로켓 점화체계의 핵심 부분이다. Euler 방정식과 Induction parameter 방정식이 지배방정식으로 이용되었으며 반응 항은 상세 반응 기구로 얻어진 화학 반응 데이터베이스로부터 모델 되었다. 연계된 방정식의 풀이에는 2차 정확도의 내재적 시간적분과 3차 정확도의 TVD 알고리즘이 이용되었다. 2백만 개를 초과하는 격자를 이용하여 붕괴와 재 점화를 포함하는 데토네이션파의 거동을 포착할 수 있었으며, 연소파 점화기 화염관의 설계 요소를 얻었다.

1. Introduction

Numerical study of detonation wave propagation is carried out for a T-branch, a general tube connection configuration. The T-branch is considered in this study for combustion wave ignition (CWI) system, a novel concept of rocket ignition system.[1] The branching tube is a crucial part of the CWI system, since the CWI system is

---

* 부산대학교 (Pusan National University)
** Pennsylvania State University

devised for the simultaneous ignition of multiple combustion chambers by delivering deflagration or detonation waves through several flame tubes. 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. The objective of present study is to investigate detonation dynamics (including initiation, propagation, and attenuation) in the T-branch tube.

2. Theoretical Formulations

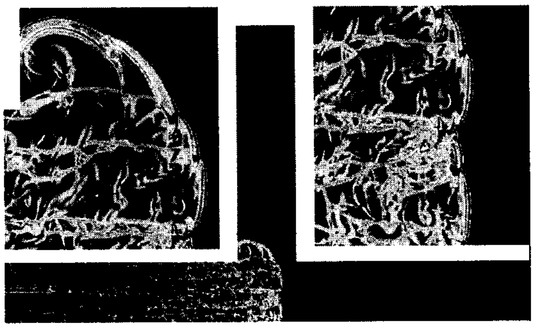
One of the advantages of CWI system is the use of main propellants as ignition material. In the present study mixture of cracked JP-7 and oxygen are considered. Thermally cracked JP-7 fuel is assumed to be composed of four major fuel components: including 50% CH_4, 21% C_2H_6, 24% C_2H_4 and 5% H_2 in 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]

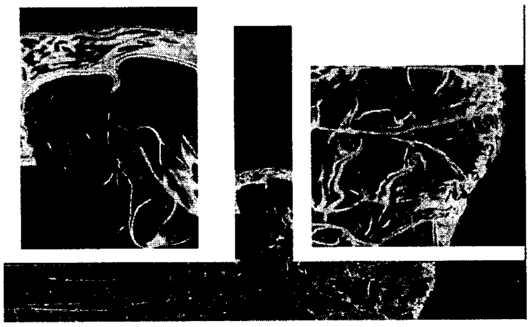
The T-shaped branch has a configuration where a vertical tube with a length of 4 tube heights is connected at the center of a horizontal tube with a length of 9 tube heights. 3,600×400 grid is used for the horizontal tube and 400×1600 grid is used for the vertical tube. For the initial condition of the 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 CEC 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.

3. Summary of Results

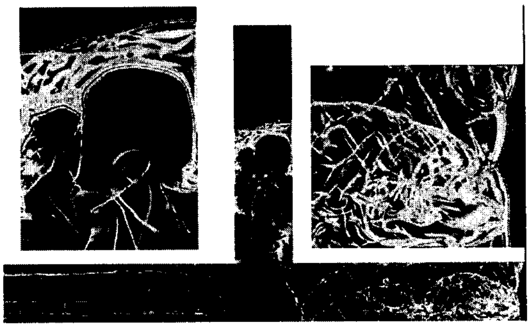
Flow field solution is plotted in Fig. 3 for several instances. Fig. 3-(a) is the instance just after passing the expansion corner. Detonation wave structure has propagated through a straight tube without big changes in the wave structure, but the shock and the combustion waves decouple due to the diffraction 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. 3-(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. 3-(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 4 is an analogy of smoked foil record during the computation period that shows the detonation wave degeneration and regeneration history.



(a) Snapshot just after passing an expansion corner.



(b) Snapshot of the degenerating detonation wave front.



(c) Snapshot of the re-initiated 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. 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.

4. Conclusions

Several facts can be understood from this study. 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.

References

1. L.C. Liou, Combustion-wave ignition for Rocket Engines, The 1992 JANNAF propulsion Meeting, Vol. 1, pp295-311.
2. Smith, G. P., Golden, D. M., Frenklach, M., Moriarty, N. W., Eiteneer, B., Goldenberg, M., Bowman, C.T., Hanson, R.K., Song, S., Gardiner Jr., W.C., Lissianski, V.V., and Qin, Z., GRI-Mech, http://www.me.berkeley.edu/gri_mech/
3. Kee, R. J., Rumpley, F. M., and Miller, J.A., Chemkin-II: A Fortran Chemical Kinetics Package for the Analysis of Gas Phase Chemical Kinetics, Gov. Pub. SAND89-9009B. Sep. 1989.
4. Oran, E.S., Boris, J.P., Young, T., Flanigan, M., Burks, T., and Picone, M., Numerical Simulations of Detonation in Hydrogen-Air and Methane-air mixtures, Proceedings of the Combustion Institute, Vol. 18, The Combustion Institute, 1981, pp. 1641-1649.
5. Choi, J.-Y., Jeung, I.-S. and Yoon, Y., "Computational Fluid Dynamics Algorithms for Unsteady Shock-Induced Combustion, Part 1: Validation," AIAA Journal, Vol. 38, No. 7, July 2000, pp.1179-1187.
6. Choi, J.-Y., Jeung, I.-S. and Yoon, Y., "Computational Fluid Dynamics Algorithms for Unsteady Shock-Induced Combustion, Part 2: Comparison," AIAA Journal, Vol. 38, No. 7, July 2000, pp.1188-1195.
7. Gordon, S. and McBride, B.J., "Computer Program for Calculation of Complex Chemical Equilibrium Composition and Applications," NASA RP-1311, Oct., 1994.