Numerical Simulation on a Pulse Detonation Engine

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Abstract

Numerical simulation has been performed to study a detail of a pulse detonation engine (PDE) using a 2-D Euler equation with a full chemistry of hydrogen-air reaction system. A TVD scheme is used to integrate a part of equations. A preliminary result of PDE simulation shows that the detonation wave still propagates in the combustion chamber after coming out of the detonation tube. A typical propagation mechanism of detonation is still carried out in the combustion chamber with a wider area. A further comprecated shape of combustion chamber will be considered for the future calculation.

Introduction

Pulse detonation engine (PDE) has recently been expected for an engine of a future aerospace vehicle because of the advantages of its low cost, light weight, and high performance. The working concept of PDE is as follows: (1) its combustion chamber is filled with a combustible mixture; (2) after ignition, detonation forms and propagates in the chamber; (3) its burned gas is jetted from the nozzle to provide a thrust; (4) another new mixture is injected into the combustion chamber and the steps (1) through (3) are repeated.

PDE is the constant volume combustion due to its high speed process and is expected a high thermal efficiency. It adjusts the thrust efficiently through changing the operational cycle. It has a simple mechanism without compressors and turbines to reduce its cost.

PDE has been studied these sixty years: single and multi cycle experiments are performed by Helman[1] and Bussing et al.[2],[3] to show the problems of insufficient initial energy, insufficient mixing, DDT(deflagration to detonation transition) and DT(detonation transmission distance), and thrust measurements; the numerical analyses are performed by Adelman[4] and Eidelman et al.[5] to calculate the thrust, the flow near inlet, and the flow near nozzle.

One of the main problems in PDE, which performs supersonic combustion for thrust, is quenching. In this study the expansion and quenching of detonation in the expansion chamber of PDE are simulated using a 2-D compressible Euler equation with a hydrogen-air detailed chemical reaction model.

Numerical simulation

The governing equation system applied for the simulation consists of a 2-D compressible Euler equation and mass conservation equation with the following assumptions: the flow field is two dimensional; the considered chemical species are H_2, O_2, H, O, OH, H_2O, HO_2, H_2O_2, and N_2; heat capacities at constant pressures of each species are a function of temperature and an equation of state for ideal gas is used; the bulk viscosity, Soret effects, Dufour effects, and pressure gradient diffusion are neglected. In order to avoid errors to concentrate on the specific species, the total mass conservation equation and each species conservation equation are solved together.

A point-implicit method is used to treat source terms implicitly and other terms explicitly. A Strang-type fractional step method is used to keep a second-order accuracy in time and space. A Harten-Yee type of non-MUSCL modified flux TVD scheme is applied for convection terms and a Crank-Nicholson type of implicit scheme for source terms. As for a grid system, a zonal method is used together with a fortified solution algorithm.

As a chemical reaction model, nine species and nineteen reactions of hydrogen-air mixture are considered to calculate their reaction rate to temperature. The hydrogen-air reaction model[6] in this study has been checked with flame velocity and ignition delay data.

A tentative computational region consists of two parts; detonation tube and combustion chamber, and is shown in Fig. 1. A rectangular grid system (x=0.005 mm and y=0.03 mm) is used for the detonation tube of 251x100 (1.255x3.0 mm) and combustion chamber of 571x220 (2.855x6.6 mm).

Boundary conditions on the wall are adiabatic, slip, and non-catalytic. Initial conditions are obtained by patching the results of 2-D self-sustained detonation, which are shown in Fig. 2. The initial mixture consists of stoichiometric combination of hydrogen and air at the pressure of 1 atm and temperature of 298.15 K.

Results and discussions

The present simulation does not have enough size of combustion chamber to know whether the detonation propagating through the tube can continue to propagate in the combustion chamber or not. As seen in Figs. 3-a and –b of time-dependent pressure contours and Figs. 4-a and –b of time-dependent temperature contours, the detonation wave deflects at the corner of detonation tube exit either to propagate or to extinguish in the combustion chamber. In the present case the detonation seems to continue for the future time, but the further calculation is necessary to make sure the final configuration of detonation. Lee et al.[7] showed that detonation continues when d>10., where d is the detonation tube diameter and. the detonation cell size, and quenches when d.10.. From this relation the present case must be the case of quenching since d.3.. However the present numerical analysis shows the possible case of continuation of ignition at the detonation front. At the time of 1.775 .s a hot ignition still occurs near the detonation front, which will support the detonation to propagate, although the front nearby the wall is dying.

Since the size of combustion chamber is 6.6 mm, its relation with the cell size is still d.10., which implies that the detonation can be quenched. At this moment the discrepancy between Lee's experimental results and our numerical ones may come from the numerical accuracy. However we like to study the detail structure and mechanism of ignition and quenching of triple points and the further dynamics and propulsion mechanism of PDE. Although the present sizes of the detonation tube and combustion chamber are in the region of quenching cases, the further different shapes and sizes of the combination between detonation tube and combustion chamber will be simulated using the same technique in the future.

References

[1] Helman, D., Shreeve, R.P., and Eidelman, S., "Detonation Pulse Engine," AIAA Paper 86-1683, 1986.
[2] Bussing, T. and Pappas, G., "Introduction to Pulse Detonation Engines," AIAA Paper 94-0263, 1994.
[3] Hinkey, J.B., Bussing, T., and Kaye, L., "Shock Tube Experiments for the Development of a Hydrogen-Fueled Pulse Detonation Engine," AIAA Paper 95-2578, 1995.
[4] Cambier, J.L. and Adelman, H.G., "Preliminary Numerical Simulation of a Pulsed Detonation Wave Engine," AIAA Paper 88-2960, 1988.
[5] Eidelman, S., Grossman, W., and Lottati, I., "Air-Breathing Pulsed Detonation Engine Concept; A Numerical Study," AIAA Paper 90-2420, 1990.
[6] Hishida, M., "Formation of Disturbed Flow and Flame Structure by an Interaction between Flame and Flow Field in Non-Steady Multi-Dimensional System," Ph.D. Thesis, Nagoya University, 1995.
[7] Lee, J.H., Knystautas, R., Guirao, C.H., Moen, I.O., Swacer Inc. Report to Chr. Michelsens Institute, Bergen, Norway, 10 July, 1980.

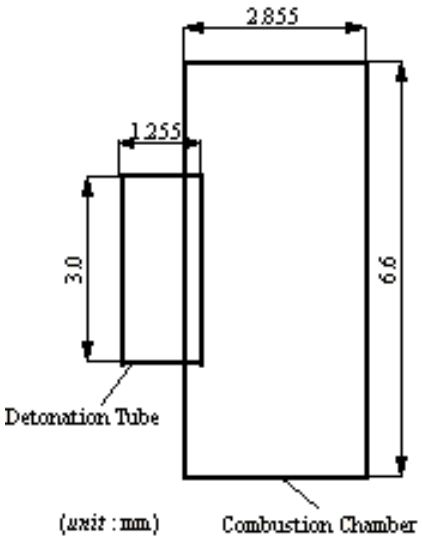
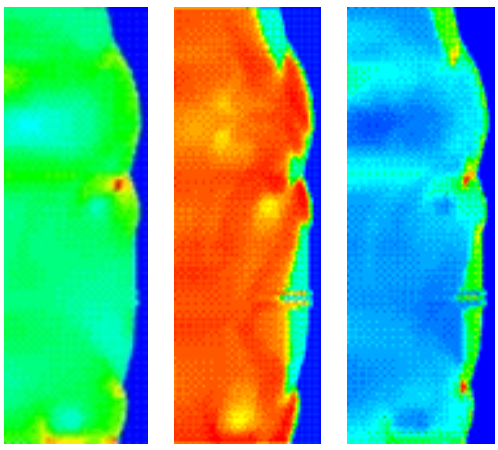


Fig.1 Computational region



Pressure Temperature Density

Fig.2 2-D result (Initial condition)

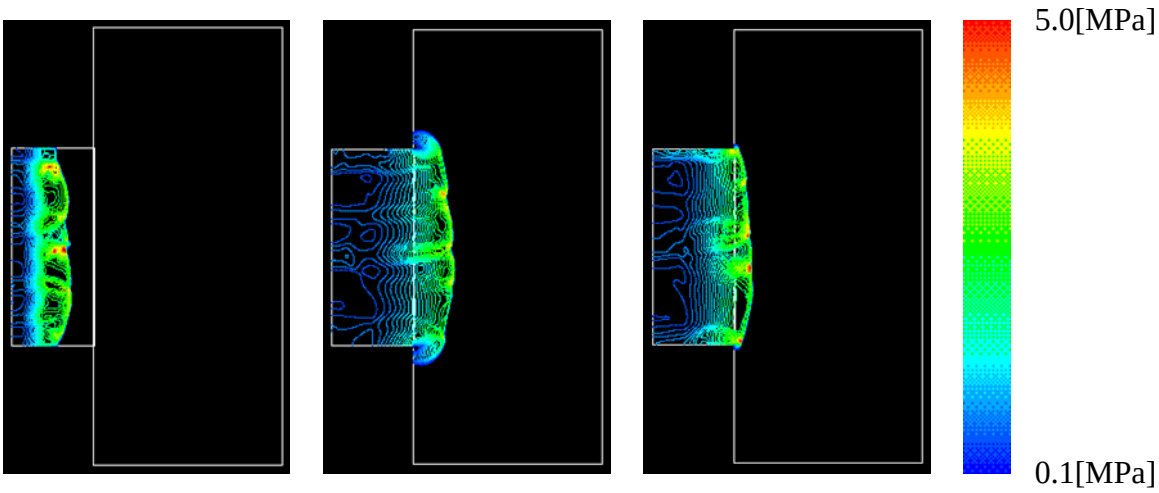


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Fig 3-a Time sequences of pressure contours

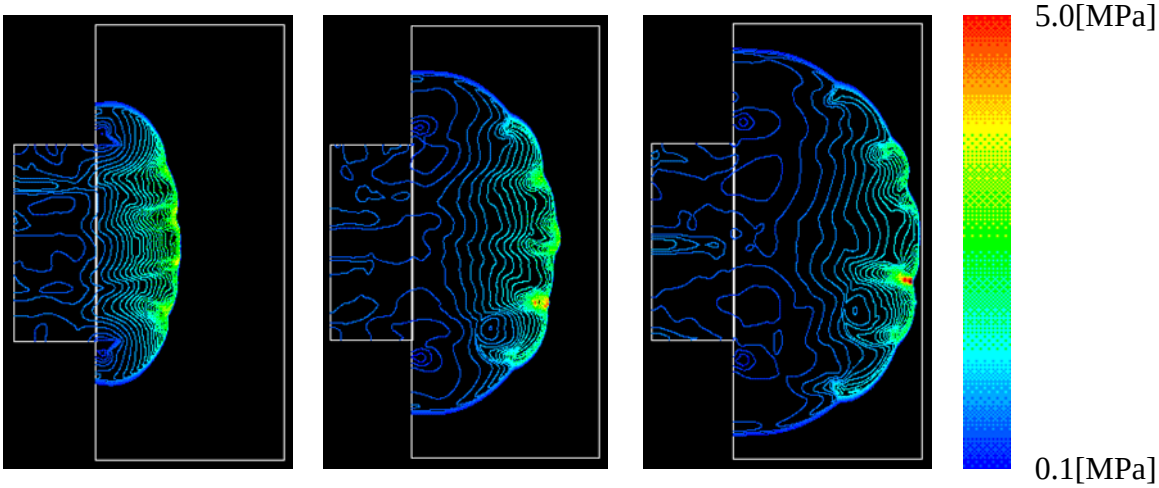

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Fig 3-b Time sequences of pressure contours

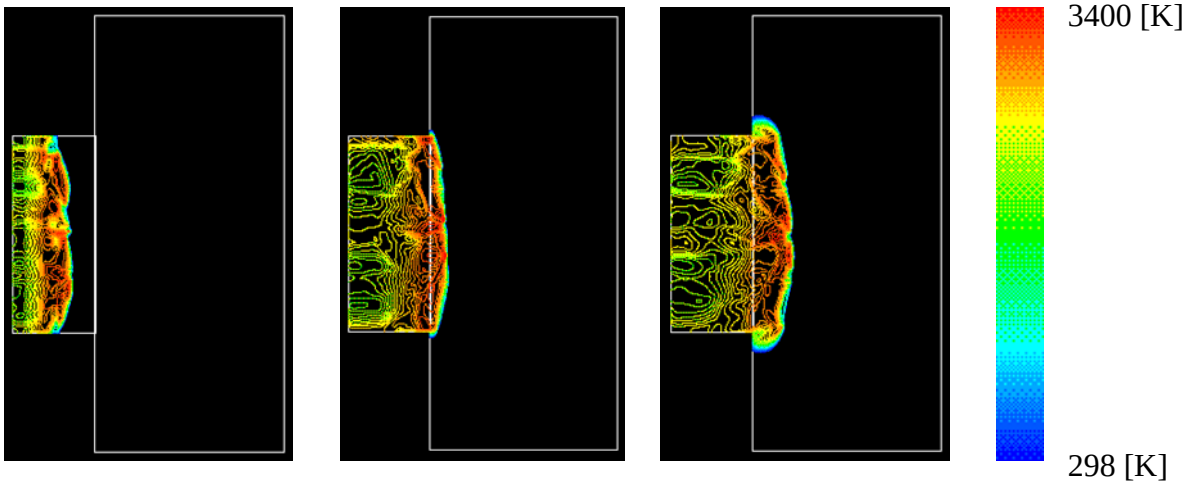

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Fig 4-a Time sequences of temperature contours

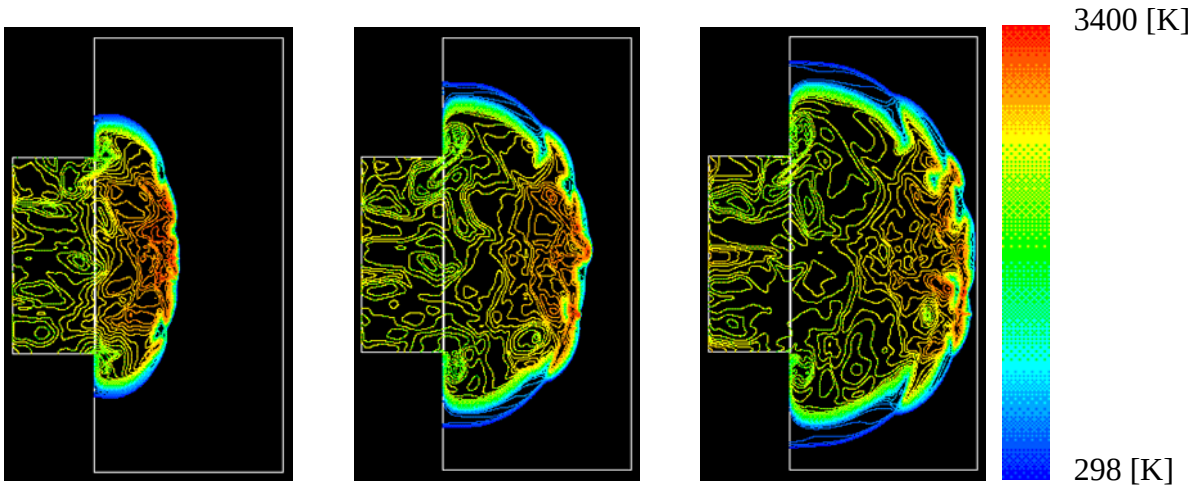

Fig 4-b Time sequences of temperature contours