2D Numerical Analysis of Flowfield Interaction in a Multi-tube Pulse Detonation Engine

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1 Introduction

As a new and alternative propulsion device, Pulse Detonation Engine (PDE) has much research interest and is developed for the purpose of practical use. The PDE has many advantages such as simplicity and easy scaling, high thermodynamic efficiency, and intrinsic capability of wide operating conditions (flight Mach number 0-5), compared with the conventional air-breathing engines [1]. The PDE supplies repetitive and intermittent thrust in its nature, and then high-frequency operation is indispensable in order to achieve high performance. As key technologies for the practical PDE, therefore, we consider how to generate stably a quasi-CJ detonation in a short distance and how to reduce the time required for one cycle. In our previous study [2], a purging and filling technique with coaxial jet "ignition-preventor" was proposed to shorten the cycle time and it was shown that this technique can reduce the cycle time effectively. But there is some limitation to reduce the cycle time safely for the single-tube PDE. Then several attempts to use multi-tubes [3-5] are seen in order to increase the operation frequency.

To investigate the feasibility of such multi-tube PDE, it is very important to understand the complicated pressure wave interaction among the combustion channels during the PDE cycle. Rasheed et al. [5] show the irregular pressure fluctuations appear in a turbine inlet of their multi-tube pulse detonation combustor (PDC) system in spite of periodical and sequential firing of multi-tube combustors. There is a risk that such irregular pressure peaks cause an undesirable vibration of apparatus and destruction of a nozzle or turbine blades in the PDE. In this study, a two-dimensional oxyhydrogen PDE model with two combustion channels and a common nozzle is simulated numerically. The HLLE scheme with MUSCL method and the four-step Runge-Kutta time integration is used to solve two-dimensional Navier-Stokes equations, where a simplified two-step chemical reaction model is introduced to simulate a practical-size PDE configuration. The wave propagation and interaction inside the channels are discussed.

2 PDE Model

The model PDE is shown in Fig.1. The model has two combustion channels, PDC-1 and PDC-2, and a common nozzle. Each channel of model PDE is straight and two-dimensional with a closed end on its left side. The size of channel is 100mm in length and 30mm in width respectively. These channels are connected with a common nozzle at an

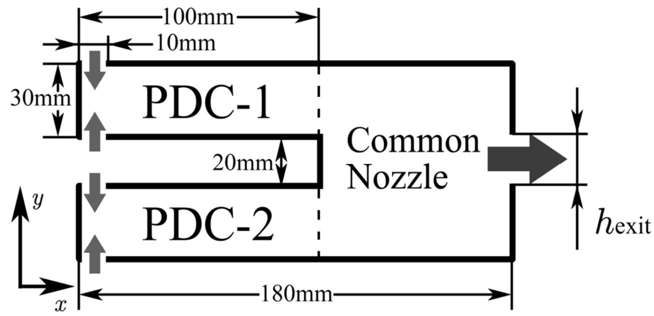

Figure 1. Multi-Tube PDE Model.

interval of 20mm. The common nozzle has a square shape with 80mm length and width, and an open exit is placed on the center of right wall. In the present study, the exit height h_{exit} is set to 20mm. Both combustion channels are initially filled with an Ar-diluted oxyhydrogen mixture ($2H_2$+O_2+7Ar) at 1.0atm and 298.15K, assuming to start from the ground condition at 1.0atm. On the other hand, the common nozzle is filled with an inert gas at same pressure and temperature as those in the channels. The wall boundary is considered nonslip, adiabatic and noncatalytic. At the exit, the specific pressure boundary condition is used, where no constraint is imposed on the flow properties when the outgoing flow is supersonic while the constraint for pressure is applied to the subsonic flow condition. In the present study, the detonation and shock wave interaction in the detonation propagation process is mainly discussed. Then the injection ports on the upper and lower walls of combustion channels shown in Fig. 1 are not used in the simulation.

The flowfield of model PDE is governed by the two-dimensional Navier-Stokes equations [6]. A full-chemistry model constructed by many elementary reactions needs excessive computation cost, making it too difficult to simulate a practical-size configuration. In the present study, the modified Korobeinikov-Levin chemical reaction model [7] is utilized. The constants in the model equations are selected to agree with Oran's elementary reaction model [8], with regard to the induction time and temperature profile.

The HLLE scheme with MUSCL method [9], in which Van Albada limiter is applied to realize the TVD condition, is used to evaluate the numerical flux of advection terms. The central difference scheme is used for viscous terms. In order to solve unsteady problems with high resolution, the four-step Runge-Kutta time integration is used in the present simulation.

A rectangular grid system with $\Delta x = 200$microns and $\Delta y = 100$ microns is used for each channel of PDC-1 and PDC-2. For the domain of the common nozzle, a coarse grid system with $\Delta x = 400$ microns and $\Delta y = 200$ microns is applied because the detonation wave does not propagate through the inert gas in the common nozzle. In order to use such grid systems, a zonal method is applied in this simulation. By using these grid systems, 6 to 7 cells can be seen within the channel width 30mm, giving the detonation cell size about $\lambda >$ 4mm, which is slightly larger than the experimental value. But the detonation cell size and the detonation propagation velocity have no fatal discrepancy caused by the grid resolution.

3 Results and Discussions

In order to investigate essential physics more or less, a primitive interaction case is numerically simulated: Ignition occurs only in the PDC-1 and a detonation or shock wave propagates in the PDE. The ignition starts by setting a CJ detonation near the head-end of each channel. Assuming that some obstacles like Shchelkin wire are located to shorten a deflagration-to-detonation transition (DDT) distance, the initial 1-dimensional CJ detonation is perturbed near the tube wall.

Figure 2 shows the temporal evolution of pressure and temperature distributions at 47.0, 100.5, 170.5 and 239.4 microseconds after the ignition. Detonation wave which propagates in the PDC-1 changes into a shock wave and spreads in the common nozzle. Then shock wave reflects on the side and right walls of the common nozzle, high pressure spot creates on the nozzle wall. Since this is two-dimensional simulation, spread and reflected waves are stronger than the practical three-dimensional flow. In addition, reflection is more emphasized due to the square shape of the common nozzle. Nevertheless, it implies that nozzle wall experiences the sudden pressure rise, causing the undesirable structural vibration and destruction. Finally, reflected waves penetrate into the PDC-2 and the mixture in the PDC-2 is pushed toward the head-end. Similar results were also obtained in the numerical simulation carried by Ebrahimi [3]. However more awkward situation appears in the PDC-2, as shown in the temperature distribution. In this figure, green to red colors correspond to the burnt gas. After the detonation wave reaches the connection between PDC-1 and common nozzle, we can see the detonation wave separates into shock wave and reaction zone. Then a part of burnt gas penetrates into the PDC-2 although each channel stands at an interval of 20mm. And the mixture in the PDC-2 "burns" due to the contact with this burnt gas before the cycle of PDC-2 begins.

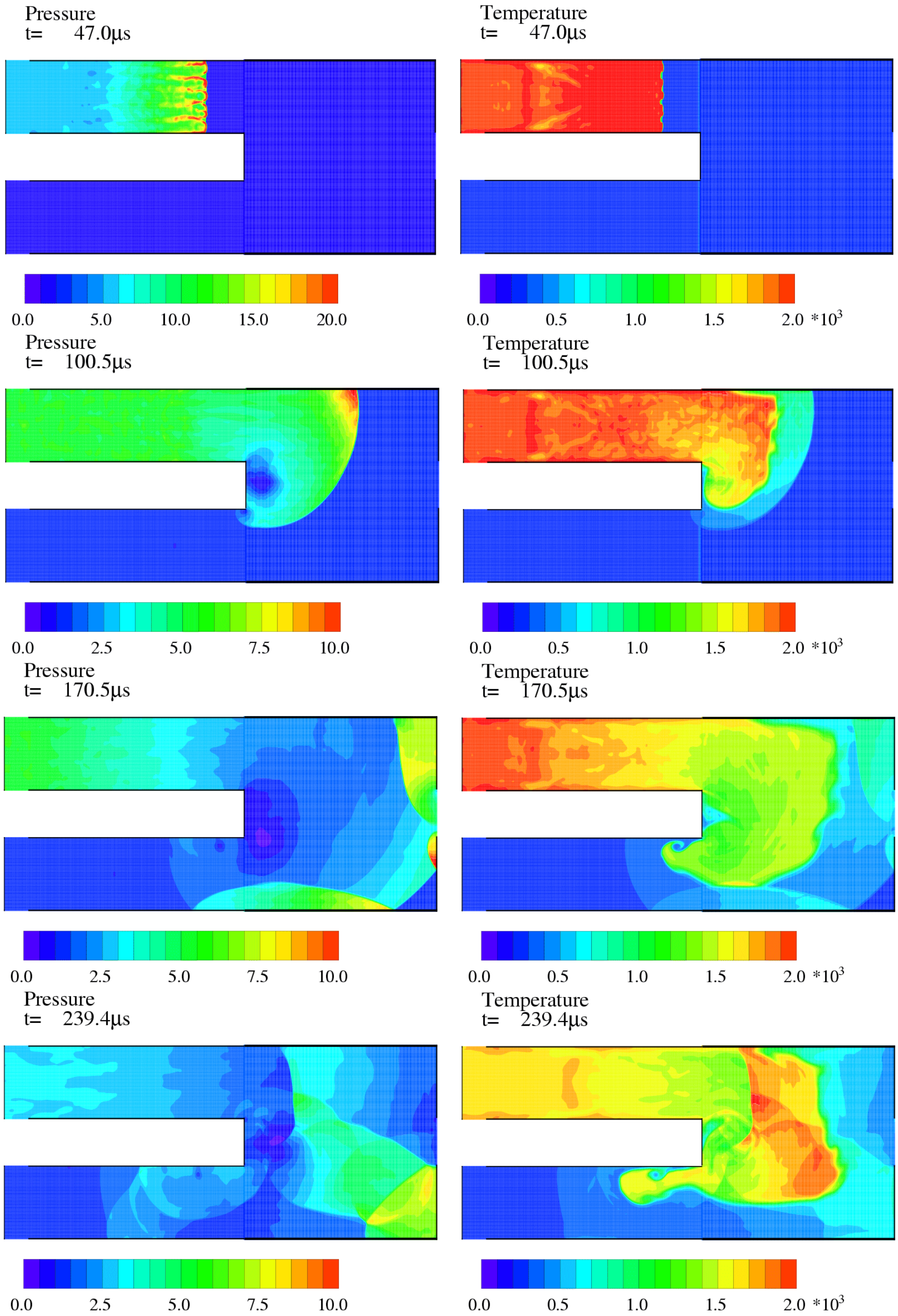

Figure 2. Wave Propagation and Burnt Gas Penetration from PDC-1 to PDC-2.

The history of mass flow rates per depth on the cross sections of the connection between PDC-1 and common nozzle, the connection between PDC-2 and common nozzle, and the open exit of common nozzle are shown in Fig. 3. After the detonation wave reaches the connection, large amount of mass blows from the PDC-1 to the common nozzle. Then reverse flow into the PDC-2 is generated and the amount of mass flow rate is a match for that on the open exit. Furthermore, this reverse flow and the penetration of burnt gas into PDC-2 are emphasized by the reflection shock waves in the common nozzle. Therefore a design of the common nozzle seems to be important to reduce the interaction between the channels. In addition, the timing when the cycle in the other channel starts is also important parameter to prevent fruitless consumption of mixture in the other channel.

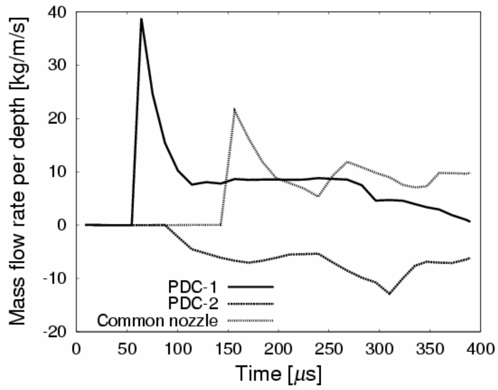

Figure 3. History of Mass Flow Rates on Each Cross Section.

4 Conclusion

A two-dimensional reactive flowfield of the multi-tube PDE with two combustion channels and a common nozzle is numerically studied for an Ar-diluted oxyhydrogen mixture. In particular, interaction of detonation and/or shock waves which propagate into the channel and nozzle is focused and investigated. The results show that, in spite of an interval between channels reverse flow is generated in the other channel after the detonation wave propagates in a channel. It may cause the undesirable difficulty against sequential firing of each combustion channel. Since such flowfield is generated in the common nozzle, a design of the common nozzle seems to be important to reduce the interaction between the channels and to achieve stable and controllable PDE cycle.

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