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무-밸브 공기흡입 펄스데토네이션 엔진의 내부 유동과 성능

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Internal Flow Dynamics and Performance of Valveless Airbreathing Pulse Detonation Engine

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ABSTRACT

This paper deals with the modeling and simulation of the internal flowfield in a valveless airbreathing pulse detonation engine (PDE) currently under experimental development at the U.S. Naval Postgraduate School. The system involves no valves in the airflow path, and the isolation between the inlet and combustor is achieved through the gasdynamics in an isolator. The analysis accommodates the full conservation equations in axisymmetric coordinates, and takes into account variable properties for ethylene/oxygen/air system. Chemical reaction schemes with a single progress variable are implemented to minimize the computational burden. Detailed flow evolution during a full cycle is explored and propulsive performance is calculated. Effect of initiator mass injection rate is examined and results indicate that the mass injection rate should be carefully selected to avoid the formation of recirculation zones in the initial cold flowfield. Flow evolution results demonstrate a successful detonation transmission from the initiator to the combustor. However, strong pressure disturbance may propagate upstream to the inlet nozzle, suggesting the current configuration could be further refined to provide more efficient isolation between the inlet and combustor.

Key Words: Pulse Detonation Engine(펄스 데토네이션 엔진), Valveless(무-밸브), airbreathing engine (공기흡입 추진기관)

1. Introduction

Pulse detonation engines (PDEs) are unsteady propulsion devices that produce periodic thrust by utilizing repetitive detonation. They differ from conventional systems in two major ways: unsteady operation and detonative combustion. A typical cycle operation of a PDE includes four basic processes: initiation of detonation wave, propagation of detonation wave, exhausting of combustion products, and filling of reactants.

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Based on how the inlet/combustor interface is realized, they can be classified as either valved or valveless PDEs. Most previous studies [1-4] have been focused on valved PDEs. In this design, the interface is a mechanical valve located at the head end of the detonation tube. The valve is closed during the detonation initiation and propagation and blowdown stages, and is open during the filling and purging stages. The second class, referred to as valveless PDEs, involves no valves in the airflow path and the isolation between the inlet and combustor is achieved through the gasdynamics in an isolator. This design is not only mechanically simpler than the valved system, but also circumvents the disadvantage associated with airflow stagnation.

The present work represents an extension of our previous work on valveless PDEs[5] andattempts to numerically examine the internal flow dynamics and performance of the valveless PDE currently under experimental development at the Naval Postgraduate School (NPS).[8] The main objectives of this research are to understand the various processes in the operation of valveless PDEs, such as detonation initiation and transmission, filling, and purging, and to provide direct insight into experimental results.

2. System Configuration and Operation

The system under consideration, as shown in Fig. 1, is the valveless PDE recently tested at the Naval Postgraduate School (NPS). It includes an air distribution (or inlet) module, an isolator, an initiator, a transition section, and a combustor. Continuous airflow is supplied to the test rig and is further heated by the vitiator before entering the inlet facility nozzle. The total pressure at the inlet venturi is determined by the desired mass flow rate. The air is mixed with the ethylene fuel (C_2H_4) injected to the four inlet arms, and a small part of the flow in the inlet arms is split to the initiator. The entire system is mounted on a linear slide rail on top of a thrust stand for direct thrust measurement with a spring/damper deflection system.

The cycle operation detailed in Ref. [8] includeed the following sequences: injection of fuel to the main combustor; injection of fuel and oxygen into the initiator; ignition of detonation wave in the initiator; propagation of detonation wave from the initiator to the combustor; and exhausting of the detonation products. With this preliminary operation, both numerical simulation10 and experimental test8 have demonstrated the existence of an air plug near the initiator exit that causes detonation degeneration. To mitigate this problem, an improved operation sequence and filling strategy was then proposed.[10,11] The major revision is to inject a fuel/air mixture to the initiator for a sufficient time period before filling it with fuel/oxygen mixture.

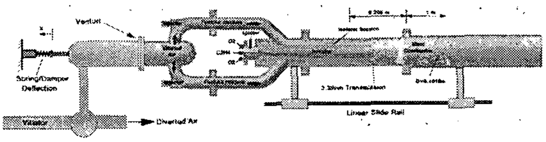

Fig. 1 Schematic of a valveless PDE (Brophy et al.[6])

3. Numerical Approach

The theoretical formulation is based on the conservation equations of mass, momentum, energy, and species concentration in two-dimensional axisymmetric coordinates. Diffusive effects are neglected because of their minor roles in determining the overall flow dynamics and propulsive performance of a PDE. The governing equations outlined above are solved numerically using a recently developed CE/SE method.[3,4] The resultant computer code is further parallelized using the MPI library and a domain-decomposition technique for unstructured grids. The entire analysis has been validated against a series of detonation problems for whichh either analytical or experimental data are available.[3,4]

4. Results of Full-Cycle Operation

The timing of a valveless PDE is more complicated than that of a valved PDE, and must be carefully tuned to achieve a successful operation. Figure 2 shows the operating time sequence for a valveless PDE. The open area at the initiator entrance is also included. The filling process in the combustor begins at t_0. After a time period delay, the initiator begins filling with fuel/air mixture at t_1 and continues for a time period of τ_{open1}. The initiator starts to fill with fuel/air/oxygen mixture at t_2 and remains for a time period of τ_{open2}. The filling processes in the combustor and initiator end at t_3 and t_4, respectively. The purge process begins at t_2 with the main injector closed. The operation timing can thus be specified by five time periods: τ_{fill}, τ_{delay}, τ_{open1}, τ_{open2}, and τ_{cycle}.

The flowfield established in the preceding subsection is used as the initial flowfield for a full-cycle operation. The propagation of detonation wave and the further flow development is shown in Fig. 12. An important observation from this flow evolution is that the disturbance arising from the detonation wave propagates all way upstream to the inlet nozzle and interferes with the shock located at the divergent section. The probe data indicates that the maximum pressure at probe 07 reaches about 8 atm, much higher than it initial value of 1.5 atm. Further refinement on the inlet

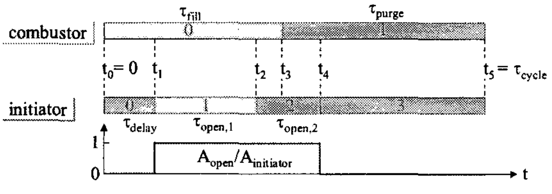

Fig. 2 Operation timing of a valveless PDE

Table 1 Calculation condition for full-cycle operation

T_{00I}, p_{00I}	430 K, 13.93 atm
T_{0CI}, $\dot{m}_{CI}$	300 K, 0.04 kg/s
T_{0II}, $\dot{m}_{II}$	400 K, 0.3 kg/s
mass fractions Z_{open1}	$[C_2H_4/air]$
mass fractions Z_{open2}	$0.271[C_2H_4/air]+0.729[C_2H_4/O_2]$
τ_{fill}, τ_{delay}, τ_{open1}, τ_{open2}, τ_{cycle}	7, 2.5, 6.5, 2, 20 ms

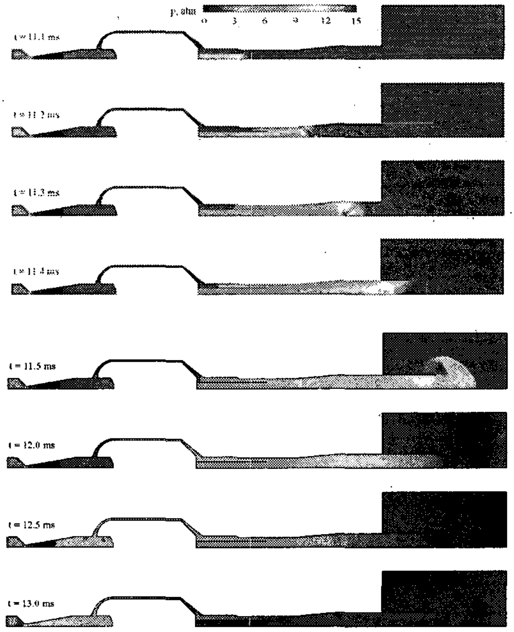

Fig. 3 Time evolution of pressure field during first cycle of operation (cycle = 20 ms, fill = 7 ms, delay = 2.5 ms, open1= 6.5 ms, open2 = 2 ms)

condition or the isolator configuration would be required to mitigate this problem. As the blowdown process continues, the disturbances decrease and the pressures at all the probes returned to around their initial values.

5. Conclusions

An integrated computational framework has been established to investigate the internal flow dynamics and estimate the propulsive performance of a valveless PDE. Successful detonation transmission from the initiator filled with an oxygen-enriched C_2H_4/air mixture to the combustor filled with a stoichiometric C_2H_4/air mixture was demonstrated. The effect of initiator mass injection rate on the initial cold flowfield was examined. At low mass rate, recirculation zones are formed downstream of the initiator due to the resulting strong shear layers. The initiator mass injection rate should be carefully selected to push the recirculation zones out of the combustor. An improved operation sequence was applied to circumvent the previous problem associated with detonation degeneration by an air plug near the initiator exit. The timing periods were estimated based on an established initial flowfield. Detailed flow evolution during a full cycle was explored. The gross specific impulse of 1966s was in agreement with the experimental result. The present work has provided direct insights into the experimental findings at NPS, and can be used effectively to optimize the design and operation of valveless PDEs. This paper is a brief summary and the complete description of present study is found in Ref 8.

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