Performance analysis of the Multiple Tube Pulse Detonation Rocket Engine

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1. Introduction

Pulse Detonation Engine (PDE) is the device that utilize high power and high density energy of detonation wave to produce thrust. PDE have the potential to obtain several advantages than the traditional deflagration-based propulsion devices because of its simplicity and high efficiency. Previous studies[1]-[6] were focused mainly on single-tube Pulse Detonation Rocket Engine (PDRE). For the performance augmentation, Li et al.[2] confirmed the availability of the partial filling effect, and Cambier and Tegner[3], Yungster[4] confirmed the diverging nozzle effect. As regards the multiple-tube analysis, the work of Houshang et al.[7] was reported. For the practical design of the propulsion system, multiple-tube and multiple-cycle engine system must be indispensable. In the present study, the performance analyses of the multiple-tube and multiple-cycle Pulse Detonation Rocket Engine (PDRE) are examined with the various exhaust part configurations and the operation frequencies.

2. Numerical Setup

The governing equations are the two-dimensional Euler equations. To describe chemichally reacting system, a simplified two-step exothermic reaction model [8] is used. Yee's non-MUSCL type TVD scheme is used for solving these equations. The computational domain is inside and outside of the multiple-tube PDRE to avoid the difficulty of the outflow boundary condition. In the current study, stoichiometric hydrogen-oxygen gas mixture, $2H_2+O_2$, is supposed as a initial detonable mixture. Initially, the tube is filled with detonable mixture, and outside region is filled with air that is assumed to be adjusted the two-step reaction parameter β to the equilibrium value. The calculation conditions are set to be as follows; initial pressure p_0 = 101.3kPa, initial temperature T_0 = 298K, and Chapman-Jouget mach number M_{CJ} = 5.30. The detonation wave is directly initiated at the closed end high pressure region（p = 50atm, T = 2500K）. Four types of the exhaust configurations of the present multiple-tube PDRE are prepared and listed in

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Table 1. The multiple-tube PDRE has 3 tubes, and each of the tubes is configured by tube diameter 0.65mm and tube length 19.53mm, and the exhaust part length is 6.51mm. The change of the operation frequency is modeled as shown in Figs. 2. Figure 2 (a) shows the multiple-cycle operation model of the successive pressure plateau, where Fuel Injection Ratio（FIR is defined as follows ; Fuel Injection Time / Cycle Time）is 33%. Figure 2 (b) is the successive combustion-exhaust time, where FIR is 66%. The thrust wall pressure is kept injection pressure（1atm）during fuel injection time t_f. The performance analyses are evaluated using impulse obtained from the thrust wall (the closed end wall of the tube and the diverging nozzle wall) during 3 cycles. In the fuel injection process, it is assumed that the fuel injection is completed instantaneously.

3. Result and Discussion

To confirm the reliability of the simulation result, single-tube and single-cycle simulation was examined and compared it with theoretical and experimental results. Figure 3 shows the closed end pressure histories of the present simulation, theory [5], and experiment [6]. In Fig. 3, time and wall pressure were normalized by the characteristic value proposed by Endo et al. [5] ; t_{ex}, combustion-exhaust time, and p_3, plateau pressure. The thrust wall pressure history in the simulation well agreed with the theoretical prediction and the experimental result. Previous study [2] reported that specific impulse (Isp) of the PDRE increased by the partial filling effect. It is important for the performance augmentation to use the partially filled tube. The single tube simulation result that uses partial filling was examined, and compared it with experimental result. Fig. 4 indicates the mixture-based Isp as a function of fuel filling ratio. The present simulation quantitatively agreed well with experimental results [6], especially the higher filling ratio (> 50%). Accordingly, the reliability of the present calculations was confirmed.

Multiple-tube and multiple-cycle simulations were conducted to realize the practical performance of the present PDRE. The performance characteristics were examined with the various exhaust configurations at the low frequency operation model as shown in Fig. 2 (b). Figure 5 shows the thrust wall pressure histories as a consequence of the change of the exhaust part configurations. Characteristic time, t_{ex} and pressure P_3 were used for the normalization. For the case of TYPE1, 2 and 4, each of the thrust wall pressures decreased to the initial pressure at the theoretically predicted time, t_{ex}, and its behavior is the same during 3 cycles. For the case of TYPE3, the thrust wall pressures do not reach the initial pressure at t_{ex} because of the partial filling effect, so that the Isp of the PDRE is simply improved. This partial filling effect was also reported in the previous work [2]. Figure 6 shows the nozzle wall thrust history of TYPE4. Periodic pressure peaks by the propagation of the shock wave through the nozzle was observed. However, the majority of the thrust history was made up of the negative thrust region, and we can expect that this negative thrust make performance of TYPE4 lower. Figure 7 shows the Isp obtained by each cycle of the exhaust configurations, TYPE1～4. In the case of TYPE1, Isp was approximately the same during 3 cycles, and their value was nearly 147s that was theoretically predicted value by the previous work [5]. TYPE1 is the basic type of the multiple-tube PDRE that has no exhaust part. In comparison with the Isp of TYPE1, the performance augmentation of TYPE3 was observed by the partial filling effect. However, that could not observed in other cases (TYPE2 and 4). It is notable that the configuration with a diverging nozzle (TYPE4) made the PDRE performance lower.

Before we conclude that the diverging nozzle does not lead the performance to the effective result, the effect of operation frequency was examined. The diverging nozzle configuration, in two cases of the diverging angle (5 and 7.5 degree) was also examined. Figure 8 shows the specific impulse as a function of FIR. Here, FIR=33% corresponds to the high frequency model, and FIR=66% is the low frequency model, as shown in Figs. 2. As the FIR decreased (operation frequency higher), Isp obtained by two cases of the diverging angle were slightly increased, and the Isp of the 5 degree exceed that of the 7.5 degree. However, these values were below the Isp obtained by the basic case (TYPE1) with no exhaust part.

The change of the exhaust part configuration could not derive the notable performance improvement except for the partial filling case (TYPE3). Especially the diverging nozzle (TYPE4) makes the PDRE performance lower.

4. Summary

The performance analyses of the multiple-tube and multiple-cycle Pulse Detonation Rocket Engine (PDRE) were examined with the various exhaust part configurations and the operation frequencies. The change of the exhaust part configuration could not derive the notable performance improvement except for the partial filling case (TYPE3). In the case of TYPE2 (shroud) and TYPE4 (diverging nozzle), the exhaust part made the PDRE performance lower. The undesirable effect of the diverging nozzle also appeared under the higher operation frequency case. In conclusion, the diverging nozzle is not adequate for the exhaust part configuration of the present multiple-tube PDRE.

References

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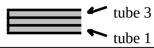
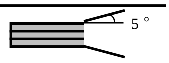
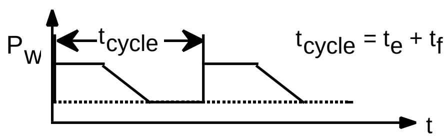
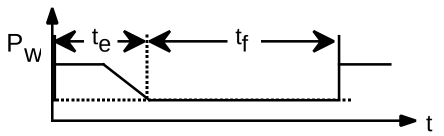
Table 1 Configuration of the three-tube PDRE and exhaust part

TYPE	Configuration
1 (basic model)	
2	
3	
4	



(a) High frequency (33%fuel injection time)



(b) Low frequency (66%fuel injection time)

Fig. 2 Operation model (Thrust wall pressure history)
Exhaust-Combustion time (t_{ex}) is constant value.
Fuel Injection Time (t_f) is changed.

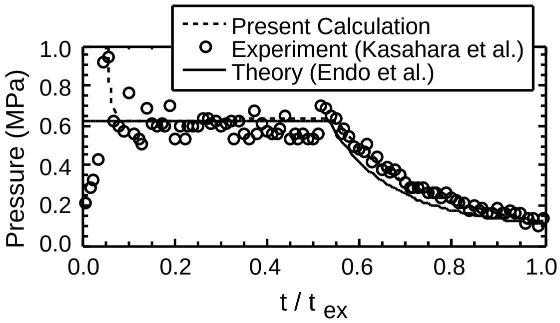


Fig. 3 Closed end wall pressure history
t_{ex} is the characteristic combustion-exhaust time proposed by Endo et al.(2003)

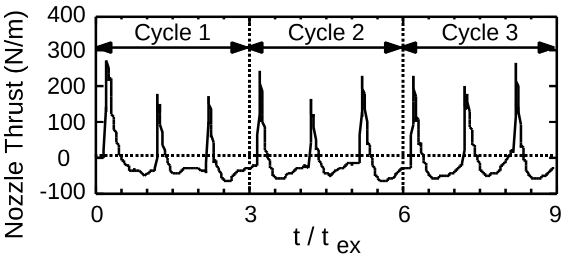


Fig. 6 Nozzle thrust wall pressure history (TYPE4)

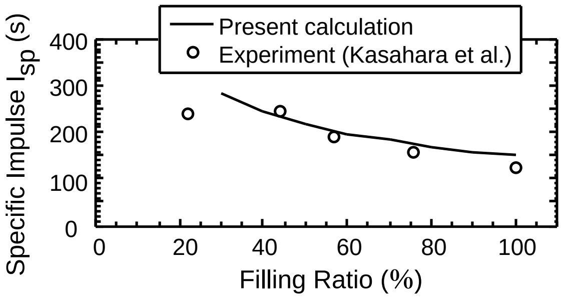


Fig. 4 Specific impulse as a function of filling ratio

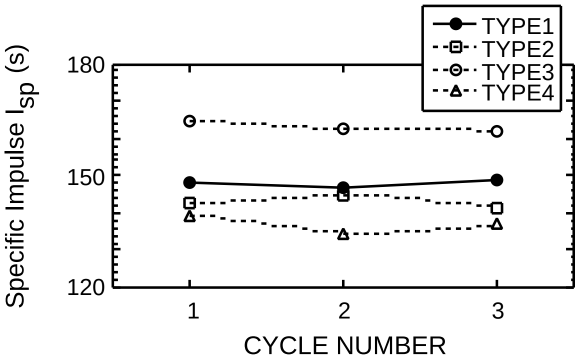


Fig. 7 Specific impulse of each cycles with a variable of exhaust configuration (Fuel injection time 66%)

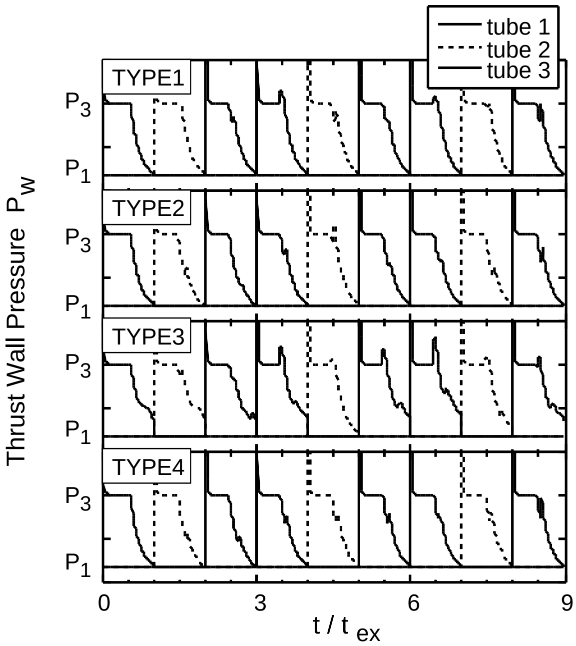


Fig. 5 Thrust wall pressure history
(TYPE1～TYPE4, low frequency operation model)

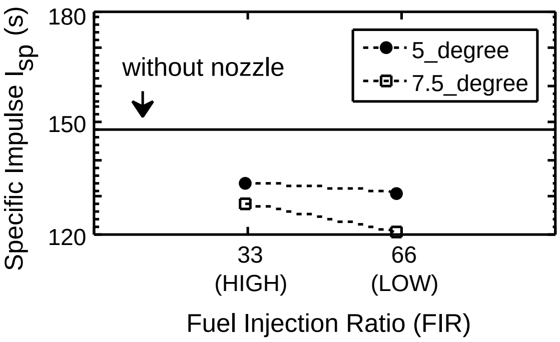


Fig. 8 Specific impulse during the 3 cycles with the change of the FIR (TYPE4)