Numerical Analysis on Pressure Gain of Rotating Detonation Engine Using H_2-O_2 Gases: Influence of Number of Injector

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1 Introduction

The concept of "Pressure Gain Combustion (PG Combustion)" more probably comes from gas turbine work and is later applied to Pulse Detonation Engine (PDE) study. In 2000-2010 the age of detonation engine was PDE. In 2010 through the present, it becomes PDE to rotating detonation engine (RDE) and PGC concept is applied to RDE. RDE is considered for two applications so far; rocket motor and gas turbine (GTE), and the present study will deal with the case of GTE. DTE has been developed step by step awhile ago and the world-wide researchers are competing together to attain 65% of turbine efficiency. In the present stage the urgent research must be the development of high temperature performance of GTE and of materials which tolerate such high temperature environment.

At this situation RDE turns up and gets attention to the increase of GTE performance by the Humphry cycle of detonation. In order to use detonation engine, as described earlier, PDE was subject to study in around 2000 to 2010, but since the loss of momentum and is large in PDE, the research center detonation engine moves gradually to RDE with a large frequency of about 6000 rpm, where the specific impulse of detonation rocket engine is understood as several times larger than the ordinary one. Hence RDE rocket engine must be meaningful to use with its nozzle. A cylindrical Combustion chamber without any nozzle will get at most about 60-70% pressure loss (maybe in this case we must count the pressure loss from injection too). The way of calculating PG with detonation base is developed by Paxson [1]. His calculation is to start with combustion chamber RDE.

$$\frac{\bar{T}_{t4}}{\bar{T}_{t3}} = 1 + (\gamma - 1)q_0 \tag{1}$$

where the non-dimensional heat addition q_0 is

$$q_0 = \frac{h_f}{\gamma R_0 \bar{T}_{t3}\left(\frac{a}{f}+1\right)} \tag{2}$$

Paxson rearranged Eqs. 1 and 2 to get PG through EAP (Effective Available Pressure). EPA is calculated by Kaemming and Paxson[2] as well as by Ten Eyck[3] as follows:

$$EPA = \frac{F_g + P_0 A_8 - P_{base} A_{base}}{(1+\gamma M_8^2) A_8} \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma}{\gamma-1}} \tag{3}$$

Then PG[2,3] will be calculated as:

$$P_{gain} = \frac{EAP_{abs} - P_{plenum,abs}}{P_{plenum,abs}} \tag{4}$$

One of Paxson's works shows the hybrid model[2] to get pressure gain from PDE in 2010. In this study he used both analytical approach and numerical one to avoid a complicated chemical reaction calculation. Recently Kaemming and Paxson[4] proposed the use of Equivalent Available Pressure (EAP) to calculate PG. Many researchers adopted their EAP concept for detonation based combustion since then with their figure which will discuss later in this paper.

The objective of the present study is to get a method of calculating PG for any type of RDE numerically, which can be compare with other RDE's PG and to discuss about PG gain and loss.

2 Numerical Method

The governing equations are the two-dimensional compressible Navier-Stokes equations with the UT-JAXA H_2/O_2 or Air full chemical reaction model[5] of nine species and twenty-one elementary reactions. The schemes to integrate the governing equations are: the third-order TVD Runge-Kutta method is used for the unsteady term; the AUSM-DV method with the second-order MUSCL scheme is used for the convection term; and the point implicit method is used for the chemical reaction source term.

In order to model the RDE system two-dimensionally, the following model (Fig.1) is set up to get a 2D RDE configuration:

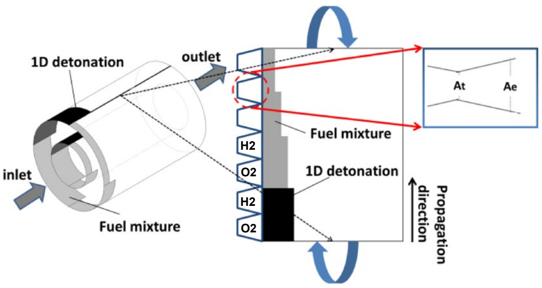

Fig. 1 2-D RDE model for numerical system

Table 1 1-D detonation numerical

Initial pressure	300 K
Initial temperature	3 atm
Number of calculation	44000
CFL number	0.9
i_ignite	800
Minimum grid width	2.5 μm
Equivalent ratio	1.0

where the H_2 and O_2 injectors alternately line up as shown in Fig.1.

The initial conditionns for the numerical system are that Pressure and temperature of fuel mixture of H2 and O2 in Fig.1 are 0.3 Mpa and 300 K, respectively. Otherwise originally the combustion chamber is filled with air of 0.1 Mpa and 300 K. The number of injection nozzles is changed by 40, 60, and 80, then we can see the effect of nozzle number on pressure gain of RDE chamber. The grid dependency on the Pressure gain is investigated by changing the grid size by 12.5, 25, and 50 μm which corressponds to the number of grid point by 2401x4801, 1201x2401, and 601x1201, respectively.

The injection inflow boundary condition is that (1) the case of high inlet pressure and no injection : p_2=p_1, u=0; (2) the case of relatively high inlet pressure and subsonic gas injection without any choke at the nozzle: p_2=p_1, pressure is extrapolated and gas is accelerated due to expansion, and velocity and density are obtained from the isentropic relation; (3) the case of rather high pressure and subsonic injection due to shock wave in the nozzle: p_2=p_1, pressure is extrapolated and isentropic condition is not established due to shock wave appearance: (4) the case of very low inlet pressure and supersonic gas injection: p1=p', and gas is injected at supersonic velocity, which is similar to the case 3. The injection out-flow boundary condition is that (1) the case of subsonic exhaust condition: $p_{outlet} = p_\infty$ and (2) the case of supersonic exhaust condition: $p_{outlet} = p_{exhaust}$. The periodic boundary at the upper and lower wall in order to the cylindrical configuration of combustion chamber.

3 Pressure gain dependence on number of injection port

Pressure gain is the important measure for combustion devices by knowing whether it is useful for energy based efficient combustion device or not.

Pressure gain for cylindrical RDE is studied numerically for non-premixed H2/O2 gases.

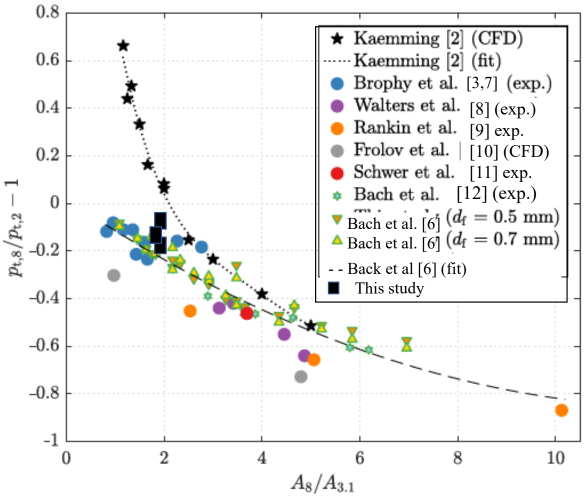

Figure 2 Comparison of RDC stagnation pressure data as a function of outlet throat to air injector area

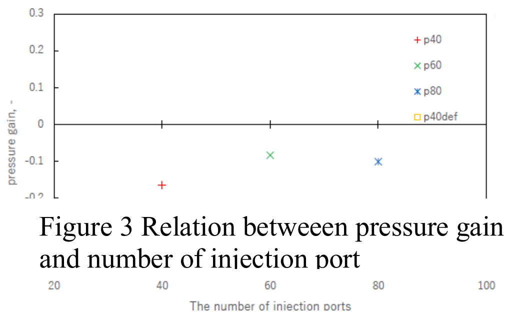

Figure 3 Relation betweeen pressure gain and number of injection port

Table 2 Detailed data of Pressure gain to threee different number of injection port

Number of injection ports	40(def/det)	60	80
Pressure gain [-]	-0.323/-0.165	-0.084	-0.101

The numerical results of pressure gain are shown in Fig. 2 for the inlet and outlet area ratio, in Fig. 3 for the number of injectioon port, and in Table 2 for the detailed values of three number of injection port. The present PG data in Fig. 2 are near the fit of Bach et al.[6], which losses are coming mostly from the straight exit nozzle. In Fig. 3 two interestingg points appear: one is that at thhe number of injection port of 40, the pressure loss of defraglation case is almost twice as much as that of detonatiion case, which is very reasonable result. The other is that the smallest PG loss is the case off the number of injjection port of 60, which is some difficulty of understanding its reason

4 Conclusions

The numerical study on the pressure gain or loss for the regular RDE with three kind of the number of injection port is performed using the two-dimensional compressible Navier-Stokes equations with the H2/O2 full reaction mechanism. The following results are found:

(1) The pressure loss for the 40 injection ports case shows the loss by deflagration is twice larger than that of detonation case.

(2) The pressure loss for the 60 injection ports case has smallest loss than that of 40 and 80 injection ports.

(3) This time all cases have pressure losses because of the straight exit without any nozzle.

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