Thresholds of Detonation Limit in H_2/O_2 Rotating Detonation Engine

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1. Introduction

Rotating detonation engine (RDE) is an innovative engine which may provide a larger thrust than the traditional ones. The dynamic process to get thrust is more intense, more thermodynamically beneficial, and more stable in smaller chambers. The size of chamber is determined by the characteristic scale of the detonation-wave front. Rotating means that detonation rotates near a wall while fuel is injected and products give thrust. Voitsekhovsky (1959) was the first researcher to deal with the rotating detonation engine [1]. In 1966 Nicholls et al. [2] performed a feasibility experiment of rotating detonation wave engine (RDWE). 20 years after their research, the experimental work on RDE has been performed mainly in Japan, Poland, France, and Russia.

MBDA in France [3,4] worked on theoretical and experimental problems connected to Pulse Detonation Engine (PDE). Lately in the newest papers they developed a Continuous Detonation Wave Engine (CDWE) as the next step for PDE. CDWE is considered as an annular combustion chamber with only one side open. The closed wall side is also the place to inject the fuel as well as the oxidizer. ICARE (Institute de Combustion, Aérothermique, Réactivité et Environnement) in France cooperating with ITAM (Khristianovich Institute of Theoretical and Applied Mechanics) in Russia [5] shows that Continuous Detonation Wave Rocket Engine (CDWRE) was simulated numerically for two dimensional model.

Bykovski et al. [6,7] presented a series of continuous spin detonation performance numerically as well as experimentally. Nagoya University group [8] presented a numerical study on RDE to show some detail of its structure. And Wolanski et al. shows their recent experimental work on RDE [9].

The present work will show the detonability limits and thresholds of rotating detonation engine performance. The detail analysis of such limit structure will be revealed using 2D compressible Euler equations with a high pressure detailed hydrogen-oxygen reaction mechanism.

2. Numerical method

The evaluation of rotating detonation engine performance is obtained by the two-dimensional compressible Euler equations applied together with the mass conservation equations for the H_2/O_2 system [10].

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For the numerical method, the 2nd-order Strang-type fractional step method is used for the time integration, the 2nd-order Harten-Yee non-MUSCL modified-flux type upwind-TVD scheme for the convection term, the point implicit method for the source term, and the Petersen and Hanson model [11] with 9 species and 18 elementally reactions for the chemical reaction model.

2.1 Numerical conditions

In the present study, the static RDE in the laboratory condition is considered that the flight velocity $u_\infty$is 0, the ambient pressure is p_∞=0.1 MPa and ambient temperature is T_∞=298 K. In order to see the pressure, temperature, and Mach number sensitivity, the inlet reservoir pressure is set from 2.4 to 3.5 MPa at the reservoir temperature of 298 K. In order to check the grid size sensitivity, 5 micron and 10 micron grid system are used. The physical size of numerical space is 3 mm to 6mm.

2.2 Boundary conditions

There are two boundary condition systems; one is the supersonic inlet condition and another is the subsonic inlet condition. Most experiments are using the supersonic inlet condition since the most of inlet nozzles for fuel have a choke condition at the exit of small nozzles. However most of real cases may have a subsonic inlet condition. The subsonic inlet condition is discussed by Zhdan et al. [12] The inlet subsonic condition is calculated depending on the following four cases. Then three cases are

1. The case that the inlet pressure is so high that the gas injection is not possible. if $p_2 \geq p_0$ (the inlet pressure is higher than the manifold pressure), $p_1 = p_2$ and $u = 0$ (pressure is extrapolated and velocity is zero).

2. The case that the inlet pressure is high and there is no choking at the throat with a subsonic gas injection. If $p_0 > p_2 \geq p''$(the pressure just before the inlet is lower than the manifold pressure and is higher than the pressure just after the inlet), $p_1 = p_2$(the pressure is extrapolated). The gas is accelerated by the isentropic expansion without choking.

3. The case that the inlet pressure is relatively high and the shock wave yields in the nozzle with the subsonic gas injection. (Since this is not the isentropic case, the energy conservation is used).If $p'' > p_2 \geq p'$ (the inlet pressure is higher than the supersonic condition and lower than the subsonic condition.), $p_1 = p_2$ (the pressure s is extrapolated).

4. The case that the inlet pressure is very low and gas is accelerated due to expansion with the supersonic injection. If $p' > p_2$ (the inlet pressure is higher than the supersonic condition), $p_1 = p'$ (pressure becomes supersonic one). The gas injection velocity u and density ρ calculate same as the case 3.

   (p_0: manifold pressure p_1: inlet pressure p_2: chamber wall pressure p' :supersonic nozzle exit pressure p'': subsonic nozzle exit pressure)

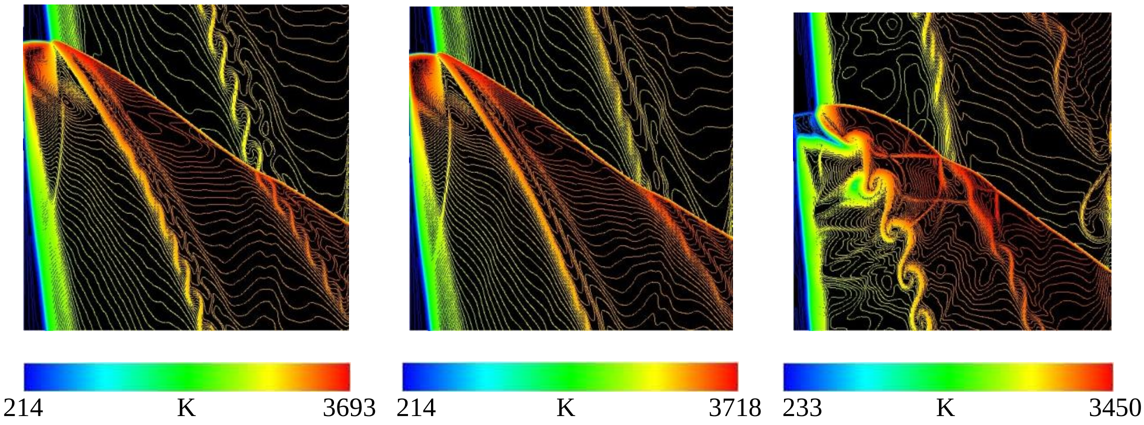
3. Results and discussion

The numerical study of rotating detonation engine is performed using hydrogen oxygen mixture.

The recent previous work [13] performed the sensitivity analysis of the reservoir pressure, inlet temperature, and inlet Mach number on RDE performance for a certain inlet nozzle area ratio between throat and nozzle exit. This paper extends to study the RDE threshold to the wider reservoir pressure to see the further corresponding RDE performance. Especially the cases of the nozzle throat/exit area ratios between 0.04 and 0.90 will be investigated for the threshold of detonation.

3.1 Typical temperature profiles of RDE

Figure 1 shows a typical temperature profile of RDE case using a nozzle throat/exit area raio of 0.0657. The temperature profiles give the rotating detonation structure more drastically. The shock-vortex interaction and Kelvin-Helmholtz instabilities are seen. When the initial reservoir pressure is lower than the critical value, the detonation collapses that its front leaves from the inlet wall (Fig. 1-(c)). This structure is explained in detail at the presentation by Fujiwara et al. [8].



(a) Temperature profiles at 300K and 3.0 MPa

(b) Temperature profiles at 300K and 3.5 MPa

(c) Temperature profiles at 300K and 2.0 MPa (no detonation)

Fig. 1 Temperature profiles for Hydrogen-oxygen RDE pressure sensitivity

3.2 Thresholds of detonation propagation limit of RDE

The relation between the reservoir pressure and the inlet Mach number is important for the initial condition to numerical analysis. Figure 2 shows the relation of inlet pressure or inlet Mach number with the reservoir pressure at the nozzle throat/exit area ratio of 0.0657. From the present calculation the critical reservoir pressure for detonation or deflagration is obtained as 2.6 or 2.7 MPa. When the reservoir pressure becomes lower than the critical number, no detonation appears at the combustion chamber and rotates in the cylinder. At these cases the inlet pressures are more or less 0.6 to 0.8 MPa and the inlet Mach numbers are between 0.3 and 0.4 which is about 120 m/s in velocity.

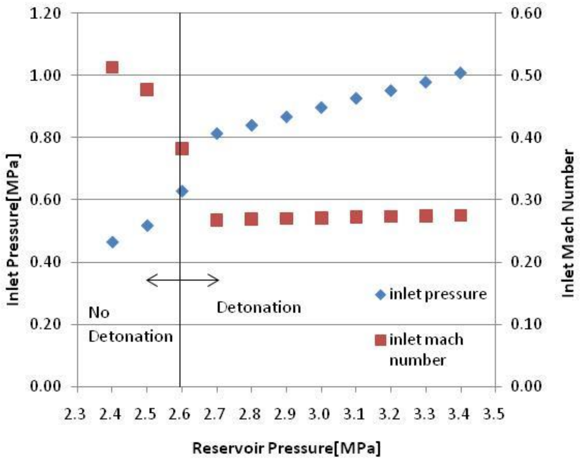


Fig. 2 The relation of inlet pressure and inlet Mach number to the reservoir pressure

4. Conclusion

The thresholds of rotating detonation at various inlet reservoir pressure and nozzle throat/exit area ratios are studied numerically using 2D compressible Euler equations with the full H_2/O_2 reaction mechanism. In the present case the inlet reservoir pressure of 2.7 MPa at is the threshold of detonation propagation for the nozzle throat/exit area ratio of 0.0657. In the full paper the further nozzle throat/exit area ratios will be shown. The reason for existence of such thresholds will be also discussed.

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