# Propulsive Performance Study of Rotational Detonation Engine

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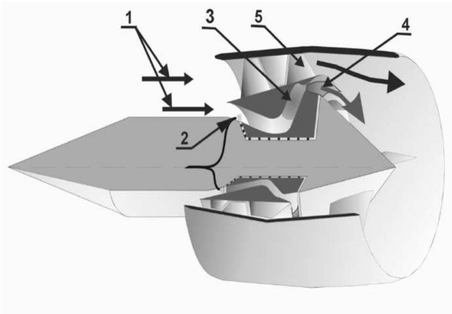
## 1 Introduction

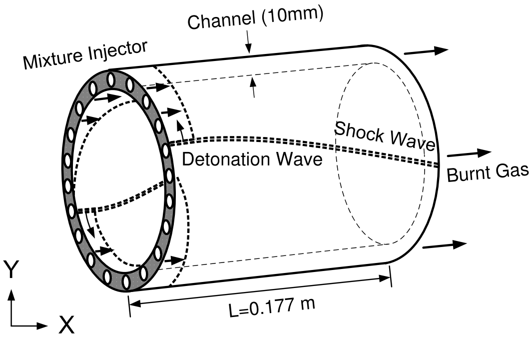
A variety of detonation-based engine concepts have been proposed and investigated to assess their feasibility to a propulsion system since 1950s. Amongst others are pulse detonation engine (PDE) and continuously rotating detonation engine (RDE) of which researches were initiated by Nicholls [1, 2] and Voitsekhovskii [3, 4], respectively. Recently, particular attention has been placed on continuously rotating detonation engine since it has many advantages to overcome the problems of PDE in generating thrust. The advantages of RDE include that it produces constant trust in a short tube, it is operated at very high frequency, typically an order of kHz and it requires only a single initiation of detonation. Over the past 30 years, Bykovskii et al [4] investigated continuously rotating detonation in various combustion chambers with several different fuel-oxidizer mixtures. The numerical investigation of RDE was performed with parametric studies in a two-dimensional chamber by Zhdan [5] and Davidenko [6]. Yi [7] numerically investigated continuously rotating detonation that produces a constant thrust in the three-dimensional RDE.

In addition, Wolanski et al [8] have proposed the novel concept of rotating detonation engine as illustrated in Fig. 1(a). The concept uses a single or multiple detonation waves propagating in the azimuthal direction of an annular chamber as shown in Fig. 1(b). The principle of RDE is based on the creation of continuously rotating detonation in a ring-like combustion chamber. A fresh mixture is supplied from one closed-side and combustion products are expanded from the other open-side of the chamber. Because of the inertia force of flowing-out burnt products, a rarefaction wave will be created inside the chamber, which significantly helps to evacuate the products from the chamber and refills the chamber. The expansion of detonation products in the nozzle will produce a thrust, allowing RDE to operate continuously. The frequency of chamber operation depends on the detonation velocity and the size of the combustion chamber.

In this study, a single detonation wave continuously rotating in an annular chamber is numerically simulated to investigate the effect of injection conditions, particularly total pressures, on the propulsive performance of RDE. The comparison of thrust and specific impulse with different injection total pressures is carried out in a two-dimensional chamber that represents the outer area of an annular chamber used in the experiments [8]. The injection conditions are chosen as a total pressure of 5, 10 and 15 atm with a fixed total temperature and injector area ratio. Moreover, an overall flowfield structure in the




(a) Concept of rotating detonation engine




(b) Annular chamber used in experiments [8]

Figure 1: Schematic of rotating detonation engine and its annular chamber: 1–inlet, 2–fuel injection, 3–ring-like detonation chamber, 4–tilted nozzle (turbine) and 5–fan.

chamber is described with the injection conditions at the total pressure of 10 atm, the total temperature of 500 K and the injector area ratio of 0.2.

## 2 Mathematical Formulation and Physical Configuration

A computational code is based on two-dimensional Euler equations with source terms due to chemical reactions. Since only the gas dynamics properties in the chamber are considered for this work, one-step, irreversible Arrhenius kinetics of a hydrogen-air mixture is adopted. In order to overcome stiffness associated with chemical reactions, time-operator splitting is used to decouple the governing equations into homogeneous partial differential equations and an ordinary differential equation. For the former equations, a finite volume approach with a MUSCL-based Roe scheme is employed for spatial integration. For temporal terms, the equations are discretized by a second-order, three-step Runge-Kutta method.

In the current work, the detonation is modeled in a 0.177 m long and 0.471 m wide chamber. A mixture injection system is assumed to be placed on the left-end wall with the large number of injectors so that the incoming mass flow rate is controlled by the total pressure ($p_0$), total temperature ($T_0$) and injector area ratio (AR). The injection system is modeled with three different conditions, depending on the injection wall pressure [6, 7]. The detonation transferred from a one-dimensional simulation is placed on the left wall to initialize the flowfield and it propagates into the azimuthal direction of the chamber. Slip boundary conditions with mixture injections are imposed at the left-end, while the subsonic or supersonic outflow boundary conditions are applied to the right-end, depending on the local Mach number at the exit. On the upper and lower boundaries, periodic conditions are employed.

## 3 Simulation Results and Discussion

A continuously rotating detonation engine has unique features in the flowfield structure that can be distinguished from that of pulse detonation engine. The typical features are presented as follows: (1) A fresh fuel-oxidizer mixture is continuously injected into a chamber, based on the left-wall pressure. This results in the formation of a triangular layer of the mixture that flows in the axial direction of the chamber. The thickness of the mixture layer is directly proportional to the duration between the successive detonation waves rather than the injection conditions. (2) The mixture injected into the chamber is non-uniform due to the combustion product expansion. The pressure and temperature of the mixture decrease across the axial direction of the chamber, but the axial velocity increases. (3) The successive detonation wave burns the injected mixture and propagates in the azimuthal direction,

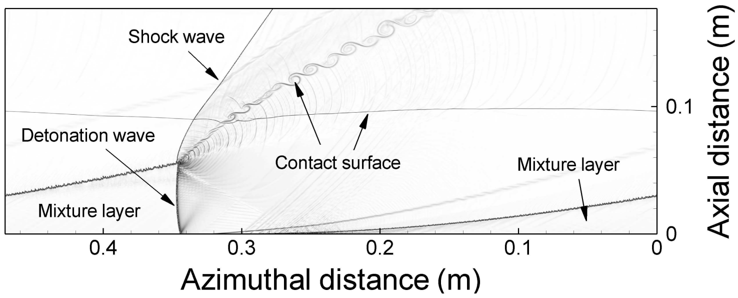
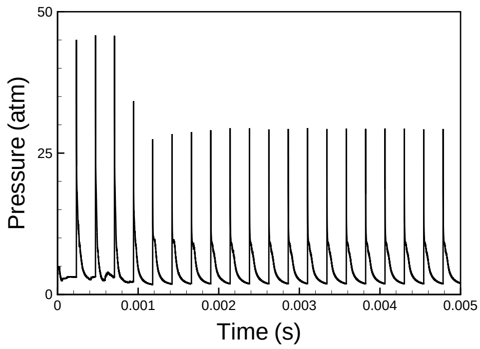
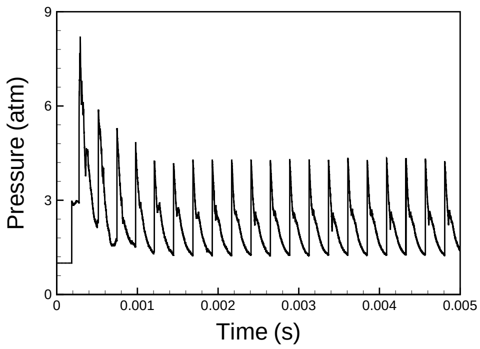



Figure 2: Density gradient of a continuously rotating detonation wave with the injection conditions of $p_0 = 10$ atm, $T_0 = 500$ K and AR = 0.2.




(a) $x = 0.005$ m



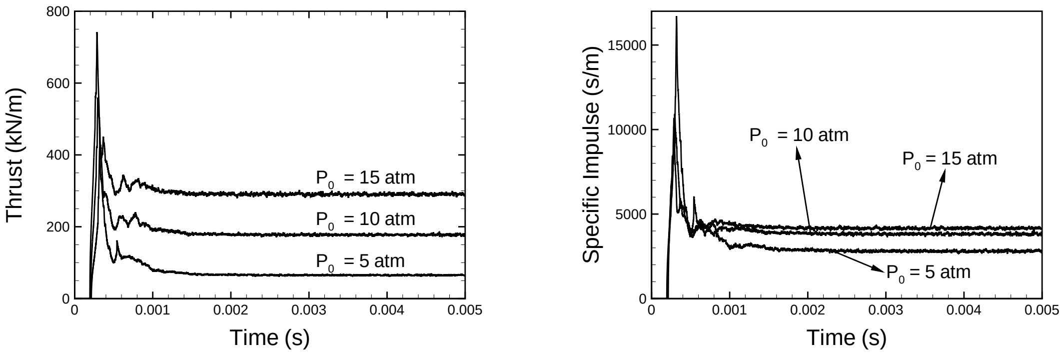

(b) $x = 0.15$ m

Figure 3: Temporal history of the pressures at different axial locations on upper boundary.

followed by a non-reacting shock wave and contact surface that emanate from the right end of the detonation. The shock wave propagates into the chamber exit at a supersonic speed. (4) The detonation around the left wall is inclined backward due to the mixture injection and the detonation strength increases across the axial direction of the chamber. (5) The hot expansion wave interacts with the fresh mixture, resulting in the mixture burning. These unique features are depicted in Fig. 2.

The detonation propagates at approximately 1961 m/s in the azimuthal direction of the chamber, which is close to the theoretical CJ detonation velocity at the calculated mixture conditions. The operating frequency is computed as $f = N_w U_D/\pi d = 4.16$ kHz where $N_w$ is the number of detonation waves resided in the chamber, $U_D$ is the detonation velocity and $d$ is the outer diameter of the chamber [4]. The temporal history of the pressures on the upper boundary of the chamber are presented in Fig. 3(a) at $x = 0.005$ m where the detonation propagates, and Fig. 3(b) at $x = 0.15$ m where the combustion product expansion is located. After five cycles, the flowfield was stabilized and the peak detonation pressure reaches 29.4 atm. At $x = 0.15$ m, the pressure ranges from 1.25 to 4.35 atm.

The thrust and fuel-based specific impulse per unit depth of the RDE are evaluated to investigate the effect of a reservoir total pressure, and are presented in Fig. 4. Detailed equations to evaluate these parameters can be found in Yi [7]. In Fig. 4(a), the thrust converges to roughly a constant value after large variations at the early time. This is one of main advantages compared to PDE, which produces a repetitive and intermittent thrust with time due to blowdown and refilling processes. The thrust increases linearly as the total pressure increases. The fuel-based specific impulse also increases with increasing the total pressure, but its gradient is much less than that of the thrust due to the injected fuel-mass flow rate that has the same trend. The weighted-average fuel-mass flow rate per depth at $p_0$ = 5, 10 and 15 atm are computed as 2.37, 4.74 and 7.12 kg/s $\cdot$ m, respectively, after stabilized.




(a) Thrust per unit depth (b) Fuel-based specific impulse per unit depth

Figure 4: Propulsive performance of one-waved RDE with different reservoir total pressure.

# 4 Conclusion

The propulsive performance of a rotating detonation engine was numerically studied to investigate the effect of a reservoir total pressure with a fixed total temperature and injector area ratio. A hydrogen-air mixture was modeled with one-step Arrhenius kinetics. All typical flowfield features, which are observed in experiments, of continuously rotating detonation wave in an annular chamber were captured and described in this study. It was found that the thrust of the rotating detonation engine converges to a roughly constant value and is directly proportional to the reservoir total pressure. Thus, the rotating detonation engine performance is strongly dependent on the reservoir total pressure that limits its operation. The fuel-based specific impulse also increases with the reservoir total pressure, but its rate of increase is less than that of the thrust.

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