Numerical investigations of Tail Laval Nozzle Effects on Rotating Detonation Engines

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1 Introduction

Rotating detonation engine (RDE) is one kind of new-concept detonation-based engines. It has several advantages, including one-initiation, high thermal efficiency and simple structure. Due to these characteristics, it is expected to bring revolutionary advancements to aviation and aerospace propulsion systems and now has drawn much attention throughout the world.

The basic concept of RDE was introduced by Voitsekhoviskii [1] in the 1960s, and he experimentally achieved a short-lived continuous detonation in a circular tube, using premixed acetylene and oxygen. The feasibility of RDE has been experimentally shown at the Lavrentyev Institute of Hydrodynamics (LIH) [2]. And in recent years, Wolanski et al. [3], Wang et al. [4], Shank et al. [5], Naour et al. [6] have also conducted experiments with various mixtures, mixture compositions, initial pressures and mass flow rates in different setups. However, experimental research, focusing on mapping out operational regimes for different configurations, has provided little information on the flow field within the detonation channel. And this shortcoming has been addressed by numerical investigation. In conjunction with experimental researches, numerical modelling and simulations of RDE have been performed to provide more information regarding the flow field within the detonation chamber. The early two-dimensional simulations of rotating detonation were performed by Zhdan et al. [7], and now overall descriptions of the flow field, parametric effects, and propulsive performance of RDE have since been clarified numerically by several groups [8-11]. In our group, specifically, algorithms have been developed successfully to simulate detonations in RDE combustion chambers and several different aspects of hydrogen/air and hydrogen/oxygen RDE have been investigated [12-16]. These include fuel injection limits, self-ignition, particle path, thermodynamic performance, shock reflections near the head end, propagation mode and detailed descriptions of the flow field.

In these previous numerical simulations, the physical model of RDE is usually a coaxial cylinder without tail nozzles. The detonation products flow out of the combustor at high temperature, wasting a lot of energy. In 2010, Shao et al. [13] computed RDE with four different tail nozzles. However, he mainly focused on the tail nozzle effects on the propulsive performance of RDE and concluded that the tail Laval nozzle has some advantages among the four. For practical application, RDE with a tail nozzle is necessary. Based on the work by Shao et al. [13], the main purpose of this paper is to discuss the effects of tail Laval nozzle on the flow field and flow properties of RDE in detail.

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2 Numerical methods and physical model

2.1 Numerical methods and grid dependence

In our simulation, a one-step chemical reaction model is used to describe premixed stoichiometric hydrogen/air detonation reaction. Three-dimensional Euler equations in generalized coordinates are used as governing equations. The detailed description of governing equations is given in Ref [13]. Flux terms here is solved by the fifth-order monotonicity-preserving weighted essentially non-oscillatory scheme (MPWENO). Time integration is performed by a third-order total variation diminishing (TVD) Runge-Kutta method. The averge grid size is 0.4 mm. The thermochemical model and computation scheme have been validated for some simple one-dimensional and three-dimensional test cases with grid size of 0.1 mm, 0.2 mm and 0.4 mm, respectively. The results are shown in figure 1. The detailed information is discussed in Ref [13]. The above comparision proves the numerical convergence and grid dependency.

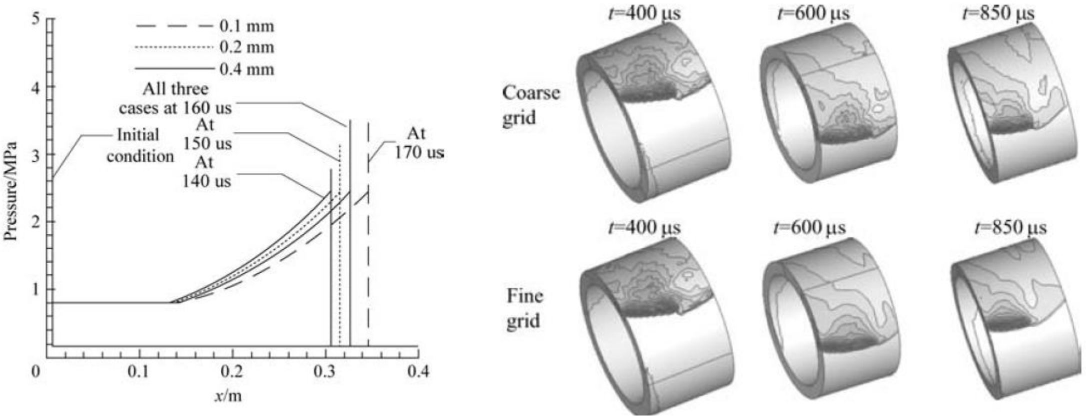

Figure 1. Grid dependency for one-dimensional and three-dimensional rotating detonation waves [13].

2.2 Physical model

In our simulation, the RDE combustor is a coaxial cylinder. To better explore the tail nozzle effects, three different combustors are designed and their physical models are shown in figure 2. The first model is a tail Laval nozzle combustor. The other two models are combustors without tail nozzle. For all the three combustors, the inner radii are all 50 mm and outer radii 62 mm. The axial length of Model 2 is 7 cm, equal to that of the front section of Model 1. The Model 3 and 1 have the same total axial length 11 cm.

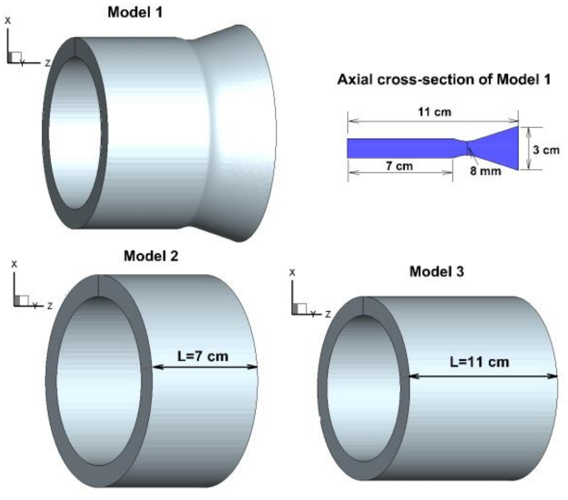

Figure 2. Physical models of three different combustors.

At the head end, premixed stoichiometric hydrogen/air is injected into the combustors. The injection condition depends on the local wall pressure following Laval tube theory. The inlet stagnation pressure is 30 atm. The side walls are considered solid and assumed to be adiabatic, slipping, and non-catalytic. Conditions on the outflow boundary correspond to a non-reflecting surface and the environment pressure is set to 0.5 atm. At starting time, RDE is ignited by one section of one dimensional detonation wave. The detailed information of above setups can be found in Ref [16].

3 Result and Discussion

3.1 Flow field

After ignition, a detonation wave is formed in one cycle and then it keeps running. When the whole flow field is under quasi-steady state, the pressure and temperature contours of the three combustors are shown in figure 3. The typical wave structures inside RDE are revealed. The detonation wave 1 leans on the head end, rotates in the circumferential direction and combusts the injected reactants 2 ahead of it. The oblique shock wave 3 connected with the detonation wave sweeps over products of the previous cycle. There is a contact surface 4 between products of different cycles. In the expansion area of Model 2 and 3, secondary shock wave 5 appear. From the figure, it is seen that the differences of the flow fields between Model 2 and Model 3 are few. Compared with the other two models, the detonation height of Model 1 is smaller and the detonation strength is stronger. In addition, due to the expansion effects, the pressure and the temperature decrease inside the tail Laval nozzle of Model 1.

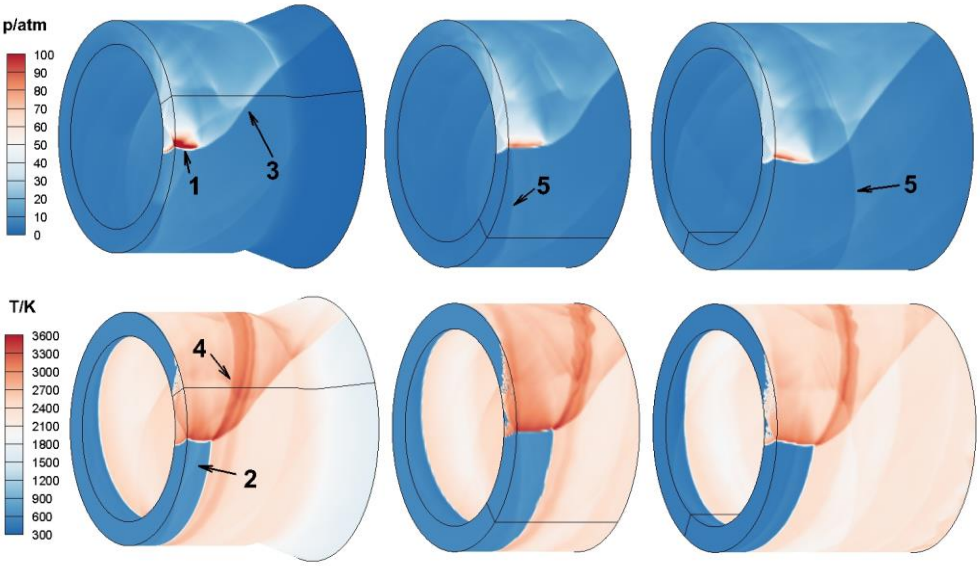

Figure 3. Pressure and temperature contours of the flow fields of the three combustors. 1-detonation wave, 2-fresh reactants, 3-oblique shock wave, 4-contact surface, 5- secondary shock wave.

3.2 Flow properties

To analyze the specific flow properties, the axial velocity and Mach number contours of the flow field of the three models are shown in figure 4.It is also seen that the chamber length has few effects on the RDE flow filed, comparing that of Model 2 to that of Model 3. The largest axial velocity and Mach number in Model 2 and 3 are about 1200 m/s and 1.2, respectively. At the exit of Model 2 and 3, only a small part of the flow is supersonic. Thus, when a tail Laval nozzle is connected to RDE, like Model 1, the flow acceleration is obvious in the tail nozzle. In Model 1, both the largest axial velocity and Mach number appear along the exit of the tail Laval nozzle and their values are about 2400 m/s and 2.4, respectively.

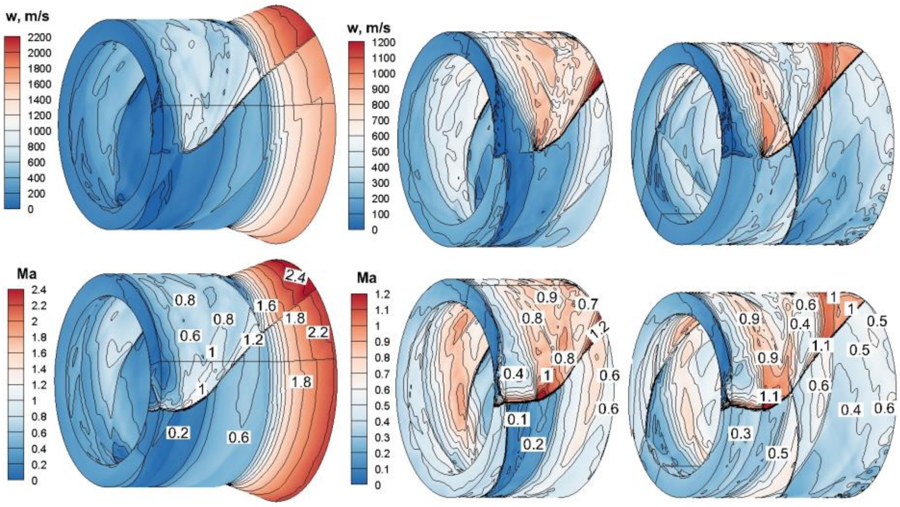

Figure 4. Axial velocity and Mach number contours of the flow fields of the three combustors.

The averaged properties of the flow are focused in this subsection and the equations are as follows:

$$w_{aver} = \frac{1}{2\pi}\oint w d\theta \tag{1}$$

$$p_{aver} = \frac{1}{2\pi}\oint p d\theta \tag{2}$$

The calculated results are shown in figure 5. It is seen that the average axial velocities of the three models are approximately the same within the detonation wave area (from 0 to 20 mm, corresponding to the detonation front area). In the following area of the combustors, the average axial velocities of Model 2 and 3 show no obvious increase even nearby the exit of the combustors. In Model 1, the average axial velocity also keeps almost constant before the tail Laval nozzle. However, it is increased from about 400 m/s to 1900 m/s inside the tail Laval nozzle, reflecting the obvious flow acceleration phenomenon. At the exit of the tail Laval nozzle, the average pressure is about 0.5 atm, matching the environmental pressure. However, the average pressure at the exit of Model 2 and 3 are about 7 atm, much bigger than the environmental pressure. That's why secondary shock waves appear in the expansion area of the flow fields, as shown in figure 3.

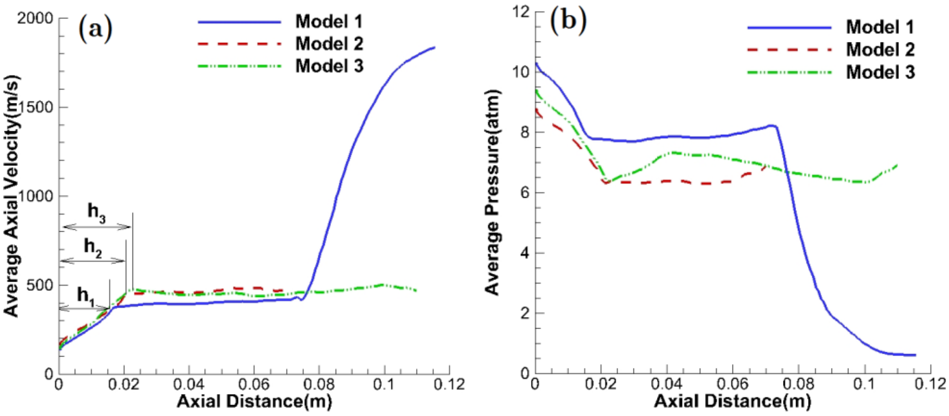

Figure 5. Average axial velocity (a) and pressure (b) along the axial direction of the three combustors.

3.3 Propulsive performance

The propulsive performance of RDE is evaluated in terms of mass flux $\dot{m}$, thrust *F*, and specific impulse I_{sp}. They are calculated using the following equations:

$$\dot{m} = \oint_{head} \rho w dA \tag{3}$$

$$F = \oint_{exit} (\rho w^2 + p - p_\infty) dA \tag{4}$$

$$I_{sp} = \frac{F}{g\dot{m}_f} \tag{5}$$

The results are shown in Table 1. It is seen that both the flow rate and thrust of the Model 1 is a little smaller, and the specific impulse of the Model 1is a little bigger. Therefore, on a whole, the propulsive performance of Model 1 shows no obvious advantages.

Table 1: Propulsive performance of the three cases

Model	Flow rate Kg/s	Thrust N	Specific impulse s^{-1}
1	1.768	4006	2080
2	1.865	4102	2020
3	1.844	4132	2058

4 Conclusion

Three-dimensional simulations of RDE are carried out here. The effects of the tail Laval nozzle on the flow field and flow properties of RDE are investigated in detail. It is found that the chamber length has almost no effects on either the flow distribution or the flow properties of RDE. Inside the tail Laval nozzle, the flow speeds up. At the exit of the tail Laval nozzle, the flow is all supersonic and the average pressure matches the environmental pressure. However, in terms of the propulsive performance, the RDE with tail Laval nozzle shows no obvious advantages.

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