# Thermodynamic Performance Numerical Simulation of Rotating Detonation Engine

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#### **1** Introduction

In this paper, a new method of analyzing RDE flow field and describing the thermodynamic performance is proposed. The trajectories of fluid particles are tracked. The impact of detonation wave, deflagration wave, oblique shock wave and contact surface on the trajectories and physical parameters at fluid particles is investigated deeply. The corresponding p-v diagram and T-S diagram are obtained by numerical simulation, and the numerical simulation results and ideal detonation combustion model are compared qualitatively and quantitatively. The numerical simulation results agree well with the theoretical results. The superior performance of RDE is further defined.

The flow field is approximated as a plane two-dimensional area. The entire flow field is initially filled with the premixed stoichiometric hydrogen and oxygen mixture at 1atm and 300K, except near the head wall region where an azimuthally propagating C-J detonation wave is artificially placed to initiate 2D detonation. The inlet total pressure is 3Mpa. If the pressure at the head end is larger than the inlet total pressure, the fuel can't be injected, the head end gives a wall boundary condition. If the pressure at the head end is smaller than the inlet total pressure, the inflow condition is given according to Laval nozzle theory. At the exit plane, we use Non-reflecting outlet boundary condition. The upper and lower sides are connected by periodic boundary conditions. The radius of the combustion chamber is 1cm, the length is 5cm. the number of grid cells is 500\*400,  $\Delta z = 0.1mm$ ,  $\Delta(r\theta) = 0.157mm$ .

The flow field is governed by the two-dimensional conservation Euler equations in the cylindrical coordinate system and Korobeinikov[4] two-step chemical reaction model. The viscosity, thermal conduction and mass diffusion are ignored in this study. The parameters in equations are selected to agree with Ref.[1] and [2]. Spatial terms are discretized with 5-step WENO scheme[3], and temporal terms are discretized with 4-step Runge-Kutta method[5].

#### 2 Trajectory Analysis

The flow distribution and the initial position of injected fluid particles when the detonation wave propagate stably are shown in Fig.1, Three representative fluid particles tracked are marked 1,2,3 in Fig.1. At this moment, the fluid particles are just injected to the head wall. In the flow field of RDE, there are detonation wave, deflagration wave, entailing oblique shock wave and contact surface which extends to the far downstream.

Fig.2 shows the trajectories of three fluid particles when they move in the combustion chamber. We can see from the figure that the trajectories are generally along axial direction no matter where their initial positions are. From the data, the trajectories only have tiny fluctuations along the azimuthal direction, the distance of fluctuations is less than 0.25 percent of circumference. This is the reason that a RDE can achieve greater thrust. The average experience time of three fluid particles is  $58.2 \mu s$  in the combustion chamber, and the detonation cycle is  $26.2 \mu s$ . That is to say detonation propagate nearly two cycles during the fluid particles moving.



(a) temperature contour (b) pressure contour and streamline Figure 1. The flow distribution and the initial position of just injected fluid particles.





Figure 3. The trajectory of particle 1

Fig.3 shows the trajectory of fluid particle 1 enlarged along the azimuthal direction. We use a,b,...g to mark seven key points at the trajectory 1. Fig.4 shows fluid-particle-1 density, pressure, temperature, axial and azimuthal velocity variation as a function of time in the process of movement. Fig.5 shows temperature distribution and the position of particle 1 in the flow field when the fluid particle 1 moved to corresponding point, corresponding to Fig.3.

Firstly, fluid particle 1 is injected to the head wall of combustion chamber, see point a in Fig.3 and Fig.5(a). It continues moving to point b which is near the detonation wave, see Fig.5 (b). And then the particle encounters with the detonation wave, its trajectory deflects, see Fig.3. In the moment of encountering with the detonation wave, density, pressure, temperature and azimuthal velocity increase rapidly, and axial velocity decrease, see Fig.4. The particle moves following closely the detonation until azimuthal velocity decreasing to zero (point d in Fig.3 and Fig.5 (d)), and azimuthal velocity continue decreasing to negative number, the trajectory deflects again.

Subsequently, the fluid particle 1 moves to downstream with the combustion products. At point e,

the particle encounters with the oblique shock wave coupled with detonation wave, see Fig.5 (e), its trajectory deflects again, see Fig.3. In the meantime of encountering, density, pressure, temperature and azimuthal and axial velocity all increase flashily. In addition, it is easy to find the variation trends of several physical parameters (except axial velocity) are similar when the particle encounters with the oblique shock wave and the detonation wave, merely the change degree of the latter is more intense than the former. The trajectory all deflects when encountering with the detonation wave and the oblique shock wave. After passing through the oblique shock wave, the particle moves following closely the oblique shock wave, until azimuthal velocity decreasing to zero, see point f in Fig.3 and Fig.5(f), continuing decreasing to negative number, so the trajectory deflects again. The particle continues moving to downstream until exhausted to the combustion chamber, see point g in Fig.3 and Fig.5(g).



(a) density (b) pressure and temperature (c) axial and azimuthal velocity Figure 4. Temporal variations of physical parameters at the fluid particle 1.



Figure 5. Temperature distribution when fluid particle 1 moved to corresponding point

In conclusion, in the process of from the fluid particle 1 injected to the head wall to exhausted the combustion chamber, it encounters with the detonation wave once, encounters with the oblique shock wave once, and doesn't encounter with the contact surface.

The fluid particle 2 is burned by the deflagration wave propagating slowly after injected to the combustion chamber, which is different from the fluid particle 1. Fig.6 shows the trajectory of fluid particle 2. Fig.7 shows temperature distribution and the position of particle in the flow field when the fluid particle 2 moves to corresponding point, corresponding to Fig.6.



Figure 6. The trajectory of fluid particle 2



Figure 7. Temperature distribution when fluid particle 2 moved to corresponding point

The process from the point b to the point c is exactly the deflagration combustion. In this process the trajectory is not affected, see Fig.6. Fluid particle 2 keeping moving to point d, encounters with the oblique shock wave, the trajectory deflects. The variations of physical parameters is same to the fluid particle 1, so we no longer repeat them. When the particle 2 moves to point e, it encounters with the contact surface. The strength of the contact surface, where the particle encounters with the contact surface, is weak, so the variations of physical parameters are not obvious. But it is sure the trajectory doesn't deflect because of the contact surface. The particle 2 moves to point f, and encounters with the oblique shock wave again. Then the particle 2 exhausts from the combustion chamber.

In conclusion, the fluid particle 2 encounters with the deflagration wave once, encounters with the oblique shock wave twice, and encounters with the contact surface once.

#### **3** Analysis and Comparison of Thermodynamic Performance

Fig.8 shows the comparison diagram in the p-v curve and the T-S curve of two-dimensional, onedimensional numerical results and ideal detonation combustion process. Numerical simulation results are consistent qualitatively with the ideal detonation model. The compressed process by the leading shock wave in the 2D numerical simulation(point 1 to point 2 in Fig.8) coincides wonderfully with the ideal process. However there is difference in combustion process and expansion process(point 2 to point 4). The *T*-*S* diagram shows the expansion process isn't entirely isentropic in the numerical simulation results. Because in the two-dimensional numerical simulation the size of combustion chamber is small, and no nozzle is added at the exit, the fluid particles exhausted to outside in the case of the expansion process uncompleted. Two-dimensional detonation has a special complex structure. The above reasons cause the difference between two-dimension numerical simulation results and ideal detonation combustion. In addition, in the 2D numerical simulation the particle encountering with the oblique shock wave due to the fluctuation of the p-v curve, entropy increment increases slightly. However the general trend of the p-v curve and the T-S curve doesn't change. That shows the loss of RDE performance caused by the oblique shock wave is not very clear.



(a) p-v diagram

(b) T-S diagram

Figure 8. The comparison of one-dimensional, two-dimensional numerical simulation and ideal detonation model

Table 1	. Net	mechanical	work	and	thermal	efficiency
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Combustion type	Net mechanical work(KJ/kg)*1000	Thermal efficiency
Ideal Detonation	3.63	51.11%
1D numerical simulation	1.92	39.67%
2D numerical simulation	1.50	35.41%

The net mechanical work and the thermal efficiency of the whole cycle can be calculated using the p-v curve and the *T*-*S* curve.Table 1 shows the net mechanical work and the thermal efficiency of above three cases. The thermal efficiency of ideal detonation combustion can reach 51.11%, the thermal efficiency of 1D numerical simulation is 39.67%, and the thermal efficiency of 2D numerical simulation is 35.41%. The net mechanical work of 2D numerical simulation can reach 41.32 percents of the ideal cycle, and the net mechanical work of 1D numerical simulation is 53.05 percents of the ideal cycle. If a nozzle is added at the exit in the 2D numerical simulation, the net mechanical work and the thermal efficiency of numerical simulation will be closer to the ideal results.

### 4 Conclusions

- (1) Detonation wave, deflagration wave, oblique shock wave and contact surface only have a very small interference on the trajectories of fluid particles. Fluid particles are injected into flow field, burnt by detonation or deflagration, and then ejected rapidly almost along the axial direction. The fluctuation at the azimuthal direction is less than 0.25% of the circumference of the combustion chamber. When fluid particles encounter with the detonation wave or the oblique shock wave, their trajectories deflect. And then the fluid particles follow the detonation wave or the oblique shock wave for a distance, their trajectories deflect again until the azimuthal velocity decreasing to 0. When fluid particles encounter with the deflagration wave or the contact surface, the trajectories don't deflect.
- (2) The *p*-*v* diagram and the *T*-*S* diagram obtained by numerical simulation qualitatively consistent with the theoretical results. The entailing oblique shock wave can cause a loss of RDE performance, but the loss is not obvious. In addition, the expansion process that obtains from the numerical simulation isn't entirely isentropic. The thermal efficiency of 2D numerical simulation is 35.41%. The cycle net mechanical work of 2D numerical simulation is 41.32% of ideal detonation cycle.

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