# An Analysis of the Performance of a Continuous Rotating Detonation Engine

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The thrust performance of a continuous rotating detonation engine is analyzed with the aid of one dimensional flow theory. Analysis shows high thermal efficiency does not guarantee that the thrust performance of a rotating detonation engine must be higher than that of a deflagration engine. This will be showed by an example analysis of a continuous rotating detonation engine.

# **1** Introduction

As the basic theory of aerodynamics, one dimensional flow theory neglects many details of flow, so it has great limitations in practical application. However, because it shields the interference of many flow details, we can extract the key characteristics affecting the flow from the complex flow structure, and grasp the operation law of the flow from the perspective of the three conservation laws, so as to point out the direction for further detailed research. In this study, the thrust performance of a continuous rotating detonation engine is analyzed and evaluated with the aid of one dimensional flow theory.

Detonation combustion has higher thermal efficiency than deflagration combustion, and the rotating detonation engine based on detonation combustion has received extensive attention in recent years<sup>[1]</sup>. A continuous detonation engine is a new concept engine using continuous detonation combustion to generate thrust. It has the advantages of simple structure, high thermal cycle efficiency, high thrust to weight ratio, low fuel consumption rate and so on. Such engines usually use annular combustor, and propellants are sprayed from closed ends, and one or more detonation waves propagate along the circumferential direction at the head of the combustion chamber. The high temperature and high pressure products after the waves expand rapidly, and push away from the open ends to generate thrust. It only needs initial detonation, and detonation wave, the combustible mixture can be pressurized by detonation wave to a certain pressure, which can produce more effective power at lower pressure ratio. In application, it has a good application prospect in punching or rocket engine<sup>[2, 3]</sup>.

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At present, there is not much work on the theoretical analysis and performance simulation of a continuous rotating detonation engine. One dimension and two dimensional analyses of the thermodynamic properties of the continuous rotating detonation engine show the thermodynamic cycle efficiency of a continuous rotating detonation engine is close to the ideal ZND model<sup>[4, 5]</sup>. The influence of combustion chamber length, diameter and width on propulsion performance shows that continuous rotating detonation engine has higher performance under different configuration dimensions <sup>[6]</sup>. Lu<sup>[7]</sup>, The University of Texas at Arlington, etc, has made a comprehensive elaboration on the deep field needed in the research of continuous rotating detonation engine and the technical challenges that will be applied to aerospace propulsion. Braun <sup>[8]</sup> analyzed the application range of the air breathing continuous rotating detonation engine with the help of thermodynamic cycle analysis, and pointed out that the rotating detonation engine can maintain the highest speed of Mach 5.

# **1** Parameters of engine thrust performance

For one dimensional flow, the thrust produced by an engine depends on the impulse difference between the inlet and outlet. When the inlet parameter is constant, the engine outlet impulse will determine the thrust produced by the engine. When the engine outlet is in a state of complete expansion (i.e., the static pressure of the outlet is equal to the static pressure of the environment), the thrust of the engine will be the greatest.

In order to simplify the derivation, it is assumed that the physical parameters of the gas are constant. When the engine is in a state of complete expansion, the expression of the outlet impulse is as follows (the subscript of the outlet parameter is 2)

$$I_{2} = \dot{m}_{2}V_{2} = \dot{m}_{2}Ma_{2}\sqrt{\gamma RT_{2}} = \dot{m}_{2}Ma_{2}\sqrt{\frac{\gamma RT_{02}}{1+0.5(\gamma-1)Ma_{2}^{2}}}$$
  
$$= \dot{m}_{2}\sqrt{\gamma RT_{02}}\sqrt{\frac{Ma_{2}^{2}}{1+0.5(\gamma-1)Ma_{2}^{2}}} = \dot{m}_{2}\sqrt{\frac{\gamma RT_{02}}{0.5(\gamma-1)}}\sqrt{1-\frac{1}{1+0.5(\gamma-1)Ma_{2}^{2}}}$$
(1)  
$$= \dot{m}_{2}\sqrt{\frac{2\gamma}{\gamma-1}R}\sqrt{T_{02}}\sqrt{1-\frac{1}{\left(\frac{P_{02}}{P_{\infty}}\right)^{(\gamma-1)/\gamma}}}$$

The formula (1) shows that the outlet impulse value is determined by mass flow, total pressure and total temperature. For a specified case, the engine inlet parameters and mass flow rates have been determined, so the thrust of the engine is determined by the impulse of the outlet, and the outlet impulse is determined by the total temperature and total pressure at the outlet. So the total and total pressure of the engine outlet flow can be regarded as an index parameter of engine thrust performance, which can directly reflect the thrust performance of the engine.

# 2 An example of a rotating detonation engine

According to the upper section analysis, for a one dimensional flow, the total temperature and total pressure are the index parameters of engine thrust performance. To analyze engine thrust performance, we just need to compare the total temperature and the total pressure of the gas flow at the outlet of the engine. Considering the influence of combustion on engine performance, in order to simplify the analysis, assuming that the engine is equipped with a perfect nozzle matching with the combustion chamber, there

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is no total temperature and total pressure loss in the tail nozzle. The analysis of the thrust performance of the engine only needs to compare the total temperature and total pressure of the air flow at the combustor outlet.

It is assumed that the engine combustor is an annular straight combustor, and the combustion heat release of the fuel is completed successfully in the middle of the combustion chamber by using the rotating detonation wave. As long as the velocity of the flow is less than the velocity of the detonation wave, this type of flame stabilization should be feasible. The wall surface is smooth wall, and the length of the combustion chamber is sufficient to ensure the uniform parameters of the entrance and exit (see Fig. 1).





Section 2

Figure 1. Combustor diagram

In an annular combustor, the pressure of the wall passes through the center axis, the moment of momentum relative to the center axis is 0. If the inlet air flow of the engine combustion chamber is not moving in a circumferential direction, according to the conservation of moment of momentum, the integral of the moment of momentum of the combustion chamber outlet air flow relative to the center axis should also be 0. As the length of the combustor increases, the outlet flow of the combustion chamber will gradually become uniform. As the length of the combustor is long enough, the outlet flow will have only a single axial velocity, no circumferential velocity.

According to the definition of impulse, the expression of the inlet (section 1, the parameter subscript is 1) and outlet (section 2, the parameter subscript is 2) impulse is as follows

$$I_{1} = \dot{m}V_{1} + p_{1}A = \dot{m}Ma_{1}\sqrt{\gamma RT_{1}} + \rho_{1}RT_{1}A$$

$$= \dot{m}Ma_{1}\sqrt{\gamma RT_{1}} + \frac{\dot{m}}{Ma_{1}\sqrt{\gamma RT_{1}}A}RT_{1}A = \left(Ma_{1}\sqrt{\gamma} + \frac{1}{Ma_{1}\sqrt{\gamma}}\right)\dot{m}\sqrt{RT_{1}} \qquad (2)$$

$$= \frac{Ma_{1}\sqrt{\gamma} + \frac{1}{Ma_{1}\sqrt{\gamma}}}{\sqrt{1 + 0.5(\gamma - 1)Ma_{1}^{2}}}\dot{m}\sqrt{RT_{01}}$$

$$I_{2} = \frac{Ma_{2}\sqrt{\gamma} + \frac{1}{Ma_{2}\sqrt{\gamma}}}{\sqrt{1 + 0.5(\gamma - 1)Ma_{2}^{2}}}(\dot{m} + \dot{m}_{f})\sqrt{RT_{02}} \qquad (3)$$

According to the momentum theorem, the relationship between the thrust of the combustor and the impulse of the inlet and outlet is as follows:

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$$F = I_2 - I_1 \tag{4}$$

As the wall of the combustion chamber is straight, the axial force of the combustion chamber is 0. This means

$$I_1 = I_2 \tag{5}$$

The substitution of formula (2) and (3) into (5) can be obtained

$$\frac{Ma_2\sqrt{\gamma} + \frac{1}{Ma_2\sqrt{\gamma}}}{\sqrt{1 + 0.5(\gamma - 1)Ma_2^2}} (\dot{m} + \dot{m}_f) \sqrt{RT_{02}} = \frac{Ma_1\sqrt{\gamma} + \frac{1}{Ma_1\sqrt{\gamma}}}{\sqrt{1 + 0.5(\gamma - 1)Ma_1^2}} \dot{m} \sqrt{RT_{01}}$$
(6)

According to the conservation of energy

$$T_{02} = T_{01} + Q$$
 , Q is the heat released by the burning (7)

The parameters of  $\gamma$ , R, Q,  $\dot{m}$ ,  $\dot{m}_f$  and parameters at inlet are all fixed at a given case, so the outlet Mach number meets the following relation

$$\frac{Ma_2\sqrt{\gamma} + \frac{1}{Ma_2\sqrt{\gamma}}}{\sqrt{1 + 0.5(\gamma - 1)Ma_2^2}} = constant$$
(8)

Constant is only related to combustion chamber inlet condition, fuel flow rate and fuel release heat. It has nothing to do with deflagration or detonation wave heat release.

Figure 2 is a relational change curve of  $\frac{Ma_2\sqrt{\gamma} + \frac{1}{Ma_2\sqrt{\gamma}}}{\sqrt{1 + 0.5(\gamma - 1)Ma_2^2}}$ 



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Figure 2 and formula (8) show: when the combustion chamber inlet condition, fuel flow rate and fuel release heat are given, constant will be a fixed value. At this time, there are three possible solutions to the corresponding combustion chamber outlet Mach number ( $Ma_2$ ).

The first is the unsolvable, that is, the burning of heat has gone beyond the maximum amount of heat that the flow can accept, and the flow of heat is choked up.

The second is the supersonic solution, which corresponds to the outlet Mach number when heat is released in supersonic flow.

The third is the subsonic solution, which corresponds to the outlet Mach number when heat is released in subsonic flow.

After the  $Ma_2$  is obtained, the corresponding outlet total pressure  $(P_{02})$  can be calculated according to the outlet total temperature  $(T_{02})$  and the flow area (A).

$$P_{02} = p_{2} \left(1 + \frac{\gamma - 1}{2} Ma_{2}^{2}\right)^{\frac{\gamma}{\gamma - 1}} = \rho_{2} R T_{2} \left(1 + \frac{\gamma - 1}{2} Ma_{2}^{2}\right)^{\frac{\gamma}{\gamma - 1}}$$

$$= \frac{\dot{m}}{V_{2}A} R T_{2} \left(1 + \frac{\gamma - 1}{2} Ma_{2}^{2}\right)^{\frac{\gamma}{\gamma - 1}} = \frac{\dot{m}}{Ma_{2} \sqrt{\gamma R T_{2}} A} R T_{2} \left(1 + \frac{\gamma - 1}{2} Ma_{2}^{2}\right)^{\frac{\gamma}{\gamma - 1}}$$

$$= \frac{\dot{m}}{Ma_{2} \sqrt{\gamma A}} \sqrt{R T_{2}} \left(1 + \frac{\gamma - 1}{2} Ma_{2}^{2}\right)^{\frac{\gamma}{\gamma - 1}} = \frac{\dot{m}}{Ma_{2} \sqrt{\gamma A}} \sqrt{R \frac{T_{02}}{\left(1 + \frac{\gamma - 1}{2} Ma_{2}^{2}\right)^{\frac{\gamma}{\gamma - 1}}} \left(1 + \frac{\gamma - 1}{2} Ma_{2}^{2}\right)^{\frac{\gamma}{\gamma - 1}}$$

$$= \frac{\dot{m}}{Ma_{2} \sqrt{\gamma A}} \sqrt{R T_{02}} \left(1 + \frac{\gamma - 1}{2} Ma_{2}^{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$$
(9)

The above solution process shows that the total temperature and total pressure of the combustor outlet can be obtained only by the specified inlet condition, fuel flow rate and fuel release heat, without considering whether detonation wave or deflagration wave is adopted in the combustion organization. This means that although the current example assumes that detonation wave tissue combustion in the engine combustor, it will not have higher thrust performance than the engine using deflagration wave tissue combustion, because the total temperature and total pressure of the rotating detonation engine and deflagration engine are equal.

## **3** Analysis

In the case of the upper section, the rotating detonation engine does not show higher thrust performance than the deflagration engine. Why the high thermal efficiency of detonation wave is not reflected in the example? This section will analyze the problem.

Suppose there is a deflagration engine (see Fig. 3), whose combustion is organized by deflagration wave. The combustion forms a stable solution satisfying the constraint of equal cross section impulse (formula (5)). Now we replace the deflagration wave with the detonation wave (see Fig. 4). Because the detonation wave has higher thermal efficiency than the deflagration wave, it converts more heat into mechanical energy. Compared with Fig. 3, the detonation engine in Fig. 4 will have more mechanical energy. If this extra mechanical energy is given to the axial flow, which must increase the outlet impulse, the constraint of equal cross section impulse (formula (5)) will be broken. This means the previous stable solution will be false. To get a stable solution, a feasible way is to give the extra mechanical energy to the circumferential flow (just like what the rotating detonation engine do). The circumferential flow doesn't

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change the outlet impulse, so the constraint of equal cross section impulse will be maintained. However the circumferential flow can't propel the engine, and just increase the circumferential flow non-uniformity. The integral of the moment of momentum of outlet relative to the center axis is 0 because of the conservation of moment of momentum, so the circumferential flow can't keep too long. With the flow moving downstream, the extra circumferential kinetic energy converted by detonation must gradually dissipate to heat energy. The assumption that the length of the combustor is sufficient to ensure the uniformity of the inlet and exit parameters is introduced in the upper section, which means the extra kinetic energy converted by detonation will be all consumed back to the heat. Then the characteristics of the high thermal efficiency of the detonation wave are not reflected in the example.

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Figure 3. Combustor diagram of deflagration engine



Figure 4. Combustor diagram of detonation engine

The process of engine work is essentially the process of converting the heat released by fuel into mechanical energy to produce thrust. The high thermal efficiency of the detonation wave means that the thermal energy released by the fuel can be more converted into mechanical energy compared with the deflagration wave, but it does not mean that the detonation engine must have a higher thrust than a deflagration engine. The engine needs to meet at least two conditions to produce the thrust effectively: a) transform heat energy into mechanical energy as high as possible; b) the converted mechanical energy is used to propel the engine as high as possible. If the mechanical energy converted from heat can't be effectively used to propel the engine, then high thermal efficiency will be meaningless.

The stability of the detonation wave in the combustion chamber is artfully realized by the detonation wave moving along a circle. However it also pays for it, which has improved the difficulty of using mechanical energy to propel the engine.

Flow contours of 2D flow field unfolding along circumference of a rotating detonation engine is given in Fig 5. Ratio of Cross section mass-weighted average total pressure to inflow total pressure at different axial posion is given in Fig 6.



Figure 5. Flow contours of 2D flow field unfolding along circumference of a rotating detonation engine



Figure 6. Flow contours of 2D flow field unfolding along circumference of a rotating detonation engine

Fig 5 shows detonation waves move in high speed along the circumferential direction. The flow field after the detonation wave shows highly circumferential non-uniformity. When high speed flow meets low speed flow, it even produces an oblique shock wave. The non-uniformity of the circumferential flow will cause the flow loss and consume the extra mechanical energy converted by detonation.  $P_0/P_0$  in Fig 5 shows that due to the boosting effect of detonation wave, a strong high total pressure region appears in the flow filed after detonation wave. However, this high total pressure region is confined to a very small range. After leaving this region, the total pressure of flow decreases rapidly. The local high total pressure in the flow field cannot guarantee the thrust performance of the engine. The real reflection of the thrust performance of the engine is the overall characteristics of the flow. Fig 5 and Fig 6 show that although the total pressure rises sharply after detonation waves, the mass-weighted average total pressure rises slightly across the cross section of the flow and decays rapidly along the axis. According to the previous one dimensional flow analysis, the total pressure loss is determined by the law of momentum conservation, which is difficult to avoid by optimum design at the technical level. Because of the restriction of the law of momentum conservation, the additional energy converted by detonation wave can only be converted into circumferential motion to ensure the stability of the flow field. The circumferential motion will lead to strong circumferential inhomogeneity of the flow field, so the total pressure loss of the flow field will be very strong.

In order to show the advantage of high thermal efficiency of detonation wave, we can only design the engine nozzle as close as possible to the detonation wave, so that it can be converted into axial kinetic

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energy as much as possible before the circumferential kinetic energy is lost. This will greatly increase the difficulty of nozzle design because of the strong circumferential non-uniformity of the flow field.

## 4 Conclusion

At present, the high performance expectation of a continuous rotating detonation engine is mainly due to the high thermal efficiency of the detonation wave. The process of engine work is essentially the process of converting the heat released by fuel into mechanical energy to produce thrust. The high thermal efficiency of the detonation wave means that the thermal energy released by the fuel can be more converted into mechanical energy compared with the deflagration wave, but this does not mean that a detonation engine must have a higher thrust than a deflagration engine. The engine needs to meet at least two conditions to produce the thrust effectively: a) transform heat energy into mechanical energy as high as possible; b) the converted mechanical energy is used to propel the engine as high as possible. If the mechanical energy converted from heat can't be effectively used to propel the engine, then high thermal efficiency will be meaningless.

The stability of the detonation wave in the combustion chamber is artfully realized by the detonation wave moving along a circle. However it also pays for it, which has improved the difficulty of using mechanical energy to propel the engine. The circumferential motion of detonation wave causes some kinetic energy to be wasted on the circumferential motion, which is not helpful to increase the axial thrust of the engine. If the kinetic energy of the circumferential motion can not be reasonably utilized, it will inevitably cause the performance loss of the rotating detonation engine, and even cause the characteristics of high thermal efficiency of detonation engine can not be reflected at all. However, it is not easy to convert the kinetic energy of circumferential motion into that of axial motion. Because the circumferential motion will bring about strong non-uniformity of flow, the total pressure of flow loses very quickly in the process of downstream transportation. To reduce the loss, it is necessary to complete the transformation within as short a distance as possible, and the transformation must be carried out under the condition of strong non-uniformity of flow. The design difficulty of nozzle is greatly increased.

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