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# Performance Analysis of Propulsion Powered by Rotating Detonation Rocket Based Combined Cycle (RDRBCC)

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## Abstract

The propulsion technology based on combined cycle engines will be a main trend in the future space missions, which can realize single stage to orbit. We proposed a new conceptual propulsion system powered by rotating detonation rocket based combined cycle fueled by LOX/Methane, and analyzed its performance in the paper. The working modes included rotating ejection, ramjet, scramjet and rotating detonation rocket, depending on different flight conditions. For low Mach numbers, the propulsion operates basically on the ejecting mode, while for higher Mach numbers the based rotating detonation engine is mostly used as the gas generator of fuel rich products, which are further afterburning with air in the combustor of the ramjet. The ring-type rotating detonation engine was designed as the ejector of the combined cycle engine, which was embedded in the central cone of the ramjet combustor. The performance of ejecting from the rotating detonation engine was then compared to the traditional rocket engine as an ejector. We revealed the mechanisms of mixing between the high speed combustion products from the rotating detonation engine and the incoming air from the diffuser in ramjet section. The calculations obtained thrust and specific impulse of the combined cycle propulsion system under different flight conditions. The results of numerical simulation showed that the rotating detonation ejector augments the propulsion system's specific impulse, and the thrust are increased significantly, if the Mach number is around smaller than 3. Therefore, the rotating detonation rocket based combined cycle engine can activate the better ejecting mode at sea level.

## Nomenclature

| | |
|---|---|
| m | mass flow rate |
| T | temperature |
| V | velocity |
| M | combustion product molecular mass |
| $\gamma$ | heat capacity ratio combustion products |
| $\varphi$ | augmentation coefficient |
| $\alpha$ | ejection coefficient |
| $\eta$ | air inlet efficiency |

Subscripts

| | |
|---|---|
| sp | specific impluse |
| F | thrust |
| c | combustor |
| det | detonation |
| S | Secondary air |
| i,e | engine stations (see Fig. 1) |

## Introduction

The combined cycle propulsion based on Rotating Detonation Engine (RDE) [1-3], called as Combined Cycle Engine Based on Rotating Detonation Rocket (CC-RDR) engine is proposed. Due to continuous detonations generated in the combustor, which undergo at constant volume combustion which is more efficient than the common constant pressure combustion process, higher performance are achieved. Besides, the RDE can stably work under lean and rich fuel conditions, which ensure the thrust demand of aircraft in complex environments [4], and only one successful ignition is required in the whole operation process.

The theoretic analysis and experimental measurements were carried out for CC-RDR to evaluate the performance advantage as a propulsion system. The ejection mode is one of the important statuses in RBCC engines [7]. The ejection driven by the piloted rotating detonation primary combustor was different from that by the combustor of Liquid Rocket Engine (LRE), because the detonation waves propagate rotationally along the circumferential direction in the annular combustor of RDE. The combustion exhausts are axially discharged with high velocity companying with complex oblique shock and expansion waves [1]. Therefore, the ejection is strengthened by the swirl momentum of high temperature exhaust from the primary combustor. Thus, the ejection performance of CC-RDR basically determines thrust level at the low flight speed condition.

This paper documented the theoretic analyzes and numerical simulations, which were conducted for comparing the ejection performance of a rotating detonation rocket based engine to that of a LRE based one, which are both fueled by LOX/CH4.

## Theoretical analysis of ejector mode

The simplified theoretical physics model of CC-RDR was shown in Fig. 1. Thus, the theoretical analyzes were performed using the theoretical method established by Cao [7], and Heiser and Pratt [8]. The following assumptions were made in the present study:

(1) The two flows ( $\dot{m}_\mathrm{p}$ denotes the mass flux of primary RDE and $\dot{m}_\mathrm{s}$ denotes the mass flux of ejected airflow) start to mix at the section $\langle \mathrm{i} \rangle$, and are completely mixed up at the exit (the section $\langle \mathrm{e} \rangle$).

(2) The two flows are steady and the fluid is taken as the ideal gas.

(3) The flow-passage wall is taken as an adiabatic wall, neglecting the effects of viscosity.

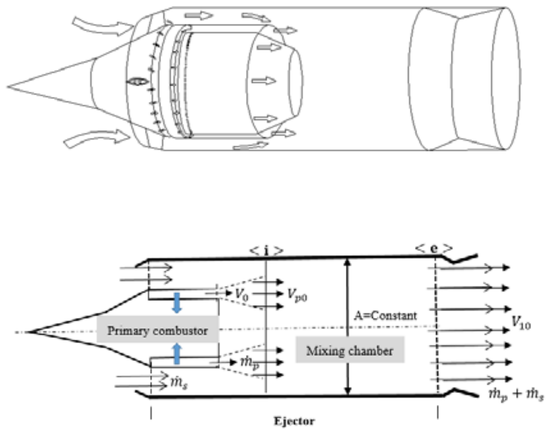

Figure 1. Simplified physical model of CC-RDR

Using the CEA© code and the Continuous Rotating Detonation Rocket (CRDR) theoretical model set up by Bykovskii et al [9], it was figured out that RDE thrust Fr equaled to 375kN when the pressure after the rotation detonation wave was approximately 162 atm in case that 5 atm was selected as the pre-detonation mixed gas pressure in combustor of RDE. The parameters of LRE at the same thrust magnitude were then set up correspondingly.

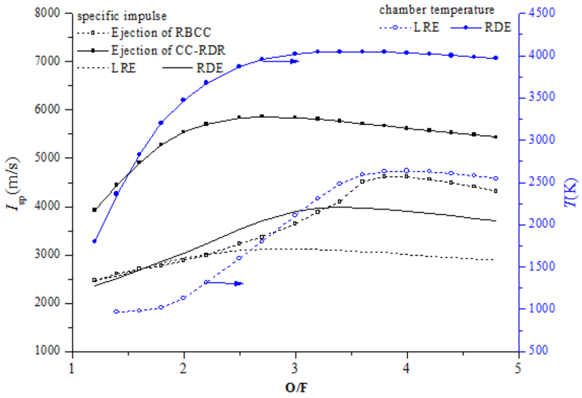

Figure 2. Specific impulse and combustion temperature in combustor

Figure 2 shows the specific impulse and combustion temperature in combustor of LRE, RDE as well as the combined engines. For the pure working mode of LRE or RDE, specific impulse and thrust change with oxidant-fuel ratio (O/F). The specific impulse formula for RDE herein is as follows [9]:

$$I_{sp}^{RDE} = \frac{\sqrt{2\left(\gamma_{det}^2 - 1\right)\left(c_{p,det} T_{det} + \frac{V_{det}^2}{2}\right)}}{\gamma_{det}}$$

where $T_{det}$ is the detonation temperature, $V_{det}$ the detonation wave speed. $c_{p,det}$ is the heat capacity at constant pressure and $\gamma_{det}$ is the heat capacity ratio. For LRE, the specific impulse is calculated at the perfect expansion,

$$I_{sp}^{LRE} = \sqrt{\frac{2\gamma}{\gamma - 1}\left[1 - \left(\frac{p_e}{p_c}\right)^{\frac{\gamma-1}{\gamma}}\right]} \cdot \sqrt{\frac{T_c}{\bar{M}}}$$

Where Pe is the exhaust pressure; Tc is the combustion temperature of combustor, and pc the chamber pressure, $\bar{M}$ the combustion product molecular mass. $\gamma$ is the heat capacity ratio combustion products.

The rocket engine can achieve the maximum specific impulse performance when the O/F is 3, while the RDE reaches its maximum at an oxidant-fuel ratio 3.4. This can be attributable to different local sound velocities as a result of dramatic difference in outlet temperatures of LRE and RDE. The changes to oxidant-fuel ratios for the maximum specific impulse take place when LRE and RDE are used as ejectors, in which the O/F shifts to about 4 in the LRE case, while that shifts towards the opposite direction to about 2.5 in the RDE case. The detonation combustion is concentrated in the heat release, with a higher temperature than the constant pressure combustion in combustor of LRE. The comparison on changes of primary products in pure RDE and LRE combustors is presented in Fig.3. The specific heat ratio of products is also shown in Fig.3. Together with the temperature varying with the O/F ratios, it can explain the shift of optimum OF ratio for pure rocket modes and ejector combined engines, as shown in Fig.2.

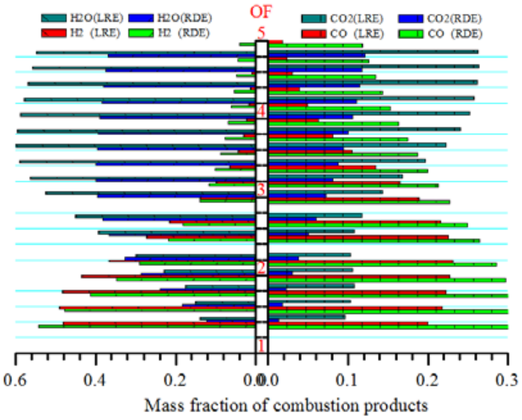

Figure 3. Combustion products in LRE and RDE combustors

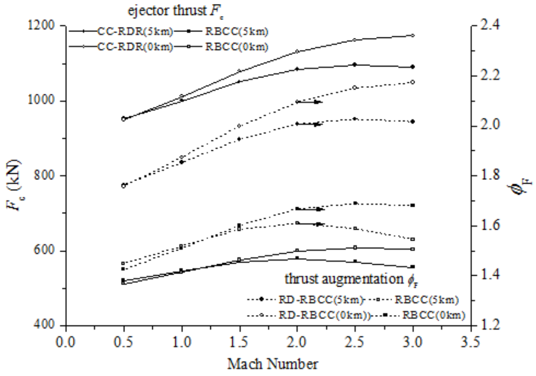

Figure 4. Ejector thrust and thrust augmentation vs. O/F ratio

The calculated thrust performance of combined cycle engine based on LRE and RDE at different flight Mach numbers respectively are presented. The ejector thrust is by,

$$F_c = \phi_F F_r$$

where Fr is the primary rocket thrust and the thrust augmentation coefficient, $\varphi_F$, was defined as

$$\varphi_F = (1+\alpha)\frac{V_{10}}{V_{p0}} - \alpha\frac{V_0}{V_{p0}}$$

where V10 is the velocity at the exit section of mixing chamber <e>; Vp0 is the velocity considering expansion at the section <i>; V0 is the exhaust velocity of primary rocket. The ejection coefficient here is defined as,

$$\alpha = \dot{m}_s / \dot{m}_p$$

As shown in Fig.4, the combined cycle engine based on RDE offered thrust about 45% higher than that of RBCC, which supported an apparent advantage of the combined cycle engine based on RDE. Moreover, these two types of combined cycle engines results in a small decrease of thrust with the increase of altitude under the supersonic flight condition. In contrast, a relatively less apparent impact of altitude increase was seen on thrust under the subsonic flight condition. The thrust augmentation coefficient could effectively indicate ejection performance of the combined cycle engine, because of the increase of mass flux. The early researches showed that it was usually difficult for RBCC thrust augmentation to exceed 1 during the subsonic take-off stage [5]. However, the follow-up study demolished the early findings and discovered that the thrust augmentation could absolutely go more than 1 [6]. The paper, by presenting calculated thrust augmentations of the two combined cycle engines as shown in Fig.4, figured out that the theoretic thrust augmentation of RBCC could theoretically maintain between 1.4 and 1.6 in subsonic flight condition. The CC-RDR thrust augmentation could be increased up to 1.9. The thrust augmentation verified a significant increase in the supersonic flight condition and started an apparent downtrend when the flight Mach number was about 3.The total pressure recovery of the air inlet could be calculated by the relation below [12].

$$\eta = \begin{cases} 1 & M_0 \le 1 \\ 1 - 0.075(M_0 - 1)^{1.35} & 1 < M_0 < 5 \end{cases}$$

The total pressure recovery of the air inlet effect in air inlet which resulted in increased loss of total pressure in high Mach number conditions formed. But how, in the meantime, that makes the thrust drop down also.

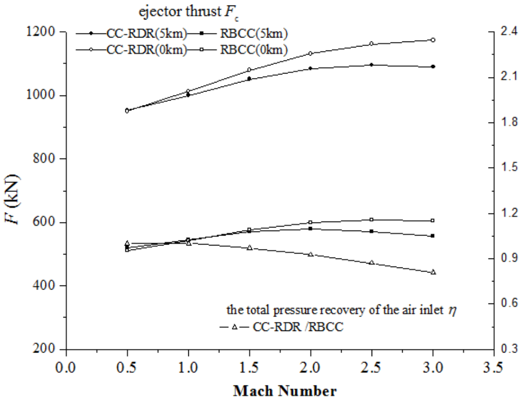

Figure 5. Thrust and the total pressure recovery of air inlet vs. flight Mach number

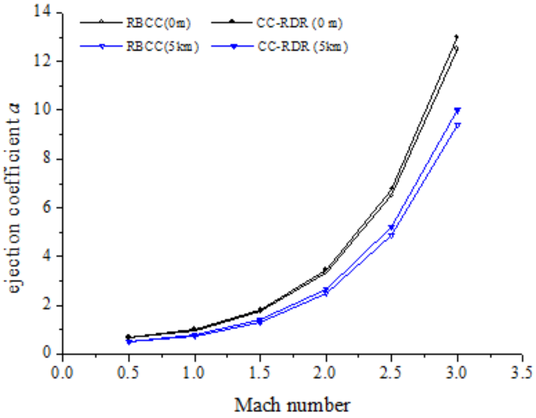

Figure 6. Ejection coefficient vs. flight Mach number

The ejection coefficient could also greatly reflect ejection performance of combined cycle engines based on LRE and RDE as ejectors. The higher ejection coefficient indicates a stronger air ejection capability. As illustrated in Fig.5, with the thrust of RDE and LRE remain the same but increase of Mach number, for both types of combined cycle engines (CC-RDR and RBCC) demonstrated a dramatic increase of ejection coefficients. Particularly, amount of secondary air ejected from RDE ejector obviously more than that of LRE under the identical flight Mach number condition. However, with the increased flight altitude and reduced atmospheric density, mass flow rate of ejected air significantly decreased if the ejection capabilities remain the same.

## Conclusions

The authors proposed a rotating detonation rocket based combined cycle engine, CC-RDR, fueled by LOX/Methane, and then theoretically analyzed its performance of ejection mode. The ring-type rotating detonation combustor, designed as the primary ejector, was embedded in the central cone of the ramjet. The analysis showed the advantage performance of thrust and specific impulse for the ejection mode of RD-RBCC compared to the traditional RBCC. The numerical simulation verified that the rotating detonation ejector augments the propulsion system's specific impulse, and the thrust are increased significantly, if the Mach number is larger than 2. Therefore, the rotating detonation rocket based combined cycle engine can activate the better ejecting mode at sea level. However, for higher Mach numbers the rotating detonation based engine is mostly used as the gas generator of fuel rich products, which are further afterburning with air in the mixing chamber of the ramjet.

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