Theoretic Analysis of Ejector Mode of Rocket Based Combined Cycle Propulsion

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Abstract
The overall theoretic physical and mathematical models are established for an ejector of liquid rocket based combined cycle (RBCC) propulsion. The LOX/kerosene liquid rocket engine (LRE) with a specified 100ton thrust force is established. The numerical solutions are then used to perform the performance analysis of the ejector mode. The influence of factors, including the flight Mach number, rocket chamber pressure, and ratio of ejecting area, are then elaborated in the present study. The configuration of combined cycle is constructed by multi-ejectors with a joint mixing and secondary combustion chamber. The ratio of ejecting area is varied by changing the area of air-breathing intake. With the increase of chamber pressure the ejection coefficient is decreased, but it is increased with the free stream Mach number increasing. For a higher Mach number, the augmentation of specific impulse of ejector rocket is larger. With the increasing of ejecting area, the specific impulse augmentation is lowered down. The present theoretic analysis is helpful to understand the integration performance of ejector rocket and guide the preliminary design of RBCC.

1. Introduction

The combined cycle propulsion technology mainly includes: Rocket Based Combined Cycle (RBCC) and Turbine Based Combined Cycle (TBCC) propulsion. The latter one has more complex parts and very high technical requirements for turbine engine; while the former has a simpler structure and is well developed in the ejector technology. The RBCC propulsion can be divided into liquid or solid rocket combined cycle propulsion based on the different uses of rocket engines. Since the liquid rocket is easier to achieve thrust control and work under variable conditions compared with the solid one, the liquid rocket combined cycle propulsion technology has been paid enough attention recently[1, 2].

Rocket Based Combined Cycle (RBCC) is an advanced propulsion system, characterized by its simple and compact structure, which reduces not only the structural mass, but also the configuration size as well as unnecessary energy loss. In operation, RBCC uses oxygen in the air as the oxidant, thus reducing the relevant quality of the carried oxidant, which has significantly improved aircraft payload. Viewing from the entire RBCC propulsion device, there are fewer moving parts, so its reliability is greatly improved. RBCC concentrates both the advantages of traditional high thrust-weight ratio but low specific impulse rocket engines, and those of low thrust-weight ratio but high specific air breathing engines. It is a system of a variety of work modes, including ejector, ramjet, scramjet and rocket mode [3]. The appropriate optimum work mode is enabled according to different flight conditions, which fully embodies the advantages of two propulsion modes and enables the rocket work in a range of wider fight speed. The RBCC propulsion can enable different work modes in different flight conditions under different altitudes and Mach numbers. The ejector mode is mainly operated under the Mach numbers less than 3 and selected for the linear rocket embedded in the flow channel. The secondary air flow enters the engine under the double actions of high speed pressing and ejecting. The second combustion will be organized in the combustion chamber, which improves the specific impulse. The operating speed range of the ramjet mode is about from 3 to 6 Mach number. At this mode, the rocket engine is off or on duty in low working conditions. The subsonic combustion is realized by employing the inflows pressing. Further, in the scramjet mode, the operating Mach number being from 6 to 8, supersonic combustion is realized in the flow channel. The rocket mode is operated when the Mach number is more than 8. At this time the intake is closed, and the rocket engine works again in the maximum working state [4-9].

The application of the ejecting rocket mode is the crux for realizing an integrated flow channel, reducing the system complexity and increasing the reliability of the system. The ejecting rocket is also a key technology in RBCC propulsion system researches. The ejecting rocket mode is operated in the take-off stage of combined engine. At this stage, the aircraft has the maximum mass. Therefore, the performance at this phase has a considerably significant impact on the ballistic performance of the entire RBCC. Viewing the state-of-the-art, the key technology of the ejector mode is the latest breakthrough in the four modes of RBCC. Because the problems in the research of the ejector mode are various and complex, current works have been neither carried out deep study on the ejector mode of RBCC, nor done a comprehensive understanding on the working process of the ejector mode. RBCC ejector mode has many critical issues, which need to be further addressed [10, 11]. Therefore, based on the combined propulsion technology of liquid rocket, this paper establishes a RBCC mathematical research model, studies a variety of affecting factors under ejector mode through numerical calculation, and then shows the impacts of a number of factors on the performance of RBCC ejector mode.

2. Analysis of ejector rocket performances

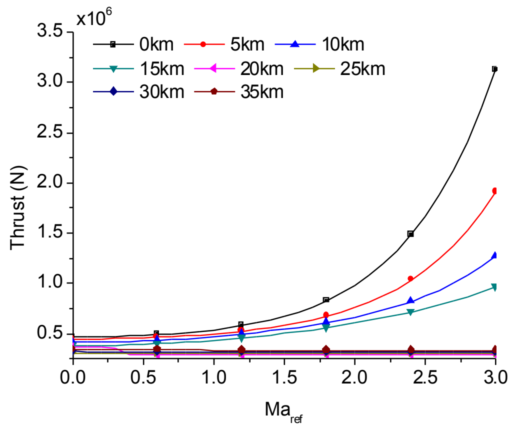
A liquid oxygen kerosene rocket engine of 100 tons thrust is firstly established for the rocket ejector. . The propellant uses a combination of liquid oxygen / kerosene and the overall O/F ratio is assumed to be 2.5. The design point of the ejector is taken at the sea level, and therefore, the expansion ratio of the liquid rocket engine nozzle is determined. The static pressure of the nozzle outlet is 1atm and therefore, the static pressure of mixing chamber is assumed at 1atm. The performance of RBCC ejector mode is obtained secondly, and the effects of flight altitude, Mach number and ejecting area ratio on the overall performance of ejector mode are finally analyzed.

2.1 Effects of flight Mach number

The effects of flight Mach number on the ejection performance, including thrust, specific impulse, ejecting performance and thrust augmentation at different flight altitudes are presented firstly. Here, the fully mixing process is assumed to happen in the mixing chamber, when the rocket engine is completely expended (at the ground design condition). The cross-section area ratio σ is taken as 0.1. The definition of cross-section area ratio can be referred in section 2.2.

Figure 1 presents the variations of thrust and its augmentation of the ejector rocket at different flight altitudes. Figure 2 then presents the variations of specific impulse with Mach number at different flight altitudes. As the flight Mach number increases, a higher rising level in the thrust and the specific impulse of ejector rocket are obtained at the lower flight altitude. The total pressure of the incoming flow increases and hence the total pressure of the secondary flow into the ejector rocket increases accordingly with an increase of the flight speed.

If the Mach number is the same, both the thrust and specific impulse of the ejector rocket are larger at lower flight altitude. If the flight altitude is above 20km, the thrust remains basically unchanged with the Mach number increasing. However, the thrust of the ejector will become smaller with the flight altitude becoming higher. As the flight altitude increases, both the thrust and specific impulse under the same Mach number continue to be decreased. Moreover, the degree of reduction is higher with the increase of flight Mach number.



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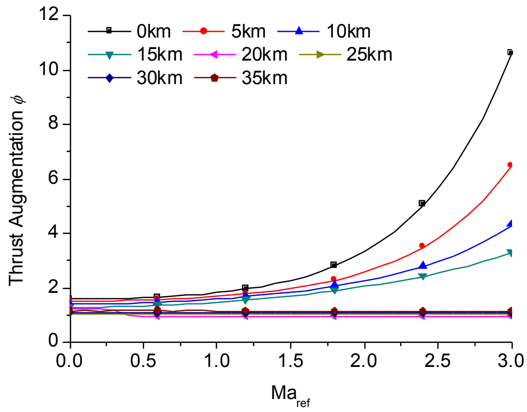

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Figure 1: Variations of ejector rocket thrust with flight Mach number.

(a) Thrust, (b) Thrust augmentation

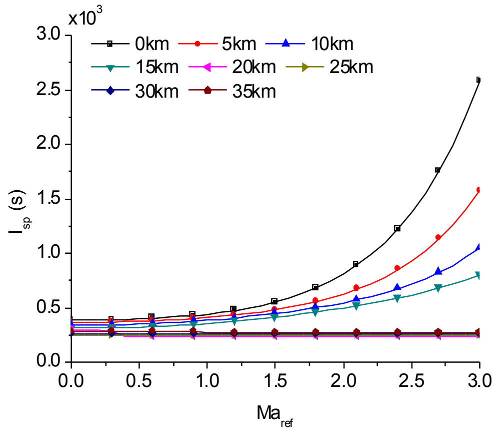


Figure 2: Variations of specific impulse of ejector rocket

Figure 3 shows the ejection coefficient of the ejector rocket at different flight Mach number and altitudes. With the flight Mach number increasing, the ejected air fluxes are increased, while the outlet flow of linear rocket does not change. Therefore, the ejection coefficient increases. It is found that the increase degree of the entrainments will be greater with the flight altitude becoming lower. As the flight altitude increases, the decrease of the ejection coefficient continuously reduces under the same condition of flight Mach number, and the difference increases with increasing of flight Mach number.

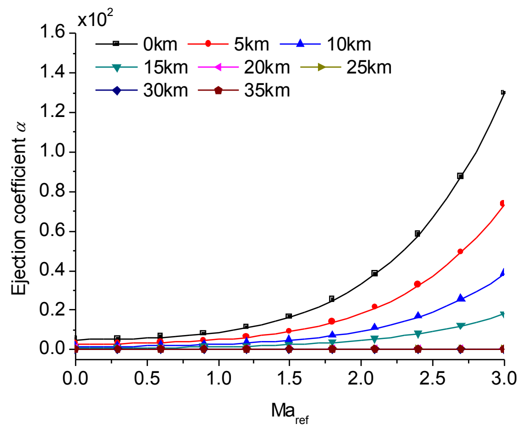


Figure 3: Ejection coefficient of ejector rocket

The ejector rocket at a fixed Mach number has better ejection performance at low flight altitude, with the increasing of flight altitude. The ejection performance has been greatly reduced compared to that at low flight altitude, and the entrainments decrease. The performance cannot be optimized through increasing the flight speed. Therefore, at the moment the thrust augmentation should be ensured through increasing the combustion chamber pressure, adding the secondary combustion or other suitable means.

2.2 Effects of cross-section area ratio

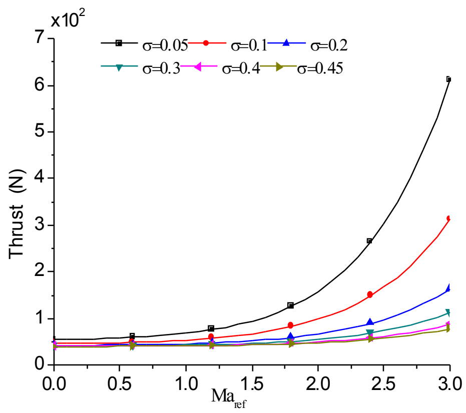
The rocket blockage in the ejector flow passage has a primary influence on the performance of the ejector rocket. The cross-section area ratio, σ , is usually used to describe the blockage, which is defined as the area ratio of the rocket nozzle outlet (A_r) to the entire flow passage cross section (A_i).

$$\sigma = A_r / A_i \tag{1}$$

The ejection performance changes with the ejected air flux, which commonly depends on the flow passage blockage. The below analyses of the effects of the cross-section area ratio σ on the ejecting performance are performed when the flight altitude is at the sea level.

Figure 4 shows the variations of thrust and its augmentation of the ejector rocket at different cross section ratios. Figure 5 presents the variations of specific impulse with the flight Mach number. If the flight altitude and the cross-section area ratios are taken as the same, the thrust, thrust augmentation, ejection coefficient and the specific impulse of ejector rocket will increase with the Mach number increasing. The smaller the cross-section area ratio is, the higher the degree of increase is. The cross-section area ratio decreases, i.e., the proportion of the outlet area of the linear rocket or the mixing chamber inlet area decreases, the ejected air flow increases for the same flight Mach number. Hence, the entrainments, thrust and specific impulse increase accordingly.

Figure 6 shows the ejection coefficient of the ejector rocket at different cross-section area ratios. An overlarge cross-section ratio will cause not enough air flow ejected, thereby resulting in no ejecting function. Conversely, a reduction of the cross-section area ratio can increase the secondary flow effectively, due to the increase of the inlet area of the secondary flow, and then increase the air entrainment ratio. In practices, due to various restrictions, the cross-section area ratio is unlikely to be too small, but should be taken within a reasonable range, thereby enhancing the ejection function.



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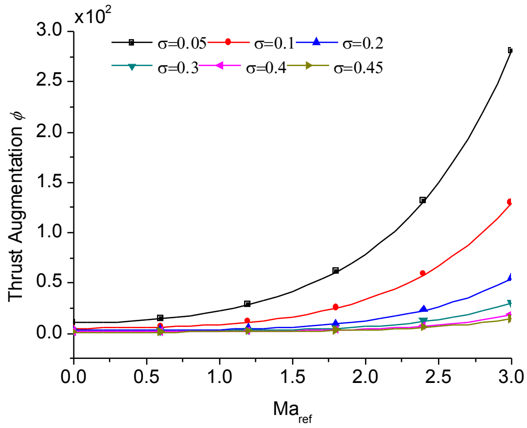

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Figure 4: Variations of ejector rocket thrust with flight Mach number.

(a) Thrust, (b) Thrust augmentation

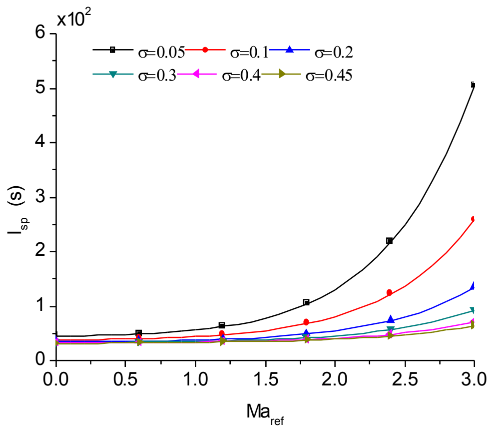


Figure 5: Variations of specific impulse of the ejector rocket for different cross-section area ratios

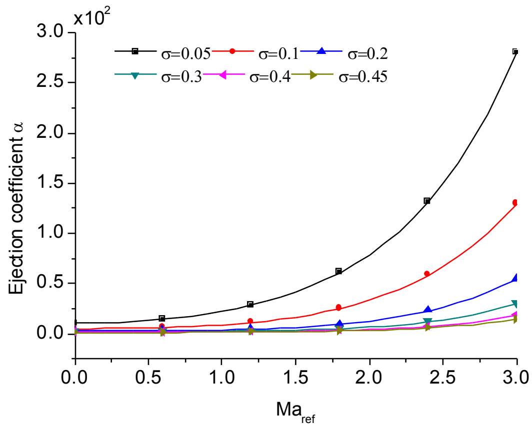


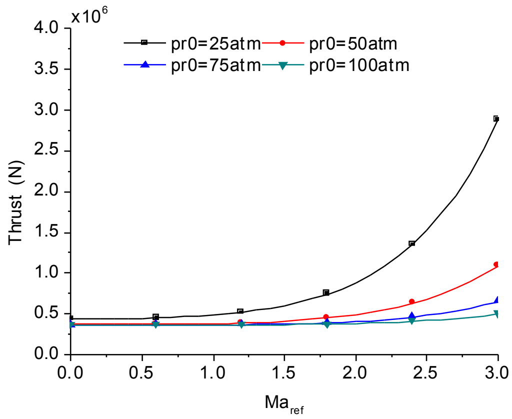
Figure 6: Ejection coefficient of the ejector rocket for different cross-section area ratios

2.3 Effects of primary rocket chamber pressure

This section analyzes the effects of rocket chamber pressure (p_{r0}) on the performance of ejector rocket when the flight altitude is at the sea level. The linear rocket is fully expanded with $p_e = p_{ref}$ and the cross-section area ratio is kept as σ =0.1.

Figure 7 and 8 show that the thrust and specific impulse increase with the increasing of the flight Mach number. If the Mach number is the same, a smaller linear rocket chamber pressure will gain a greater the thrust of ejector rocket. The pressure at the outlet of the rocket increases with the primary rocket chamber pressure increasing. However, a larger pressure is not conducive to the ejection. Thus, the thrust of ejector rocket is decreased. If the rocket combustion chamber pressures are the same, the entrainments increase with the flight Mach number. The greater the primary rocket chamber pressure is, the smaller the ejecting coefficients are for the same flight Mach number.

Taken the primary thrust chamber pressure as a constant, the specific impulse will increase with the flight Mach number increasing. The larger the flight Mach number is, the increase degree of the specific impulse with the Mach number is higher. This is because the total pressure of the incoming flow and hence that of the mixed streams increases accordingly. The increasing of the amount of the ejected air results in an increase in the specific impulse. For the same flight Mach number, the greater the pressure of the thrust chamber is, the smaller the specific impulse is.



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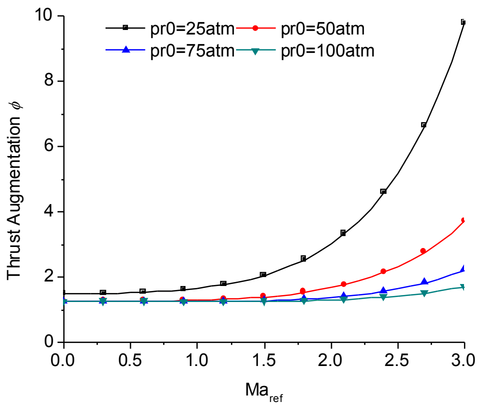

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Figure 7: Variations of ejector rocket thrust with the flight Mach number.

(a) Thrust, (b) Thrust augmentation

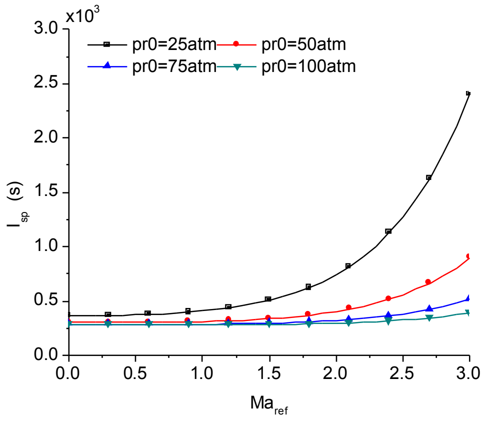


Figure 8: Variations of specific impulse of ejector rocket for different chamber pressures

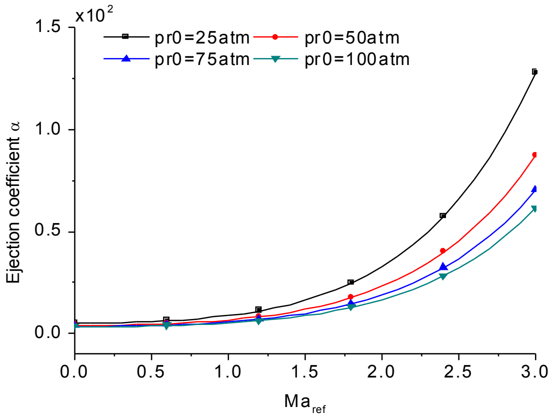
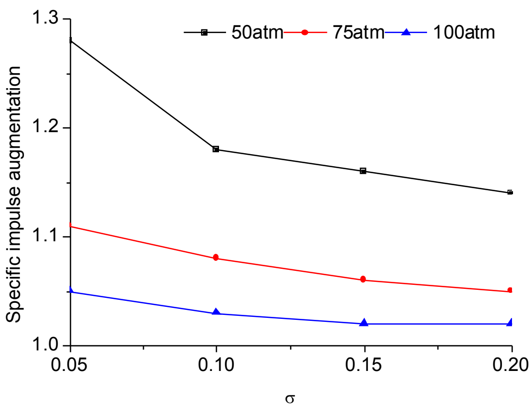


Figure 9: Ejection coefficient of ejector rocket for different chamber pressures

Figure 10 shows the augmentation of specific impulse for different chamber pressures of primary rocket engine. The specific impulse augmentation increases with the primary chamber pressure decreasing, because of the reduction of the ejection area and the flux of the primary rocket engine. For the ejector rocket with the same rocket engine combustion chamber pressure, the specific impulse augmentation decreases with the cross-section area ratio increasing. At the sea level, the ejector rocket can obtain a higher specific impulse augmentation in the combining scheme of a lower chamber pressure and a lower cross-section area ratio.



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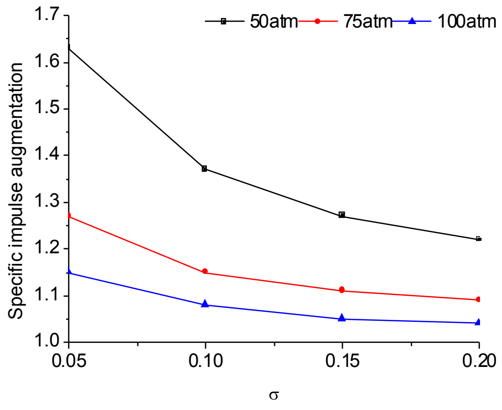

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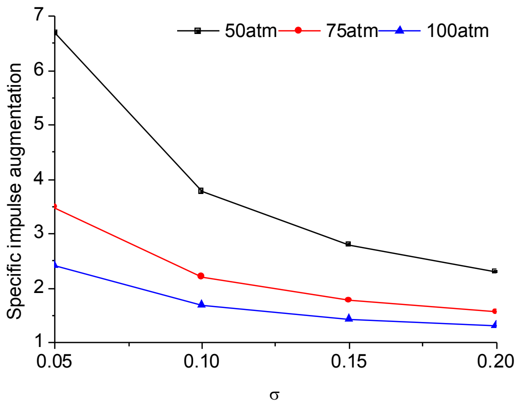

(c)

Figure 10: Augmentation of specific impulse for different chamber pressures.

(a) Mref=0.5, (b)Mref=1.5, (c) Mref=3.0.

3. **Conclusions**

Based on the theoretical analysis of general performances of the combined cycle propulsion in liquid rockets engines, the varying patterns of ejector mode of combined cycle propulsion were studied. The analysis on the effects of a number of factors, including the flight Mach number, cross-section area ratio, and chamber pressure of primary rocket chamber on the performances of RBCC ejector mode were performed successfully.

(1) The overall performance analysis shows that the well mixing of high temperature gas from the primary rocket engine with the ejected air is relatively more effective than an introduction of secondary combustion to improve the performances of ejector rocket.

(2) If the flight altitudes and the cross-section area ratios are the same for the ejector rocket, the thrust, thrust augmentation, ejection coefficient and the specific impulse will increase as the flight Mach number (0-3) increases.

(3) The cross-section area ratio is suggested between 10 and 20% at different flight Mach numbers and different flight altitudes according to the analysis of the compound engine in ejector working mode.

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