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Study on SABRE and rocket-based combined cycle engine

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Abstract. Since the 20th century, countries have been conducting researches on near-spacecraft and have proposed a series of representative space vehicle concepts. This paper reviews the brief history of the development of reusable near-spacecraft and focuses on two combined cycle propulsion modes, SABRE and RBCC, with the goal of improving the performance of future near-spacecraft propulsion systems. An improving idea of combining the RBCC with the SABRE is proposed, and its possibility is discussed by analyzing the specific impulse curve. Two combining configurations of them and design principles are obtained by citing the literature and studying similar configurations. The two designs are also compared and the more optimized one is suggested, so as to offer some inspiration for future studies.

Keywords: SABRE, rocket-based combined cycle engine.

1. Introduction

Since the 20th century, researches on near-spacecraft have been conducted with some representative space vehicle concepts proposed. In 1986, the United States formulated the National Aerospace Plane (NASP) program, with the intention of developing a fully reusable space vehicle with single-stage-to-orbit (SSTO) and horizontal takeoff-landing capability, and air-breathing rocket combination cycle engine, whose experimental spaceplane is named as X-30 [1]. In August 1989, REL proposed the SKYLON project, an SSTO vehicle applying the synergetic-air-breathing-rocket-engine (SABRE) as its propulsion system [2]. Germany proposed a two-stage-to-orbit (TSTO) "Sänger" program in the 1980s, whoes first stage, the carrier aircraft, applies a blended wing-body layout, with its second stage, the orbiter, mounted to the carrier's back [3]. As the frequency of space transportation increases, the need to develop cost-effective reusable launch vehicles (RLVs) becomes more urgent because of conventional rocket's low delivery efficiency and poor safety. In the last 20 years, the concepts mentioned above have received considerable attention again as technological breakthroughs have been made, such as the X-43A, the first human-launched vehicle powered by a supersonic-combustion-ramjet (scramjet), showing a path for the development of future hypersonic vehicles [4]. Scramjet is one of the most promising propulsion modules of TSTO. Besides high cost-efficiency, TSTO also has higher safety over conventional rockets, because the mission can be aborted easily while problems occur after liftoff, thus avoiding losses. And the first stage of the TSTO is just what we called a "near-spacecraft".

Combining theoretical and historical experience, there are two important criteria to measure the performance of a vehicle, the specific impulse of its engine and the thrust-weight ratio of the engine. Therefore, one of the challenges in building a near-spacecraft is to construct an ideal propulsion system by applying propulsion system with higher specific impulse. Based on the above analysis, it is obvious to select a combined cycle engine as the object of study. This type of engine fully utilizes the oxygen in the atmosphere and frees the vehicle from carrying a large load of oxidizers. In addition, its high specific impulse and large operating range can minimize the total take-off weight of the vehicle and maximize the speed limit of the vehicle. The rocket-based combined cycle (RBCC) and turbine-based combined cycle (TBCC) are currently the two most promising routes among combined cycle engines. The synergistic air-breathing rocket engine (SABRE), as a TBCC-like engine, has two modes of operation, air turbine and rocket, and combines the advantages of a high specific impulse of air-breathing engines and a high thrust-to-weight ratio of rocket engines. The RBCC engine can integrate three modes of operation: rocket engine, ramjet, and scramjet, and thus can also obtain the advantages of high specific impulse and even much higher thrust-to-weight ratio through the combination [5]. The recent maiden flight test of China's "Feitian-1" mission was a successful attempt in this field.

The published literature on SABRE and RBCC is divided into two main categories, one is the evaluation and improvement of the two propulsion systems [6] and the other is the analysis and study of the key technologies [7]. And there are fewer comprehensive combination studies on them. Zhou et al. have proposed the combination of a turbofan engine and RBCC and further as propulsion systems used in the carrying stage of TSTO vehicles [8]. Inspired by this idea, this paper suggests that the two cutting-edge technologies can be combined to complement each other, resulting in a new optimized solution.

2. The concept of combination

Specific impulse is an important factor to measure a propulsion system. In a study of the relationship between specific impulse and performance of hypersonic vehicles, Zhao et al. have given equation (1) showing a positive ratio of specific impulse and range for a hypersonic vehicle in its cruise flight [9].

$$R_c = 2v_c g I_{s2}\left(\frac{L}{D}\right)\frac{m_{i2}-m_{f2}}{(m_{i2}+m_{f2})(g-v_c^2/r_0)} \quad (1)$$

In the formula (1), $R_c$is the range of the cruise flight, I_{s2} is the specific impulse of the cruise flight, and L and D are the lift and drag, respectively.

This actually means that the specific impulse of a hypersonic vehicle is positively correlated with the payload, because fuel, meaning the the range, is displaceable to the payload. This suggests that the higher the specific impulse of the engine, the higher the payload or range of the vehicle. Therefore, this paper leverages the specific impulse curves of different propulsion systems as a start point for analysis. From the known data, the effective operating envelopes of different propulsion systems cover different speed ranges [10]. As shown in Figure 1, Turbojets, ramjets and scramjets have the highest specific impulse in different speed ranges, respectively. SABRE as an air-breathing rocket shares the same advantages as turbojets. In addition, the curve formed by combining different propulsion systems is approximately consecutive and linear, which has the advantage of a large speed range and keeps the specific impulse changing smoothly all the time. Therefore, this paper proposes the idea that by combining multiple engines, to extend the operating range and improve the flight performance.

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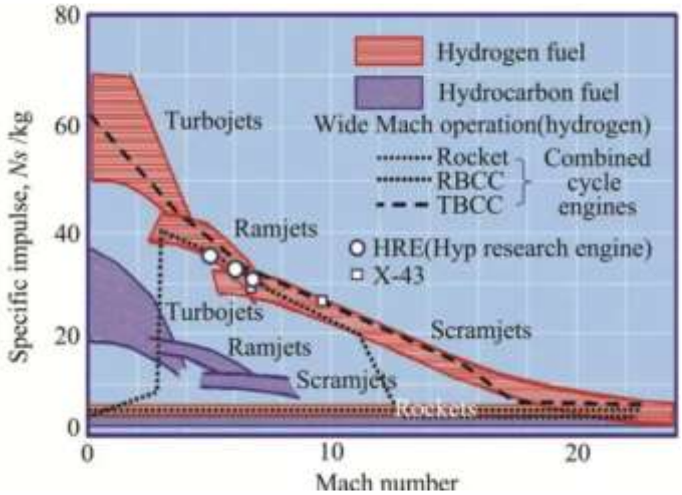

Figure 1. Specific impulse-speed curves for different propulsion systems [10].

Regarding the issue of the engines involved in the combination, SABRE and RBCC engines are used as the subjects of this paper. Structurally, the SABRE is more complex than the RBCC and will be more expensive to build [2,11].

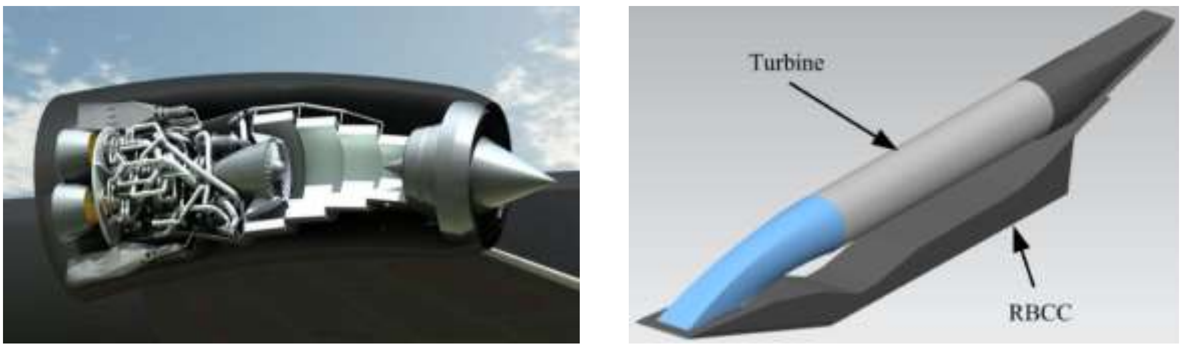

Figure 2. Schematic diagram of two propulsion system structures [2,11].

SABRE’s core technology lies in the adoption of thermal circulation technology in the form of pre-cooling heat exchanger and air-breathing modules. This type of technology allows rapid cooling of the incoming flow under supersonic flight conditions, creating conditions for the proper operation of the air-breathing rocket, when the SABRE aproaches the thermal limits when it reaches Mach 12 [8]. Thus, the second advantage of combining the two engines is derived, where RBCC is used to optimize the heavy structure of SABRE and the cooling system of SABRE can be leveraged to mitigate the thermal problems of hypersonic flying (e. g. inlet flow’s thermal excitation or ionization).

3. Feasibility analysis

For SABRE, the specific-impulse-altitude curve for this type of engine has been given in Yang et al.'s research on the optimization of SABRE [6]. It is shown in Figure 3.

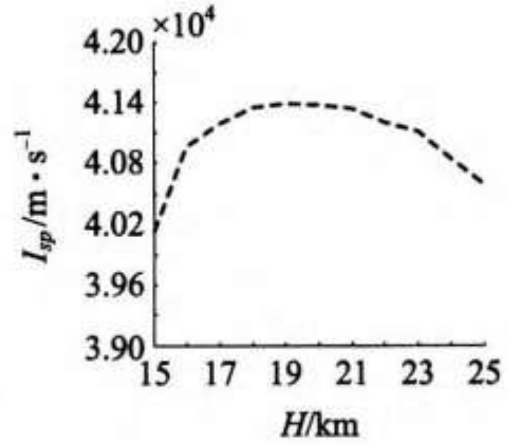

Figure 3. Specific-impulse-altitude curve of SABRE [6].

While in Figure 4, we assume an approximate motion condition of uniformly accelerated level flight into orbit is set for the vehicle. Considering the speed and altitude are nearly proportional to each other, the specific-impulse-speed curve of SABRE can be drawn. After converting the specific-impulse-altitude diagram into a specific-impulse-speed one, the SABRE can be further compared with the RBCC. As shown in Figure 4, the air-breathing operating mode of SABRE ranges from Mach 5 to below 25km [6].

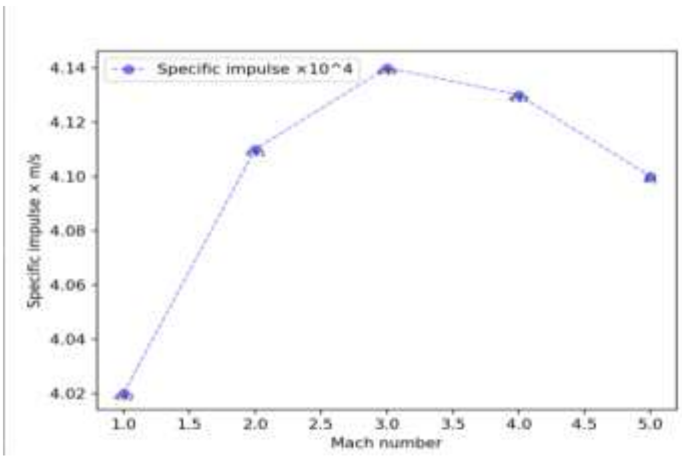

Figure 4. Specific-impulse-speed curve of SABRE [6].

Li et al. have demonstrated that the RBCC can improve its specific impulse at least at speeds greater than Mach 6 by adjusting the fuel injection [13], which is higher than the SABRE's most optimized speed Mach 5 [6].

Based on Zhao et al.'s work, Li's kerosene-based RBCC engine must be upgraded to a hydrogen version to meet SABRE's performance, even though Li's design can work on a higher speed range. Fortunately, Choubey et al.'s simulation and analysis have shown that hydrogen hypersonic scramjet is possible with the struts and multi-position fuel-injection assistance [12].

In addition, it is necessary to consider the limit of the structure. In Zhou et al. s preliminary analysis for a TSTO RLV (Figure 5), the operation envelope of single engines was given [8]. By comparing this figure and the speed-altitude curves of SABRE/RBCC, it is found that none of the selected configurations exceeds the feasibility limitation, implying that it is theoretically achievable.

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Therefore, it is concluded that the combination of SABRE and RBCC is not only necessary but also feasible.

To combine two engines theoretically successfully, it is necessary to consider the continuity of thrust. Thrust continuity means that the thrust of the engine working in the next speed range has to be comparable to that of the previous one. But the problem is that, according to Li's paper, the net thrust of the RBCC is three orders of magnitude lower than that of the SABRE [13], so this problem must be solved first. Therefore, another conclusion is that a new combination way must be found to increase the thrust of the high specific impulse RBCC.

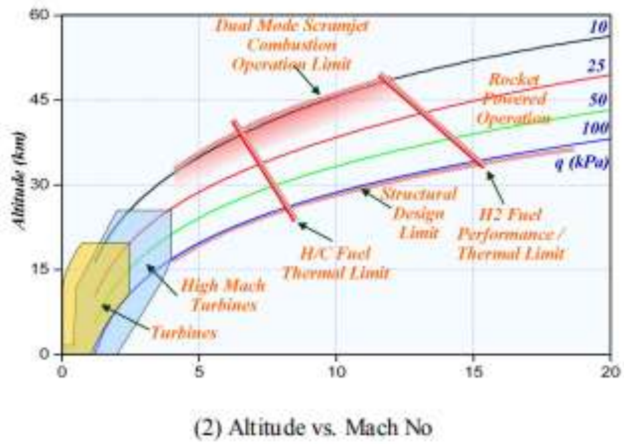

Figure 5. Operation envelope of single engines [8].

4. Combination design

The current works of literature show there are 2 main combination ways to make similar engines work in one vehicle. The first one integrates 2 engines side-by-side [14]. Inspired by Kumar et al.'s research [14], a design diagram of SABRE combined with RBCC is proposed here, referring to Figure 6.

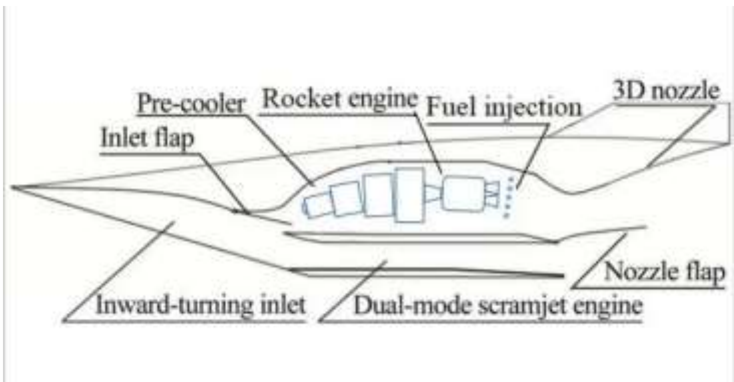

Figure 6. The first combined configuration of SABRE and scramjet.

The second one integrated them into a group of axisymmetric ducts. From the available information, the target thrust announced by SABRE is very high, and the thrust of the scramjet engine, which has now achieved the use of hydrocarbon fuel, is unable to reach the criteria [13]. This means that after SABRE stops the air-breathing mode, the next working part in the configuration shown in Fig.6 cannot provide enough thrust by its own, then SABRE will have to work in non-air-breathing mode to maintain the high Mach number required by the scramjet operation, thus reducing the specific impulse of the propulsion system. Therefore, some more improvements need to be considered.

In Li's paper, the specific impulse of the RBCC is only 1/4 of that of the SABRE [13], and the reason for this is that the engine applies kerosene fuel.

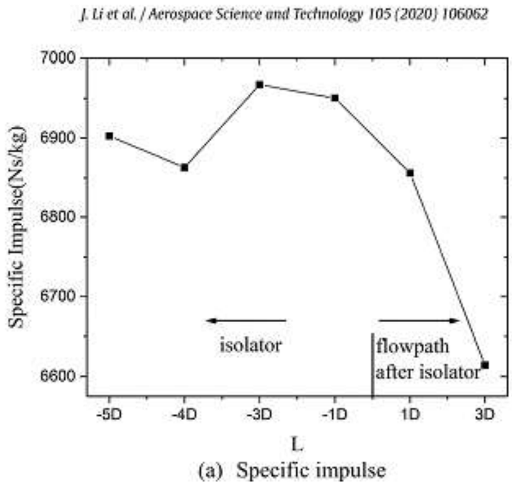

Figure 7. The specific impulse after the optimization of fuel-injection [13].

As shown in Figure 7, the highest point is the specific impulse value at Mach 7, which is the theoretical limit of RBCC using kerosene. Comparing this with the hydrogen scramjet, it can be shown that the lower specific impulse of kerosene leads to a smaller load, which is a disadvantage for spaceflight purposes.

According to Clough's modelling and optimization study of TBCC, the performance of the same engine with different fuels is clearly shown in the graphs [15].

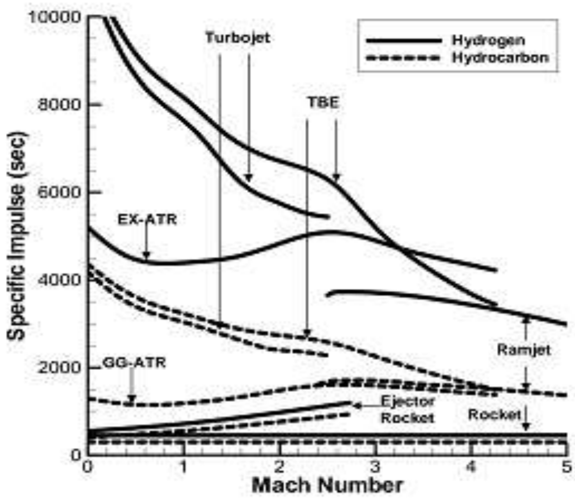

Figure 8. Possible engines for first-stage propulsion [15].

According to Figure 8, applying hydrogen fuel can result in a significant increase in engine performance. This means that the original combined propulsion system needs to consider two aspects of improvement in terms of scramjets with an operating range > Mach 6: the possibility of switching to liquid hydrogen, and the possibility of increasing thrust. Once these two issues are solved, it makes sense to combine them with SABRE.

Based on previous experience in this field, scramjet can possibly apply hydrogen fuel, as well as with kerosene-hydrogen blends.

In terms of hypersonic vehicles, Russia has implemented the "Cold" program in the last century. From 1991 to 1998, the vehicle of the "Cold" program conducted five flight tests and used hydrogen-fueled bimodal engines to transform from ramjet to scramjet, with a maximum flight of Mach 6.5 [16].

This indicates that the size of the liquid hydrogen scramjet is potentially large.

Therefore, a new configuration was designed with reference to the structure of SABRE itself: SABRE is divided into an inner duct and an external duct, with the inner duct being for air-breathing rockets and the external duct being for ramjet. At Mach 5, the external duct of SABRE can reduce the incoming flow speed from 1 to 2 Mach to accommodate the ramjet. The external duct can be directly replaced with a dual-mode ram/scramjet so that it can cover the velocity interval of 0-6 ma.

Inspired by the study of Ma et al. for the dual-combustion ramjets, a design is proposed in Figure 9 [17].

In this design, both air intakes adopt an axisymmetric design with a SABRE module mounted at the axis and with a group of scramjet modules mounted around the SABRE one. This adjustable design matches the adjustable inlet at the front of the SABRE, making the propulsion system more streamlined overall and reducing flight drag when converted to scramjet propulsion mode. Most important of all, it can integrate dozens of scramjet engines around the SABRE central body, which could meet the thrust requirement while the air-breathing mode stops working.

Therefore, the second design in Figure 9 makes more sense because of having larger number of scramjet engines and the posibility to let scramjet leverage the pre-cooled air by some reconfiguration, which may contribute to a TSTO's first-stage propulsion system.

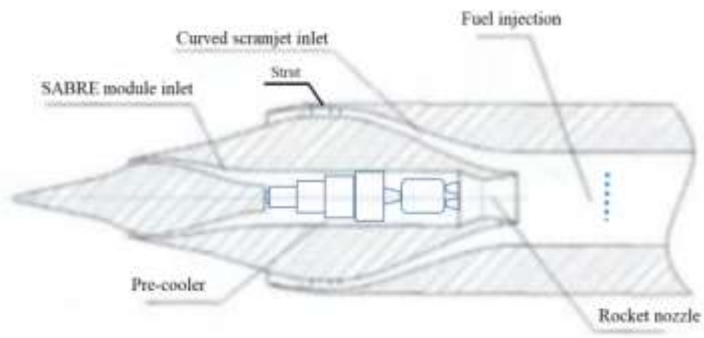

Figure 9. Combined figuration based on dual-combustion ramjet.

5. Conclusion

This paper discussed the possibility that different propulsion systems can be combined based on their respective specific impulse curves, and a simplifying method of converting the specific-impulse-altitude curve into a relationship between specific-impulse-speed was found. The application of hydrogen fuel was confirmed. Two engine configurations for combining SABRE and RBCC propulsion systems were proposed, and comparative analysis suggests the axisymmetric one be applied for future hypersonic near-spacecraft.

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