Sensitivity Analysis of the Key Design Parameters of Turbomachinery in the Closed Helium Cycle System of Pre-cooling Air Turbo Rocket Engine

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Abstract: The Pre-cooling Air Turbo Rocket Engine (PATR) can meet the power demands of future aerospace vehicles across a wide range of speeds and altitudes. The closed helium cycle is the core of the thermal cycle of the PATR engine, and the design parameters of the turbomachinery determine the performance of the closed helium cycle. In this paper, a simulation model of the pre-cooling air turbo rocket engine was established based on the component method, and the effects of the design parameters of the helium compressor and turbine on the engine performance in the closed helium cycle were analyzed. The results show that increasing the efficiency of the helium turbine or reducing the pressure ratio leads to a linear increase in engine thrust; there exists an optimal design solution for the nonlinear relationship between helium turbine flow and engine thrust; increasing the efficiency of the helium compressor or reducing its flow leads to an approximate linear increase in engine thrust; and when the pressure ratio of the helium compressor increases, the engine thrust increases nonlinearly. The research results provide certain guidance for the design of closed helium cycle.

Keywords: Pre-cooling Air Turbo Rocket Engine, Closed Helium Cycle, Turbomachinery Parameters, Sensitivity Analysis

1 Introduction

The pre-cooling air turbo rocket engine (PATR) is a key technology for expanding the flight envelope of engines for aerospace vehicles. It involves placing a unique heat exchanger before the air compressor, effectively cooling the high-temperature air entering the engine, thereby significantly reducing the power consumption of the compressor, improving the overall performance of the engine, and enabling the engine to continue operating at high Mach numbers. Currently, several major pre-cooling engine schemes include the Deeply Cooled Air Turbo rocket (ATRDC) proposed by Russia in 1991[1]; the SABRE scheme proposed by Reaction Engines Limited of the United Kingdom in 1994[2]; the Air Turbo Ramjet Engine with Expander Cycle (ATREX) scheme proposed by the Japan Aerospace Exploration Agency (JAXA) in 2000[3]; and the Scimitar scheme proposed by Reaction Engines Limited of the United Kingdom in 2005. Among these, ATRDC and ATREX are hydrogen pre-cooling engines, belonging to single-cycle pre-cooling engines, wherein apart from fuel, only air serves as the working fluid, with low-temperature fuel serving as both propellant and coolant. SABRE and Scimitar are multi-cycle coupled pre-cooling engine strategies, where, in addition to fuel and air, an additional heat transfer medium is introduced as a working fluid. Their notable feature is the close coupling of the air open cycle and the heat transfer medium closed cycle, achieving heat and power transfer between air and liquid hydrogen[4, 5]. Domestic research has conducted efficiency calculations and cycle optimization for the SABRE engine using helium circulation, analyzing the operational mechanisms and performance advantages of multi-cycle coupled precooled engines[6]. The research results indicate that adopting a multi-cycle coupled precooled engine scheme can significantly reduce fuel consumption and enhance the overall performance of the engine. However, it is worth noting that the multi-cycle coupled scheme may also increase the design and manufacturing complexity of the engine.

Based on the aforementioned configuration research, a new hybrid propulsion scheme has been proposed domestically, namely the Pre-cooling Air Turbo Rocket (PATR)[7]. It is primarily aimed at addressing the reusable needs of spacecraft and the power demands in near-space environments. To effectively expand the flight envelope of the engine, a closed-cycle helium circulation is introduced to facilitate the transfer of heat and power between air and hydrogen. Meanwhile, PATR has become a hot topic in the field of aerospace propulsion technology due to its outstanding performance and compact structure. For this type of engine, the current main research efforts include: conducting preliminary computational analyses on performance parameters such as helium flow rate, performance, and specific impulse of PATR at typical trajectory points[8]. Thermal cycle analysis methods have been employed to analyze parameters such as compressor pressure ratio and turbine pressure ratio of the engine[9]. Through model simulation and calculation studies, it has been found that increasing the maximum design pressure of the helium circulation system and reducing the helium inlet temperature of the air precooler can effectively reduce pressure losses and helium compressor power[10]. The component matching patterns and system performance characteristics of the precooled air turbo rocket engine at maximum thrust conditions have been studied. A nonlinear variable operating condition model for the PATR engine has been established, and the control laws for maximum thrust and maximum specific impulse states of the engine have been obtained. Flight envelopes for the engine under maximum thrust and maximum specific impulse conditions have been provided[11, 12]. Analysis has been conducted on the impact of input parameters on the thermodynamic cycle scheme of the PATR. Simulations have been carried out to study the ballistic characteristics, altitude characteristics, and speed characteristics[13].

Currently, research is primarily focused on engine concepts and overall control laws, with insufficient comprehensive studies on the impact of turbomachinery characteristics within the closed helium cycle. The closed helium cycle is the core of the thermal cycle of the PATR engine, determining its performance. Among these, the design parameters of the turbomachinery are crucial parameters of the closed helium cycle. Therefore, it is essential to conduct systematic studies on these parameters. This paper conducts research on the closed helium cycle system of the PATR engine at a design point of high-altitude Mach number (Ma) of 5 and altitude (H) of 25. Reasonable design reference values are selected, and within a certain range, deviation analysis methods are employed to study the effects of changes in turbomachinery efficiency, pressure ratio, and flow rate on the performance of the engine system.

2 Mathematical model of the PATR engine

2.1 Working principle

The PATR engine is a multi-cycle coupled precooled engine, characterized by the tight coupling of an air-open cycle and a closed helium cycle, enabling the transfer of heat and power between air and liquid hydrogen. Among the engine's three sub-cycles, the air cycle directly generates thrust; the helium cycle serves as the energy supply system for air cycle intake and compression, and acts as the cooling source for the engine precooler; the hydrogen cycle primarily assists the helium cycle in completing the temperature loop and serves as the engine's fuel. Fig. 1 depicts the schematic diagram of the PATR engine system.

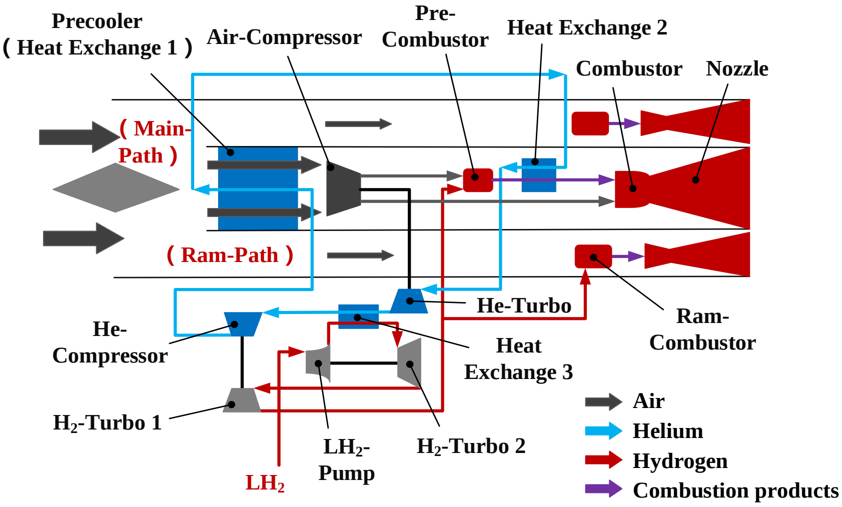


Fig. 1 Schematic Diagram of the PATR Engine System

The specific operating principle is as follows:

Air Path: Incoming air enters the engine through the inlet duct, with the majority entering the main flow path and a smaller portion entering the ram flow path. In the main flow path, air is cooled by helium in the pre-cooler before being compressed in the air compressor. The compressed high-pressure gas is then partially directed into the preburner, while the remaining portion directly enters the combustion chamber. In the preburner, a portion of the gas undergoes combustion, generating partially burned high-temperature gas that also enters the combustion chamber. In the combustion chamber, the gases mix and combust to produce high-temperature, high-pressure exhaust gas, which expands in the nozzle, generating thrust as it exits at high speed.

Helium Path: The helium cycle operates as a closed Brayton cycle, with the starting point being the front section of the helium turbine. High-temperature, high-pressure helium drives the turbine to perform work, which in turn drives the air compressor to compress air, converting some of the heat from the helium into useful work. The helium first enters the hydrogen-helium heat exchanger, transferring residual heat to low-temperature hydrogen while reducing its own temperature. The outlet helium then enters the helium compressor, where it is compressed before entering the pre-cooler to cool the incoming air in the main flow path, while its temperature increases. The high-temperature helium at the outlet then enters the helium heater, where it is further heated by the high-temperature exhaust gas from the preburner before returning to the inlet of the helium turbine. This drives the helium turbine and air compressor to perform work, converting its own thermal energy into mechanical energy of the turbine, generating useful work, and forming a closed loop.

Hydrogen Path: Hydrogen, after being pressurized by the hydrogen pump, first enters the hydrogen-helium heat exchanger, where it absorbs heat from helium, cooling the helium while increasing its own temperature. The high-pressure hydrogen at the outlet drives the hydrogen turbine and helium compressor to perform work. Finally, the outlet hydrogen enters both the preburner and ram combustion chamber for combustion, providing fuel for the main flow path and the ram flow path respectively.

2.2 Construction of the Engine Model Based on Component Method

The PATR engine system consists of the following components: inlet, heat exchanger, turbomachinery, combustion chamber, and nozzle. Among these, the turbomachinery includes the air compressor, hydrogen turbine, helium compressor, and helium turbine. The focus of this paper is on the helium compressor and helium turbine. The component characteristics of the air compressor and hydrogen turbine are as follows:

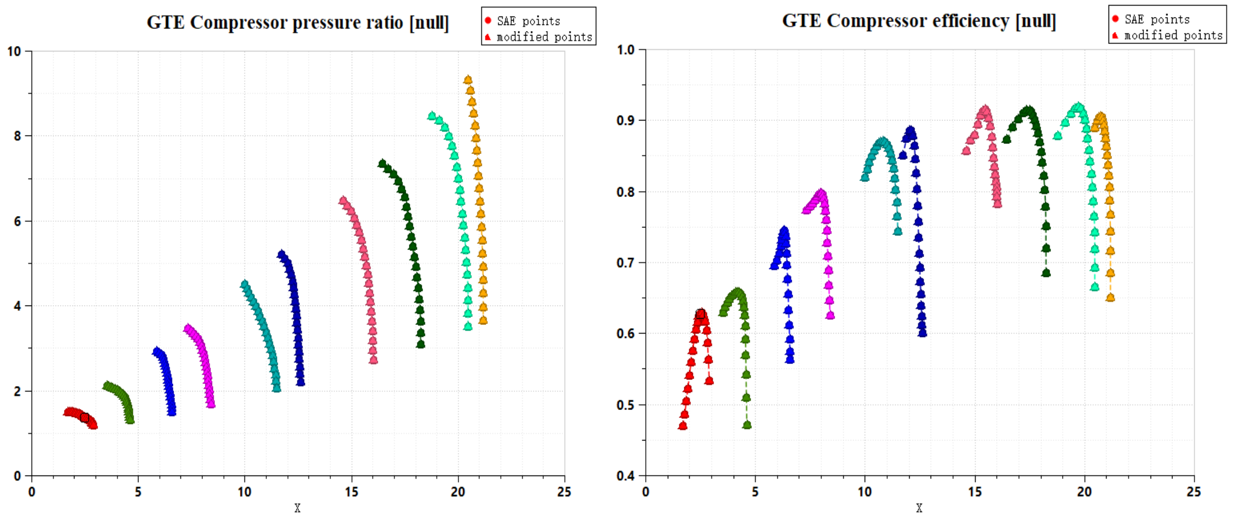
1) Air Compressor

The general characteristic curve of the compressor is represented by a function:

$$\pi_{\mathrm{a,c}} = f_1\left(W_{\mathrm{a2,cor}}, N_{\mathrm{1,cor}}\right) \tag{2-1}$$

$$\eta_{\mathrm{a,c}} = f_2\left(W_{\mathrm{a2,cor}}, N_{\mathrm{1,cor}}\right) \tag{2-2}$$

Fig. 2 shows the characteristic curves of converted flow rate, pressure ratio, and efficiency of the air compressor at different converted speeds.



(a) The relationship between flow rate and pressure ratio at different speeds.

(b) The relationship between flow rate and efficiency at different speeds.

Fig. 2 Characteristic Curve of the Air Compressor in the PATR Engine

2) Hydrogen Turbine

The calculation formula for the hydrogen turbine is as follows:

$$Ltad = C_{\mathrm{p}} \cdot T_{\mathrm{h3}} \cdot (1-(1/Pr)^{(k-1)/k}) \tag{2-3}$$

$$Cad = \sqrt{2 \cdot Ltad} \tag{2-4}$$

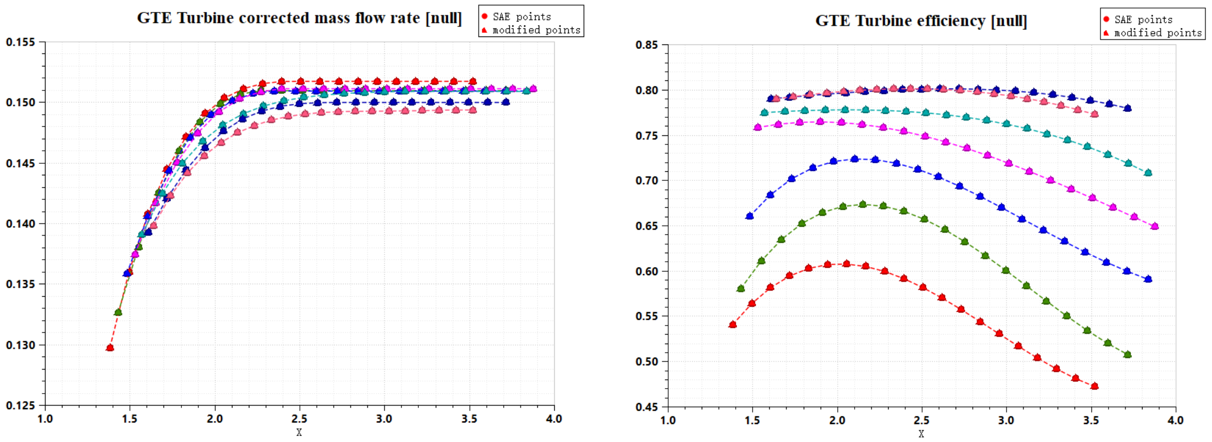
$$U = d_{\mathrm{m}} \cdot \pi \cdot nt / 60 \tag{2-5}$$

$$UC = U / Cad \tag{2-6}$$

$$\eta = -23.4937 \cdot UC^2 + 6.5216 \cdot UC - 0.2329 \tag{2-7}$$

Ltad represents the power of the hydrogen turbine, *Pr* represents the pressure ratio of the hydrogen turbine, and d_{m} represents the mean diameter of the hydrogen turbine.

Fig. 3 shows the characteristic curves of pressure ratio, flow rate, and efficiency of the hydrogen turbine at different converted speeds.



(a) The relationship between pressure ratio and flow rate at different speeds.

(b) The relationship between pressure ratio and efficiency at different speeds.

Fig. 3 Characteristic Curve of the Hydrogen Turbine in the PATR Engine

The common operating conditions of the PATR engine include flow balance, pressure balance, and rotor power balance.

Nozzle flow balance:

$$e_1 = W_{\mathrm{b}} - W_{\mathrm{e}} \tag{2-8}$$

Helium heater outlet pressure closed-loop:

$$e_2 = P_{\mathrm{h3}} - P_{\mathrm{0h3}} \tag{2-9}$$

Pre-combustion chamber pressure balance:

$$e_3 = P_{\mathrm{a3}} - P_{\mathrm{q3}} \tag{2-10}$$

Power balance between the air compressor and the helium turbine:

$$e_4 = N_{\mathrm{a,c}} - N_{\mathrm{h,T}} \cdot \eta_{\mathrm{mL}} \tag{2-11}$$

Power balance between the hydrogen turbine and the helium compressor:

$$e_5 = N_{\mathrm{q,T}} - N_{\mathrm{h,c}} / \eta_{\mathrm{mL}} \tag{2-12}$$

e1~e5 represent the equation constraints required for calculation. By iteratively solving the system equations that satisfy the constraint conditions, the common operating point is determined, thereby obtaining the performance of the engine.

The performance parameters of the PATR engine include thrust, specific thrust, specific impulse, etc.

thrust:

$$F = W_{\mathrm{e}} c_{\mathrm{e}} - W_{\mathrm{a}} c_0 + (P_{\mathrm{e}} - P_0) A_{\mathrm{e}} \tag{2-13}$$

specific thrust:

$$F_{\mathrm{s}} = F / W_{\mathrm{a}} \tag{2-14}$$

specific impulse:

$$Isp = F / (g \cdot W_{\mathrm{q3}}) \tag{2-15}$$

3 Impact of Helium Turbine Design Parameters on Engine Performance

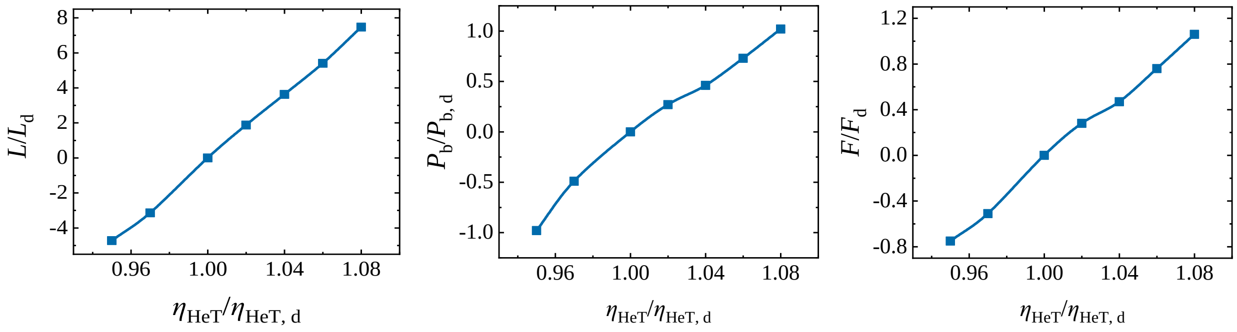
The helium turbine is a crucial mechanical component in the closed helium cycle of the PATR engine. As the closed helium cycle is the core of multiple coupled cycles within the engine, determining its performance, studying the impact of helium turbine design parameters is of paramount importance.

The helium turbine is responsible for providing power to the air compressor, thereby influencing the power of the air compressor, the combustion process in the combustion chamber, and ultimately affecting performance parameters such as thrust of the engine. Therefore, in this section, with the reference to high-altitude conditions of Ma=5 and H=25, the deviation analysis of helium turbine efficiency, pressure ratio, and flow design parameters is conducted to assess their effects on shaft power, combustion chamber pressure, and thrust, using relative value deviations.

3.1 Helium Turbine Efficiency

When the efficiency of the helium turbine increases, the power output of the turbine increases accordingly. This results in a linear increase in shaft power as the helium turbine provides more power to the air compressor. With the increase in power obtained by the air compressor, its rotational speed increases, leading to stronger suction capability and increased airflow. This, in turn, allows for more efficient combustion in the combustion chamber, leading to an increase in chamber pressure.

As both the air compressor and combustion chamber operate more effectively, the overall performance of the engine improves, reflected in the linear increase in thrust. Therefore, optimizing the design of the helium turbine to achieve higher efficiency can enhance the overall performance of the engine.



(a)The relationship between helium turbine efficiency and shaft power

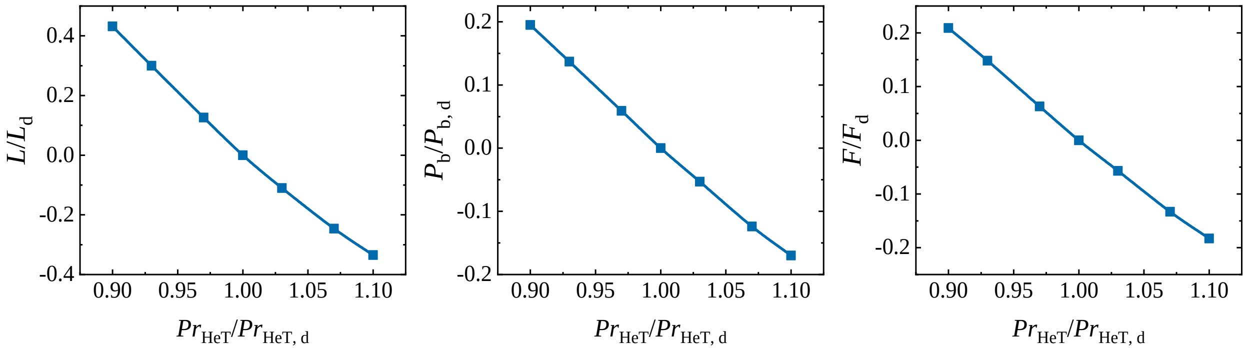
(b) The relationship between helium turbine efficiency and combustion chamber pressure

(c) The relationship between helium turbine efficiency and thrust

Fig. 4 The impact of helium turbine efficiency on engine performance.

3.2 Pressure Ratio of the Helium Turbine

As the pressure ratio of the helium turbine increases, its output shaft power continuously decreases. Due to the decreasing output power of the helium turbine, the suction capability of the air compressor also decreases, resulting in a decrease in airflow through the air path. This, in turn, affects the combustion in the combustion chamber, leading to a decrease in chamber pressure. Ultimately, this impacts the overall performance of the engine, resulting in a decrease in thrust.



(a) The relationship between helium turbine pressure ratio and shaft power

(b) The relationship between helium turbine pressure ratio and combustion chamber pressure

(c) The relationship between helium turbine pressure ratio and thrust

Fig. 5 The impact of helium turbine pressure ratio on engine performance

3.3 Helium Turbine Flow Rate

As the flow rate of the helium turbine increases, the shaft power initially increases and then decreases. The increase in helium flow rate has the following effects:

1) It increases the rotational speed of the helium turbine, leading to an increase in shaft power output, while also increasing the rotational speed of the air compressor.

2) It improves the heat exchange performance of the precooler, resulting in a decrease in the temperature of the air entering the air compressor, thereby reducing the shaft power.

Therefore, in the ascending section of the curve, the positive impact of the increase in helium turbine rotational speed on output shaft power is greater than the negative impact of the decrease in inlet gas temperature of the air compressor. In the descending section of the curve, the positive impact of the increase in helium turbine rotational speed on output shaft power is smaller than the negative impact of the decrease in inlet gas temperature of the air compressor.

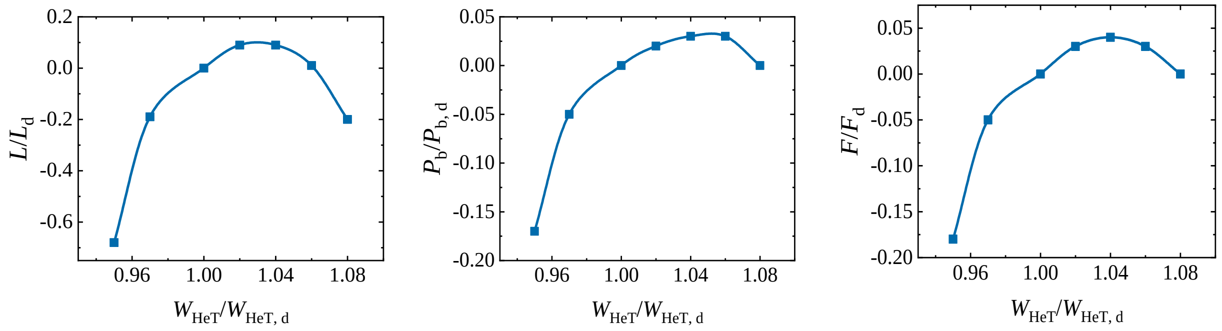
The chamber pressure of the combustion chamber is influenced by two factors:

1) The suction capability of the compressor, which is affected by shaft power. Higher shaft power results in stronger suction capability of the compressor, leading to increased airflow in the air path, more complete combustion, and higher chamber pressure.

2) The temperature of the hydrogen gas circuit affected by heat transfer. With a larger helium flow rate, more heat is transferred from the air path to the hydrogen gas circuit, resulting in higher temperature in the hydrogen gas circuit. This leads to more complete combustion after entering the combustion chamber, resulting in higher chamber pressure.

Therefore, in the relative interval of 0.95-1.02, the chamber pressure is positively influenced by the increase in airflow in the air path and the increase in temperature in the hydrogen gas circuit, showing a rapid upward trend. In the relative interval of 1.02-1.06, the chamber pressure is negatively influenced by the decrease in airflow in the air path and positively influenced by the increase in temperature in the hydrogen gas circuit. However, due to the dominant positive effect of the increase in temperature in the hydrogen gas circuit, the chamber pressure continues to rise. In the relative interval of 1.06-1.08, the negative impact of the decrease in airflow in the air path predominates, leading to a decrease in chamber pressure.

The influence on thrust is similar to that on chamber pressure. The more complete the combustion in the combustion chamber, the better the overall performance of the engine.



(a) The relationship between helium turbine flow rate and shaft power

(b) The relationship between helium turbine flow rate and combustion chamber pressure

(c) The relationship between helium turbine flow rate and thrust

Fig. 6 The impact of helium turbine flow rate on engine performance

4 Impact of Helium Compressor Design Parameters on Engine Performance

The helium compressor is another important mechanical component in the closed helium cycle of the PATR engine, and studying the effects of its design parameters is also crucial. The helium compressor is a rotor mechanical component that provides power for helium gas flow and works together with the helium turbine to achieve pressure regulation in the closed cycle. It primarily affects the cooling performance of the precooler in the air path, the heating performance of the helium heater in the helium path, and the heating performance of the hydrogen-helium reheater in the hydrogen path, ultimately influencing the engine's thrust and other performance parameters. Therefore, in this section, based on the benchmark of high-altitude Mach number 5 and altitude of 25, a relative deviation analysis is employed to investigate the impact of changes in design parameters of the helium compressor, such as efficiency, pressure ratio, and flow rate, on the temperature difference between the inlet and outlet of the precooler in the air path, the inlet and outlet of the helium heater in the helium path, the inlet and outlet of the hydrogen-helium reheater in the hydrogen path, and the engine thrust.

4.1 Efficiency of the Helium Compressor

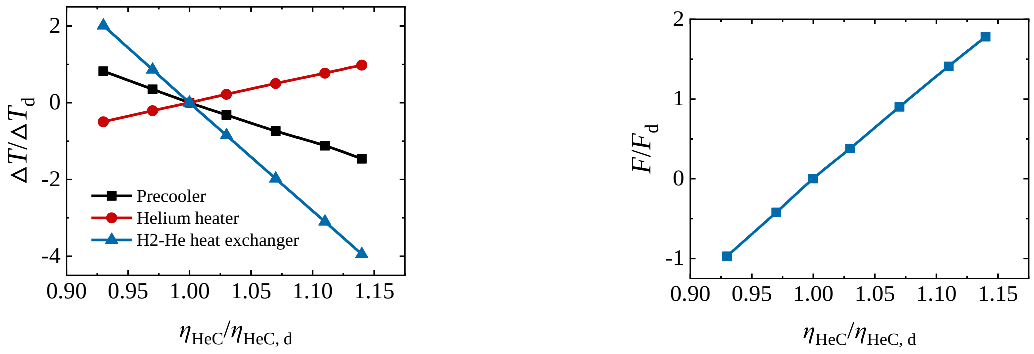
As the efficiency of the helium compressor increases, the heat exchange performance of the pre-cooler deteriorates, while the heat exchange performance of the hydrogen-helium reheater deteriorates even further, and the heat exchange performance of the helium heater improves.

The higher the efficiency of the helium compressor, the smaller the temperature rise of the helium gas passing through the helium compressor, and the lower the temperature of the helium gas route should be. According to the characteristics of the compressor curve, assuming that the speed remains constant, an increase in efficiency may lead to an increase or decrease in flow rate. In this case, it should be a decrease in flow rate. Although the temperature of the helium gas decreases, the decrease in helium gas flow rate is more significant, leading to a continuous decrease in the cooling temperature difference of the air route in the pre-cooler.

Due to the improvement in the efficiency of the helium compressor and the decrease in the heat exchange capacity of the pre-cooler, the outlet temperature of the helium gas also decreases. When the helium gas with lower temperature and flow rate passes through the helium heater, it is easier for the temperature to rise, resulting in a larger temperature rise. Therefore, the temperature rise of the helium heater continues to increase within this range.

Although the temperature rise of the helium gas passing through the helium heater may be significant, its outlet temperature may still be lower than that at low efficiency. In fact, there may still be a problem of lower gas temperature and lower flow rate at the inlet of the helium gas route in the hydrogen-helium reheater under the condition of high-efficiency compression. Therefore, the heat exchange performance of the hydrogen-helium reheater shows a rapid decline.

As the efficiency of the helium compressor increases, the thrust of the engine continues to increase.



(a) The relationship between helium compressor efficiency and heat transfer performance

(b) The relationship between helium compressor efficiency and thrust

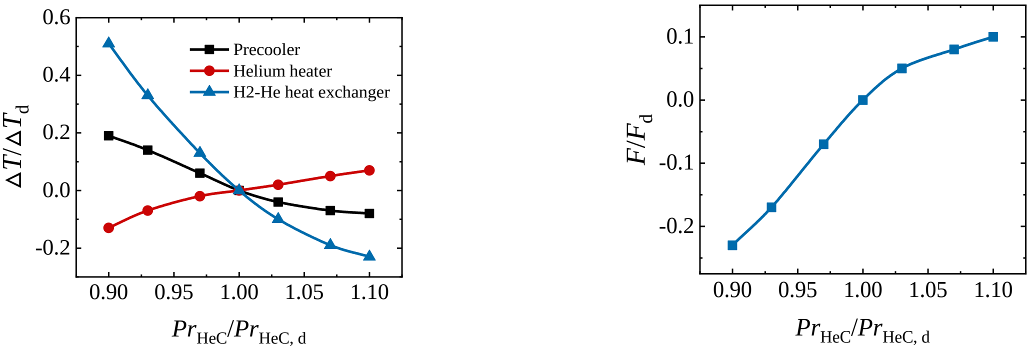
Fig. 7 The impact of helium compressor efficiency on engine performance.

4.2 Helium Compressor Pressure Ratio

As the pressure ratio of the helium compressor increases, the heat exchange performance of the precooler deteriorates, and the heat exchange performance of the hydrogen-helium reheater worsens, while the heat exchange performance of the helium heater improves, resulting in a greater engine thrust. The trend of this change is similar to that of efficiency, but the magnitude of change is not significant and the change is smoother.

With a higher pressure ratio of the helium compressor, the helium is compressed more fully. Assuming the compressor speed remains constant, according to the characteristic curve, the higher the compressor pressure ratio, the smaller the flow rate. As the helium flow rate decreases, the degree of cooling of the air in the precooler decreases, resulting in a continuous decrease in the temperature difference in the air duct of the precooler. At the same time, when the helium passes through the helium heater, the heat transferred from the air duct acts on the decreasing flow rate, making the gas heating more uniform, and the temperature rise continues to increase. With the increase of the pressure ratio of the helium compressor, although the temperature of the helium passing through the hydrogen-helium reheater gradually increases, the decrease in helium flow rate is more significant. Overall, the amount of heat that can be provided to the hydrogen gas gradually decreases, so the temperature rise of the hydrogen gas duct in the hydrogen-helium reheater also decreases continuously.

With the increase of the pressure ratio of the helium compressor, the thrust of the engine continues to increase.



(a) The relationship between helium compressor pressure ratio and heat transfer performance

(b) The relationship between helium compressor pressure ratio and thrust

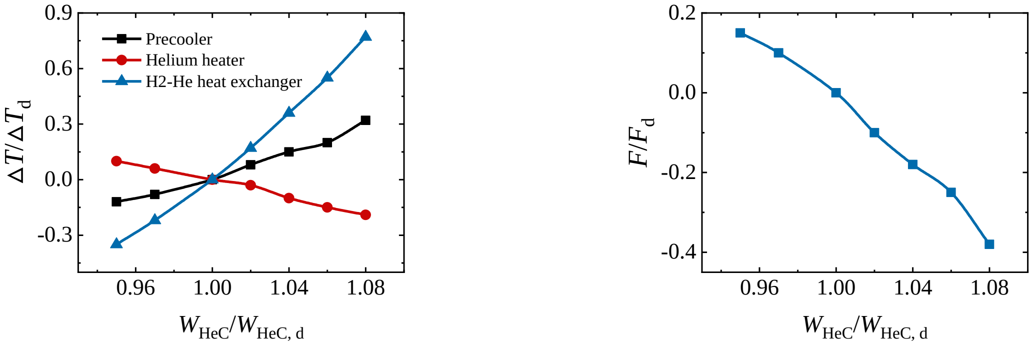
Fig. 8 The impact of helium compressor pressure ratio on engine performance

4.3 Helium Compressor Flow Rate

As the flow rate of the helium compressor increases, the heat exchange performance of the pre-cooler and the helium-hydrogen reheater improves, while the heat exchange performance of the helium heater deteriorates, leading to a decrease in engine thrust.

When the specific heat capacity of helium remains constant, a higher flow rate of the helium compressor enhances its heat transfer capability. This results in more efficient heat exchange in the pre-cooler, leading to better pre-cooling of the air path and a greater temperature drop. While the outlet temperature of the pre-cooler air path decreases, the outlet temperature of the pre-cooler helium path increases, indicating a rise in the inlet temperature of the helium heater. Although the outlet temperature after heat exchange also increases, it does so to a lesser extent than at the inlet, resulting in a decreasing temperature difference. The increased outlet temperature of the helium heater leads to a further temperature rise after passing through the helium turbine, causing the helium gas entering the helium-hydrogen reheater to carry more heat to the hydrogen, resulting in a continuous increase in the outlet temperature of the hydrogen path. Since the hydrogen supply temperature remains constant, the temperature difference in the hydrogen path also increases continuously.

With the increase in the flow rate of the helium compressor, the engine thrust continuously increases.



(a) The relationship between helium compressor flow rate and heat transfer performance

(b) The relationship between helium compressor flow rate and thrust

Fig. 9 The impact of helium compressor flow rate on engine performance

5 Conclusion

This paper establishes a simulation model of the pre-cooling air turbine rocket engine based on the component method and analyzes the effects of the design parameters of the helium pressure turbine and helium compressor on the engine performance in the closed helium cycle. The main conclusions are as follows:

1) When the efficiency of the helium turbine increases or the pressure ratio decreases, the engine thrust linearly increases. Considering the numerous components of the PATR engine and the close coupling between cycles, slight variations in design parameters may cause mismatching of the entire engine. Moreover, the helium compressor and turbine have large weights, high design complexity, and material requirements, so the optimal values within the design capabilities need to be selected.

2) The relationship between the relative flow deviation of the helium turbine and the engine thrust is nonlinear within the range of -5% to +8%, indicating the existence of an optimal design solution. The engine performance is optimal when the design deviation is around +5%.

3) Increasing the efficiency of the helium compressor or decreasing the flow rate results in approximately linear increase in engine thrust. However, when the pressure ratio of the helium compressor increases, the effect on engine thrust becomes nonlinear. Specifically, the effect is significant when the relative pressure ratio is between 0.9 and 1.03, but insignificant when it is between 1.03 and 1.1.

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