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Matching Mechanism Research on a Hybrid Cycle Engine

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ABSTRACT

With the increasing complexity of future flight conditions and the rapid development of aviation electrification, variable cycle and high-power extraction have become important directions of aero engines. This paper proposes the Hybrid Cycle Engine (HCE) conception which is the combination of heat engine, thruster and generator based on the traditional aero engines. Besides the basic thrust requirements, HCE can export high electric power, adjust the operating point of aero engine and increase thrust. The HCE breaks through the limitation of the Brayton cycle via the hybrid cycle including thermodynamics and electrodynamic. In this paper, the performance simulation model is established based on the principle of the thermoelectric hybrid cycle. The sensitivity analysis of power extraction of high and low pressure rotor under design conditions is carried out to explore the matching mechanism of the hybrid cycle. This paper provides research support for the realization of adaptive integrated energy management under all working conditions and taps the performance potential of the hybrid cycle.

Keywords: hybrid cycle, matching mechanism, hybrid power system, variable cycle, aviation electrification

NONMENCLATURE

Abbreviations	
HCE	Hybrid Cycle Engine
SFC	Specific Fuel Consumption
Symbols	
L_e	Effective work of thermodynamic cycle
L_{pes}	Work extracted of thermoelectric cycle
P_{HPT}	Power of high pressure turbine
P_{HPC}	Power of high pressure compressor
P_{LPT}	Power of low pressure turbine
P_{LPC}	Power of low pressure compressor
P_{EHPS}	Power extraction of high pressure shaft
P_{ELPS}	Power extraction of low pressure shaft
P_E	Power extraction of shaft
q_0	Internal energy of fuel consumption
z_i	Corresponding residual
η_{th}	Thermal efficiency
η_{thel}	Thermoelectric efficiency
η_{MH}	Mechanical efficiency of high pressure rotor
η_{ML}	Mechanical efficiency of low pressure rotor

1. INTRODUCTION

With the increasing complexity of future flight conditions and the rapid development of aviation electrification, variable cycle and high power extraction have become important directions for the development of aero-engines[1]. With the continuous upgrading of equipment such as airborne radar system and communication system, the demand for power supply of propulsion system is becoming more and more prominent. At the same time, it's necessary for the future power system to meet the requirements of various tasks in complex mission profiles, and the applicability requirements of the wide flight envelope for the propulsion system are constantly improving[2]. It is expected that the airborne power demand of UAV will account for more than 25 % of the total power around 2030[3]. For example, the 'Tempest' project of UK proposed that in order to meet the performance requirements of the new generation of fighters with intelligence and informatization characteristics, it's

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necessary for the propulsion system to develop revolutionary electrical management technology.

At present, it's difficult for the traditional engine configuration to meet the higher electrical power extraction requirements and variable cycle applicability requirements of the future aircraft power system[4-6]. With the substantial increase of the proportion of electric power extraction, the traditional way of generating power through accessory gearbox power extraction or APU power generation will seriously affect the thermal efficiency of the power system, which has been unable to meet the excessive demand for power extraction[7-9]: higher demand for electric power extraction affects the performance matching of the engine, resulting in the working point deviating from the high efficiency zone; the heat generation of the motor under higher electric power is easy to cause thermal safety problems of the motor, and the traditional generator position layout is difficult to meet the heat dissipation demand; in the traditional configuration, the volume of the motor responsible for power extraction increases with the higher power demand, which is difficult to meet the stringent size and weight constraints for the engine. At the same time, the adjustment of the working state of the conventional turbofan engine is limited by the Brayton cycle, and it is difficult to improve the performance under extreme conditions[10].

Therefore, the paper proposes the Hybrid Cycle Engine (HCE) with the core idea of combination of heat engine, thruster and generator based on the traditional engine concept. The deep coupling of embedded power generation and electric supercharging technology realizes the integrated design of turbomachinery and motor. The traditional energy transfer process of thermal energy to electric energy volves into a thermoelectric hybrid cycle. Besides the basic thrust requirements, HCE can achieve high electric power extraction and thrust augmentation by electricity via the electronic fan, which breaks through the limitation of Brayton cycle, improves the available power of the cycle, and optimizes the component matching.

There are few open researches on Hybrid Cycle Engine and the accumulation of related technologies is mainly included in the research of more electric engine, focusing on energy management[11-16], control system design[17-19], performance analysis and optimization [20-24]. In 2020, Rolls-Royce Plc announced the development direction of the matching engine of 'Tempest' is the coupling of embedded power generation, optimization of thermal management system, and adoption of intelligent power management system, which provides a reference for the engineering research of Hybrid Cycle Engine[25]. Based on conceptual design, it is necessary to carry out performance calculation research on Hybrid Cycle Engine to provide data support for the future development of aircraft power system electrification[26,27].

The sensitivity analysis of power extraction of high and low pressure rotor under design conditions is carried out to explore the matching mechanism of the hybrid cycle. This paper provides research support for the realization of adaptive integrated energy management under all working conditions and tapping the potential of the hybrid cycle.

2. CONFIGURATION OF HYBRID CYCLE ENGINE

2.1 Working principle of Hybrid Cycle Engine

Compared with the conventional turbofan engine, the design of the Hybrid Cycle Engine considers the needs of higher power extraction and stronger thermoelectric management of the flight platform. Aiming at the technical problems of the traditional configuration, a full-condition adaptive thermoelectric hybrid cycle energy management technology is proposed, which has three significant technical characteristics of embedded motor, multi-shaft power generation, and thermoelectric hybrid cycle, corresponding to three major sub-technologies: embedded motor integrated design technology, multi-shaft power generation intelligent matching control technology and thermoelectric hybrid cycle energy management technology, as shown in the Fig. 1.

The integration of embedded motor and turbomachinery meets the higher power demand of future aircraft while effectively ensuring the compactness of the aircraft. The multi-shaft thermoelectric hybrid cycle matching makes the power system more adaptable to the demand of electric power extraction under all working conditions. The thermoelectric hybrid cycle energy management effectively ensures the adjustment and optimization of the multi-shaft components' energy matching in the power system to achieve efficiency increase, thrust rise and fuel consumption reduction. The main components of HCE are shown in Fig. 2.

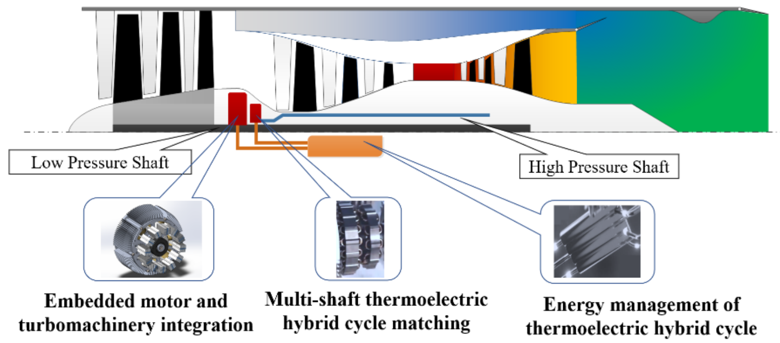

Fig. 1. Schematic diagram of major technical characteristics of Hybrid Cycle Engine

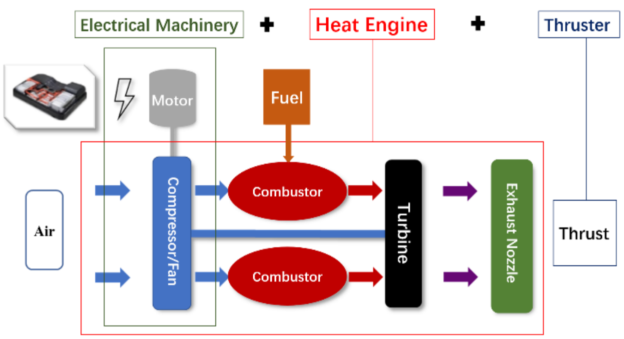

Fig. 2. Main components of Hybrid Cycle Engine

2.2 *Performance model of Hybrid Cycle Engine*

The performance model of HCE is established based on the component method as the main modeling idea and the calculation process is shown in Fig. 3. The characteristics of related components are read in the form of a two-dimensional array, and the nonlinear equations of the equilibrium equations such as flow continuity, power balance and static pressure balance of the related components are established based on the common working conditions of each component. After the control law is given, the working points of each component can be solved, so as to obtain the relevant aerodynamic and thermal parameters and performance parameters. Based on the aircraft power demand and engine thrust demand, the overall performance design of HCE is carried out. The flow chart of engine steady-state operating point performance calculation is shown in Fig. 4.

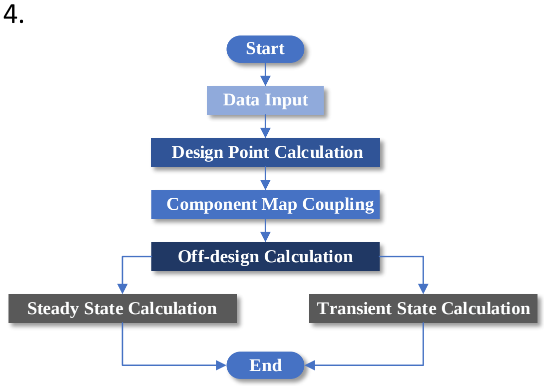

Fig. 3. Calculation process of the simulation model[28]

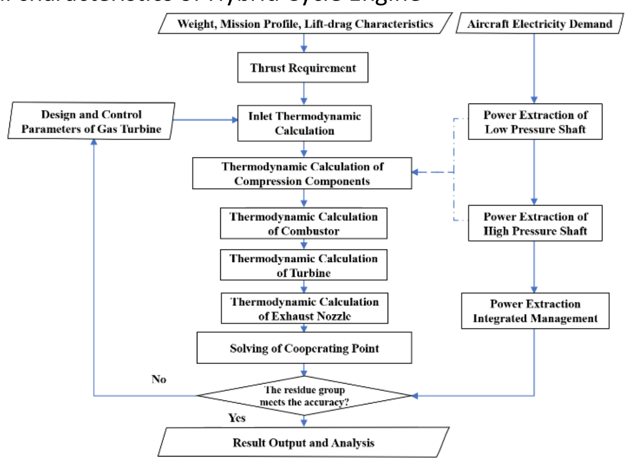

Fig. 4. Calculation Process of Engine Steady-state Operating Point Performance

The essence of solving the engine operating point is to solve the nonlinear residual equations derived from the engine balance equation. Unlike conventional turbofan engines, the power extraction term is introduced into the residual equation of power balance in HCE performance model. For high pressure rotor power balance:

$$P_{HPT}\eta_{MH} - P_{HPC} - P_{EHPS} = z_1 \tag{1}$$

In the equation, P_{HPT} is the power of high pressure turbine, P_{HPC} is power of high pressure compressor, P_{EHPS} is power extraction of high pressure shaft, and η_{MH} is mechanical efficiency of high pressure rotor, z_i denotes the residual corresponding to the residual equation[29,30].

For low pressure rotor power balance:

$$P_{LPT}\eta_{ML} - P_{LPC} - P_{ELPS} = z_2 \tag{2}$$

In the equation, P_{LPT} is the power of low pressure turbine, P_{LPC} is power of low pressure compressor, P_{ELPS} is power extraction of low pressure shaft, and η_{ML} is mechanical efficiency of low pressure rotor.

Furthermore, the performance parameters of HCE should take power extraction term into consideration. For thermal efficiency η_{th}, we have:

$$\eta_{\text{th}} = \frac{L_e}{q_0} \tag{3}$$

In the equation, L_e is the effective work of thermodynamic cycle and q_0 is the internal energy of fuel consumption in thermodynamic cycle. Based on the definition of thermal efficiency, the definition of thermoelectric efficiency η_{thel} for HCE is given as follows:

$$\eta_{\text{thel}} = \frac{L_e + L_{pes}}{q_0} \tag{4}$$

In the equation, L_{pes} is the power extraction of high and low pressure shaft in thermoelectric cycle.

3. MATERIAL AND METHODS

The ground design point (height is 0km, speed is 0 Ma) is selected as the calculation condition. Based on the HCE simulation model, the steady state performance calculation with different power extraction is carried out to study the sensitivity to thrust, fuel consumption, thermal efficiency and thermoelectric efficiency under intermediate and afterburning states.

3.1 Thrust

In design conditions, the thrust and relative loss with power extraction of high pressure shaft is shown in Fig. 5 and Fig. 6. The thrust and relative loss with power extraction of low pressure shaft is shown in Fig. 7 and Fig. 8. The high and low pressure shaft has the same rule for the comparison of thrust change in different working state. The absolute value of thrust change under afterburning state is bigger than that under intermediate state. For example, the thrust loss is 189.18 kgf on average for every 1MW high pressure rotor power extracted under intermediate state and 260.41 kgf on average under afterburning state. However, power extraction under intermediate state will bring more thrust relevant loss than afterburning state. For example, the thrust relevant loss is 2.44% on average for every 1MW low pressure rotor power extracted under intermediate state and 2.11% under afterburning state. Furthermore, the rate of thrust decline is accelerating.

For different shafts, the power extraction of low pressure rotor will bring more thrust loss both in absolute value and relevant change. The thrust loss is 189.18 kgf on average for every 1MW high pressure shaft power extracted and 195.49 kgf for low pressure shaft.

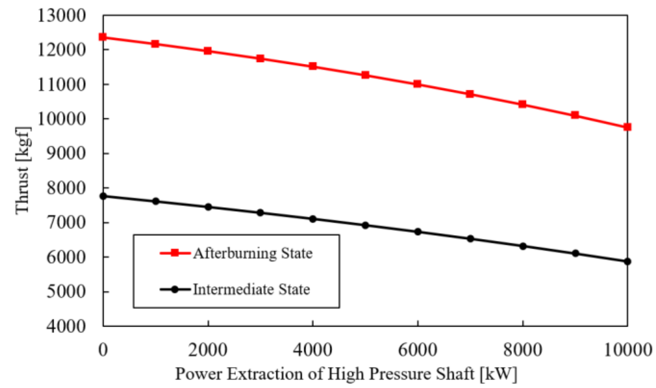

Fig. 5. Diagram of thrust with power extraction of high pressure shaft

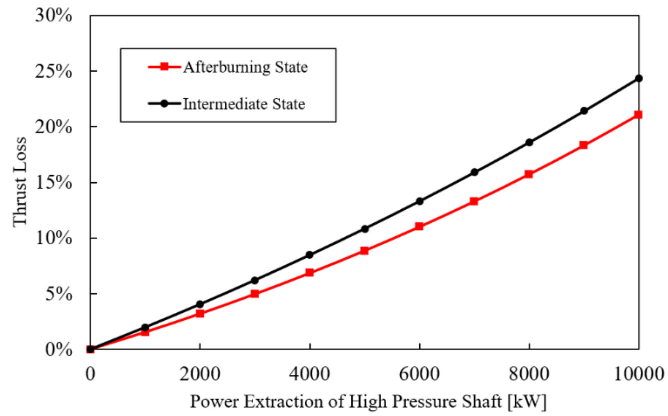

Fig. 6. Diagram of thrust loss with power extraction of high pressure shaft

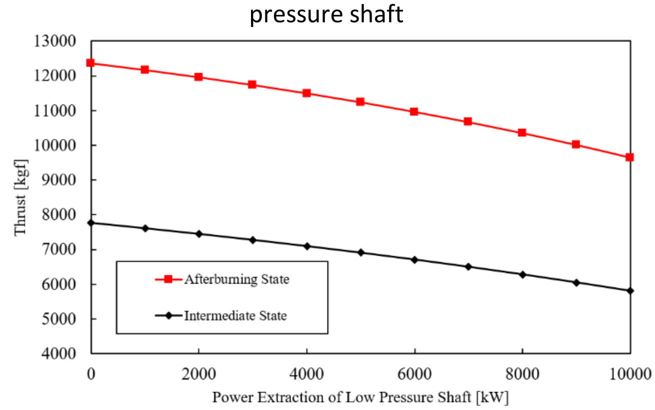

Fig. 7. Diagram of thrust with power extraction of low pressure shaft

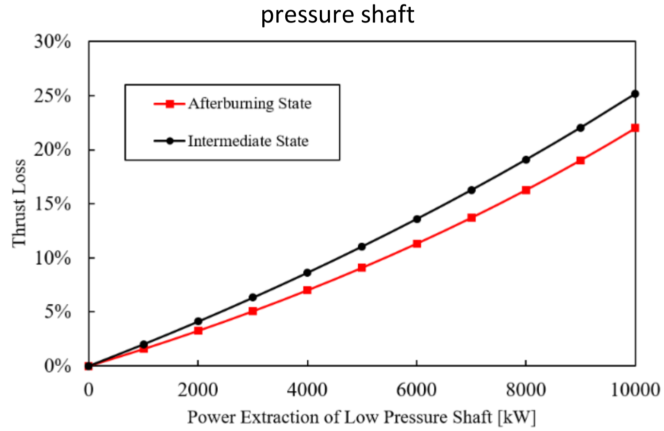

Fig. 8. Diagram of thrust loss with power extraction of low pressure shaft

3.2 Specific fuel consumption

The Specific Fuel Consumption (SFC) with power extraction of high pressure shaft is shown in Fig. 9 and that of low pressure shaft is shown in Fig. 10.The increase of SFC in afterburning state is far more than that in intermediate state with the rise of power extraction of shaft. The increase in SFC is 0.023 kg/(kgf·h) on average for every 1MW high pressure shaft power extracted in intermediate state and 0.060 kg/(kgf·h) on average in afterburning state. The power extraction of low pressure shaft will bring more fuel consumption than that of high pressure shaft. Under intermediate state, the increase in SFC is 0.023 kg/(kgf·h) on average for every 1MW high pressure shaft power extracted and 0.025 kg/(kgf·h) on average for low pressure shaft.

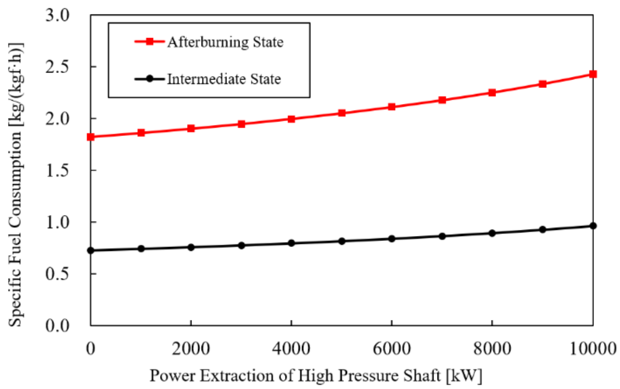

Fig. 9. Diagram of specific fuel consumption with power extraction of high pressure shaft

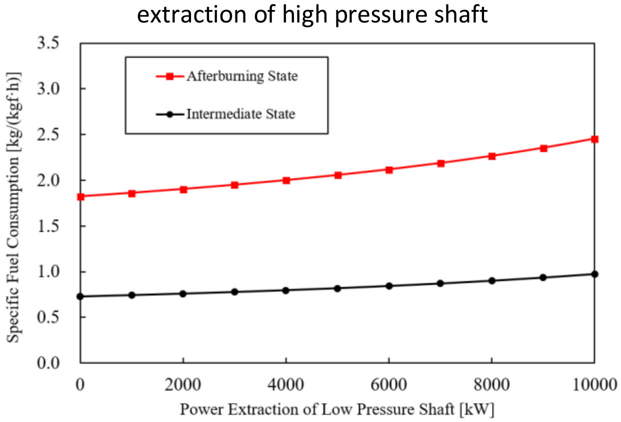

Fig. 10. Diagram of specific fuel consumption with power extraction of low pressure shaft

3.3 Thermal efficiency and thermoelectric efficiency

The thermal and thermoelectric efficiency with power extraction of high pressure shaft is shown in Fig. 11 and Fig. 12 and that of low pressure shaft is shown in Fig. 13 and Fig. 14. The thermal efficiency decreases with the increase of power extraction. The thermal efficiency reduction rate in the afterburning state is lower than that in the intermediate state, mainly due to thermal efficiency in afterburning state is mainly influenced by the combustion situation in the afterburner.

The thermoelectric efficiency increases with energy extraction. In intermediate state, the increase in thermoelectric efficiency is 1.27% on average for every 1MW shaft power extracted and in afterburning state, the value is 0.29%. The extraction of electric energy breaks through the limitation of Brayton cycle in traditional configuration, improves the distribution of circulating power, and embodies the original design intention of the HCE.

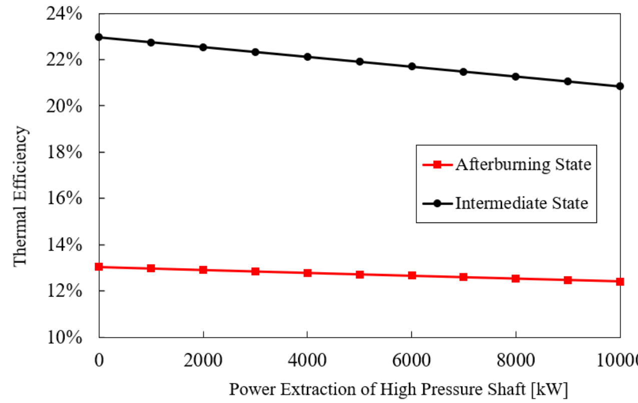

Fig. 11. Diagram of thermal efficiency with power extraction of high pressure shaft

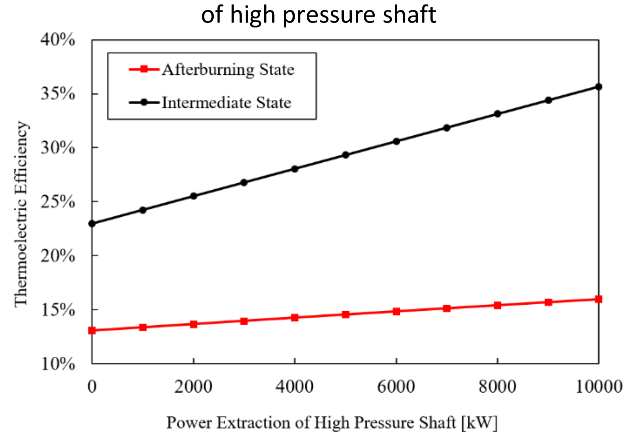

Fig. 12. Diagram of thermoelectric efficiency with power extraction of high pressure shaft

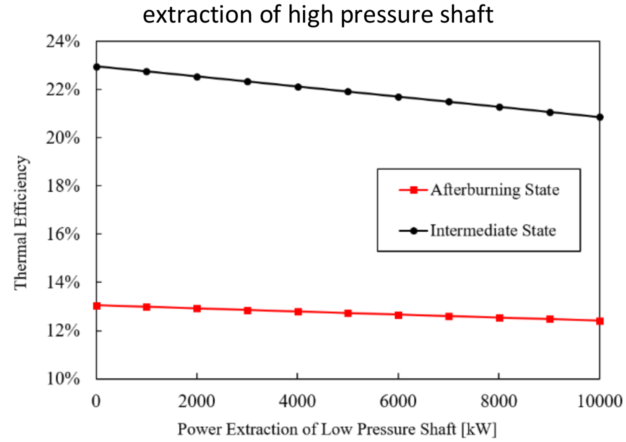

Fig. 13. Diagram of thermal efficiency with power extraction of low pressure shaft

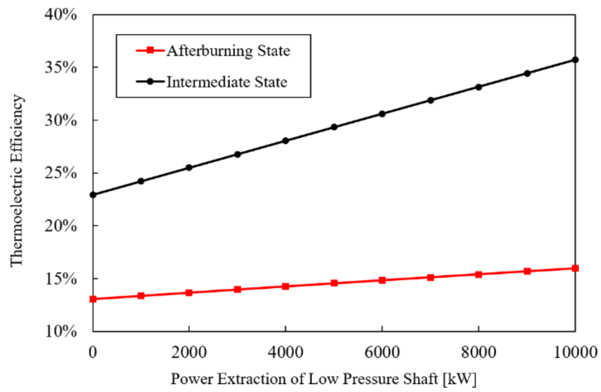

Fig. 14. Diagram of thermoelectric efficiency with power extraction of low pressure shaft

4. CONCLUSIONS

In this paper, the performance simulation model of HCE is established based on the principle of the thermoelectric hybrid cycle. The sensitivity analysis of power extraction of high and low pressure rotor under design conditions is carried out to explore the matching mechanism of the hybrid cycle. The research is summarized as follows:

(a) Power extraction under intermediate state will bring more thrust relevant loss than afterburning state. Power extraction of low pressure rotor will bring more thrust loss than that of high pressure rotor. Under intermediate state, The thrust loss is 189.18 kgf on average for every 1MW high pressure shaft power extracted and 195.49 kgf for low pressure shaft.

(b) The increase of SFC in afterburning state is far more than that in intermediate state. The power extraction of low pressure shaft will bring more fuel consumption than that of high pressure shaft. Under intermediate state, the increase in SFC is 0.023 kg/(kgf·h) on average for every 1MW high pressure shaft power extracted and 0.025 kg/(kgf·h) for low pressure shaft.

(c) The thermoelectric efficiency rises with the increase of power extraction. Under intermediate state, the increase in thermoelectric efficiency is 1.27% on average for every 1MW shaft power extracted. The extraction of electric energy breaks through the limitation of Brayton cycle in traditional configuration, improves the distribution of circulating power, which embodies the original design intention of the HCE.

DECLARATION OF INTEREST STATEMENT

The authors have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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