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带液化空气循环子系统的 ARCC 发动机研究

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摘 要 为解决空天飞机动力问题,提出一种新型带液化空气循环子系统的吸气式-火箭组合循环(ARCC)概念。该组合循环发动机集涡轮、冲压及火箭发动机优点于一身,在吸气式发动机工作过程中通过液化空气循环子系统液化大气中的氧气,存储供氢氧火箭发动机工作时使用,自身携带少量或不带氧化剂,因而经济性较好。为提高液化空气循环子系统液化比,采用多种措施设计一种新型液化空气循环子系统。计算了液化空气循环热力过程和 ARCC 发动机比冲性能,结果表明:液化空气循环子系统在整个吸气式飞行过程中具有较高液化比;ARCC 发动机在不同的飞行条件下都能得到良好比冲特性,经济性好。

关键词 吸气式-火箭组合循环发动机 液化空气循环 液化比 热力分析
中图法分类号 V421.4; **文献标志码** A

The liquefied air cycle engine (LACE) is an advanced future engine[1,2]. Taking liquid hydrogen (LH_2) as coolant, the engine liquefies the air from the atmosphere, and then pumps the liquefied air into the combustion. The liquefied air combusts with gas hydrogen, and provides propulsion power by flowing out the nozzle. Fig. 1 shows a basic LACE cycle. The engine combined with a rocket, and breathing air as the propellant of the rocket, as a result, the working range and the thrust weight ratio increases, so the LACE engine cycle interests many research groups. The US. Marquardt had ever engaged in researching on various LACE cycles in the 1950s. Japan National Aeronautics laboratory (NAL) began its LACE cycle aerospace plane research project in 1987. In 1985, Britain started the HOTOL space shuttle program, one of the cases adopted LACE cycle. As the research going on, various kinds of LACE cycles were developed, such as supercharged Ejector Ramjet (SERJ) combined cycle, coolant return LACE cycle, and LACE cycle with air separation and so on[3—5].

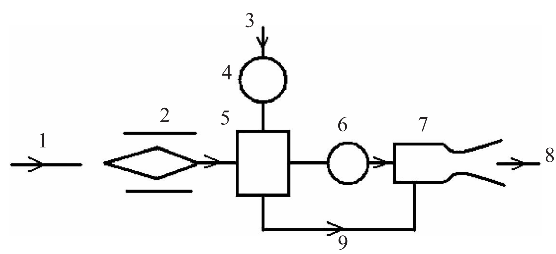

Fig. 1 Basic LACE cycle

1—Air, 2—Air intake, 3—LH_2 from tank, 4—Pump, 5—Heat exchanger, 6—Liquid air pump, 7— Rocket engine, 8—Ejected gas, 9—Gas hydrogen

There are some key technologies on the development of LACE cycle[6,7], such as improving the liquefaction ratio λ, high efficient and compact heat exchanger design, LACE combination configurations design and so on. The liquefaction ratio λ is one of the most important performance parameters. High liquefaction ratio indicates that more liquefied air could be ac-

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quired with the same volume coolant, and the quantity of oxygen taking from the ground could decrease largely or even to zero, then the aerospace plane can take more payloads into the space. At the same time, as the propellant decreases, the specific impulse increases. For the basic LACE cycle, one kilogram liquid hydrogen can liquefy about 3.8 kilogram airs at temperature of 288 K and pressure of 0.1 MPa, with the hydrogen temperature increasing from 14 K to 123 K. The mixture ratio of oxygen/hydrogen in a LACE combustor is less than 1:1, however the stoichiometric ratio of LH_2/(liquid oxygen) LO_X rocket engines is about 34, the oxygen/hydrogen combustion is not complete, a large quantity of hydrogen ejected without combusting. So in this case the specific impulse of this LACE is not distinctly higher than that of the current LH_2/LO_X rocket engines. Furthermore, it has a low thrust weight ratio. Theoretical specific impulse of LACE on sea level is up to 70 000 m/s, however it actually only get 10 000 m/s for basic LACE cycle, much lower than the theoretical value. New LACE cycle should be designed to improve the liquefaction ratio, and improve the specific impulse. Based on the proceeding discussing, a new concept air-breathing rocket combined cycle (ARCC) with LACE subsystem is presented. The ARCC engine is composed of the turbojet, ramjet and LH_2/LO_X rocket engines. It can be used as the first stage propulsion of a two-stage-to-orbit (TSTO) vehicle. As the technology developing, it can be adopted as propulsion of a single-stage-to-orbit (SSTO) vehicle further.

1 ARCC with LACE subsystem working mechanism

1.1 LACE subsystem working process

The air from intake divided into two parts, one goes into the turbojet or ramjet, the other goes into the LACE subsystem. The LACE subsystem takes slush hydrogen as coolant. As fig. 2 shows, the air 11 flowing into the LACE subsystem is cooled to about 84 K after passing through the first heat exchanger 2. Compressed by a ram-rotor 3[8,9], whose single stage compression ratio is between 12 and 15, to a pressure about 1.4 MPa, the air is cooled to the condensation temperature by passing through the second heat exchanger 4. Passing through the expander 5, most of the oxygen in the air is liquefied with a small friction of nitrogen liquefied. After a separator 6, the liquefied oxygen is pumped and stored into the liquid oxygen tank 8, and the nitrogen is led to the first heat exchanger as a coolant. When the nitrogen leaves the heat exchanger, a part of the gas goes to cool the turbine blade of the turbojet, left goes to cool the turbojet afterburner or ramjet combustor, and finally goes into the nozzle, ejected out to provide additional propulsion. As the turbine blade, turbojet afterburner and ramjet combustor are cooled, it can improve heat resisting capability of the turbojet and ramjet. More fuel can be ejected into the combustor, so the propulsion of turbojet and ramjet increases. Further more all the nitrogen goes into the nozzle, and ejected out to provide additional propulsion, which can also increase the ARCC thrust largely.

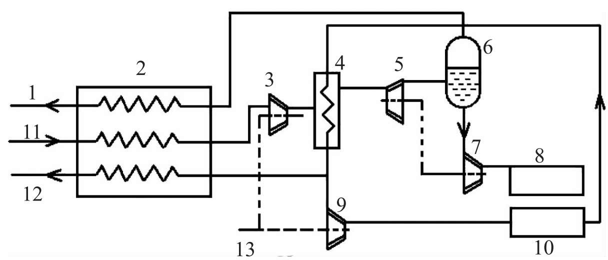

Fig. 2 The configurations of the LACE subsystem

1—Gas nitrogen, 2—Nitrogen/air/hydrogen heat exchanger, 3—Ram-rotor compressor, 4—Slush Hydrogen/air heat exchanger, 5—Expander, 6—Gas liquid separator, 7—Liquid oxygen pump, 8—Liquid oxygen tank, 9—Liquid hydrogen pump, 10— Slush hydrogen tank, 11—Inlet air, 12—Heated gas hydrogen, 13—Power imported from outer system.

For the coolant cycle, the slush hydrogen from the slush hydrogen tank first goes into the second heat exchanger 4. The gas temperature increases to about 67 K. A part of the gas hydrogen return to the slush hydrogen tank 8 to be re – liquefied, the other goes into the first heat exchanger 2 to cool the inlet air 11, and then is compressed and goes to cool the aerospace plane body or some parts which need cooled, finally ejects into the combustor to combust. In the slush hydrogen tank, when all the slush hydrogen turns to liquid hydrogen and the liquid hydrogen is heated to saturation state under the tank pressure, the tank return cycle stops. After that, all the gas hydrogen flowing out of the second exchanger goes into the first heat exchanger.

1.2 ARCC engine working process

The turbojet 5 and the LACE subsystem 4 work first, when the aerospace plane takes off from the ground. A part of inlet air flows into the turbojet 5, compressed in the compressors, burning in the combustor, expanding in the turbine, re – burning in the afterburner 8, and finally ejected from the nozzle 12 to provide propulsion. Turbojet 5 adopts two stages ram – rotor as the low pressure compressor and high pressure compressor. The ram – rotor is a simple, light, high compression ratio and high efficient compressor, so the thrust weight ratio of the turbojet 5 is very high, more than 15, but the structure is much simpler. The other part of the air flows into the LACE subsystem 4, liquefied and separated into liquid oxygen and gas nitrogen. The liquid oxygen is stored into the liquid oxygen tank; the gas nitrogen is used to cool some important parts and sent into the nozzle to be ejected out to produce additional propulsion as foreword mentioned. As the turbojet adopts heated gas hydrogen as fuel, the specific impulse is about three times of the normal turbojet.

When the aerospace plane accelerates to a speed between 2.5 and 3 Mach and a height about 20 000 m, the thrust and specific impulse of the turbojet decrease tremendously, and a ramjet 6 should be operated to functioning instead of the turbojet 5. As the turbojet and ramjet share the intake 1, the switch boards 3 before the turbojet and switch board 7 after the turbojet close, air from the intake goes through the bypass into the ramjet combustor 8 which is also the afterburner of turbojet. In this way, the turbojet stops working and ramjet replaces its function. For the LACE subsystem, its cycle process is the same as foreword.

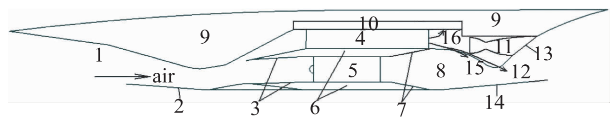

Fig. 3 ARCC propulsion configuration when turbojet works

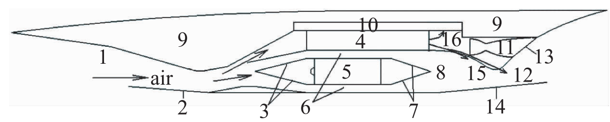

Fig. 4 ARCC propulsion configuration when ramjet works

1—Variable geometry intake, 2—Adjustable intake cowl lip, 3—Turbojet/ramjet switch boards, 4—LACE subsystem, 5—Turbojet, 6—Ramjet, 7—Turbojet/ramjet combustor switch boards, 8—Combustor shared by turbojet and ramjet, 9—Slush hydrogen tank, 10—Liquid oxygen tank, 11—LH_2/LO_X rocket combustor chamber and nozzle, 12—Nozzle, 13—Nozzle baffle of the $LH2/LO_X$ rocket engines, 14—Adjustable bottom board of the nozzle, 15—Low temperature nitrogen gas, 16—Liquid oxygen.

When the aerospace plane flies to a height or a speed that the ramjet could not work steadily, the ramjet should stop working and the scramjet starts to work, or the LH_2/LO_X rocket engines 11 start to work if the scramjet is not available. The LACE subsystem adopts oxygen and nitrogen separation technology, the liquefied oxygen can be used as propellant, and nitrogen can also be heated to provide propulsion, so the LACE subsystem can insist on working until the air-breathing propulsion is shut down. When the air-breathing propulsion stops working, the adjustable intake cowl 2 turns upwards to close the entrance of the intake, and the adjustable bottom board 14 of the nozzle turns upwards, together with the unwrapped nozzle baffle 13 of the LH_2/LO_X rocket engines to close the nozzle of air-breathing propulsion. Then the LH_2/LO_X rocket engines 11 operate. As the liquid oxygen used in the LH_2/LO_X rocket engines mostly comes from the atmosphere, not from the ground, the performance of the ARCC propulsion is excellent, and the aerospace plane can taking more payloads into the space.

2 LACE performance calculation model

To make good use of the cooling capacity of the coolants, the heat exchangers should be well designed and evaluated the performances.

For quick estimation of the heat exchanger performances, the simple and convenient correlations can be found in the following calculation equation. The heat exchanger temperature efficiency η_{cool} is defined to be the ratio of the temperature difference between coolant inlet and outlet and the temperature difference between air inlet and coolant inlet:

$$\eta_{cool} = \frac{T_c^{out} - T_c^{in}}{T_a^{in} - T_c^{in}} \tag{1}$$

Where, T—temperature,

Superscript; in: inlet, out: outlet;

Subscript: a: air, c: coolant;

The air pressure recovery ratio σ_a is defined to be the ratio of air stagnation pressures in the outlet and the inlet of the heat exchanger:

$$\sigma_a = \frac{P_a^{*out}}{P_a^{*in}} \tag{2}$$

Where, P^*—stagnation pressure

Superscripts; in: inlet, out: outlet

Subscript; a: air

Assuming the heat exchangers have no energy loss, the energy equation can be described as follow:

For the first heat exchanger:

$$m_N \bar{c}_{p1N}(T_{1N}^{out} - T_{1N}^{in}) + m_{1H}\bar{c}_{p1H}(T_{1H}^{out} - T_{1H}^{in}) = m_a \bar{c}_{p1a}(T_{1a}^{in} - T_{1a}^{out}) \tag{3}$$

For the second heat exchanger:

$$m_{2H}\bar{c}_{p2H}(T_{2H}^{out} - T_{2H}^{in}) = m_a \bar{c}_{p2a}(T_{2a}^{in} - T_{2a}^{out}) \tag{4}$$

Where, T: temperature, m: mass flow rate,

c_p: specific heat capacity at constant pressure.

Superscripts; in: inlet, out: outlet;

Subscript; N: nitrogen, H: hydrogen, a: air, 1: first heat exchanger; 2: second heat exchanger

For the low-temperature air compressor, the power and the outlet air temperature can be expressed as:

$$N_c = m_a c_{pa} T_{1a}^{out} \frac{(\pi_c^{\frac{(\gamma-1)}{\gamma}} - 1)}{\eta_c} \tag{5}$$

$$T_{2a}^{in} = T_{1a}^{out}[1 + (\pi_c^{\frac{(\gamma-1)}{\gamma}} - 1)/\eta_c] \tag{6}$$

Where, N—power, T—temperature, m: mass flow rate, π—compression ratio, η—efficiency, γ—specific heat ratio; c_p—specific heat capacity at constant pressure.

Superscripts—in: inlet, out: outlet.

Subscript; a—air, c: compressor, 1: first heat exchanger, 2: second heat exchanger.

There is phase transition existed in the process when the low temperature air passes through the expander. Normal turbine performance calculation formulas are no longer applicable to this expander. As the pressure of air inlet and the expansion ratio are known parameters, the outlet air pressure could be calculated. Assuming the expansion process is isentropic, and according to the thermal parameters of the air inlet and the outlet pressure, the power of the isentropic expansion process could be computed in the pressure-enthalpy diagram.

$$N'_e = h_a^{in} - h_a^{out} \tag{7}$$

The real power of the expander:

$$N_e = N'_e \eta_e \tag{8}$$

Where, N—power, h: enthalpy, η: efficiency

Superscripts—in: inlet, out: outlet, N': isentropic parameter

Subscript—a: air, e: expander.

3 LACE performance analysis

According to the performance calculation model, the thermal parameters of the four main parts of the LACE subsystem are calculated. Table 1 show the thermal parameters when the LACE subsystem is on the ground. After the expander, about 20 kg/s oxygen is liquefied. The heated gas hydrogen mass flow rate is only 2.5 kg/s, which is 2.5% of the total air mass flow rate. The mass flow rate of hydrogen returning to the tank is 3 kg/s, about 54.5% of the total hydrogen mass flow rate. Considering the total cooling capacity consumed, the liquefaction ratio λ_t is about 5.8, and if only considering the ratio of the liquefied oxygen mass flow rate to heated gas hydrogen mass flow rate, then the liquefaction ratio λ_g is 8.

Table 1 Thermal parameters of the four main parts of the LACE subsystem on the ground

	First heat exchanger	Compressor	Second heat exchanger	Expander
		Air side		
Inlet temperature/K	288	84	183.5	109.8
Outlet temperature/K	84	183.5	109.8	97.6
Inlet pressure/MPa	0.103	0.092 7	1.39	1.25
Outlet pressure/MPa	0.092 7	1.39	1.25	0.25
Mass flow rate/ $(kg \cdot s^{-1})$	100	100	100	100
Exchanging heat or power/kW	20 460	9 950	6 780	4 554
		Coolant side		
	N_2	H_2		H_2
Inlet temperature/K	97.6	67		13.8
Outlet temperature K	259.4	254.9		67
Mass flow rate, kg/s	80	2.5		5.5
Exchanging heat kJ	13 440	7 020		6 780

As the LACE subsystem works from the Mach number 0 to 5 or even more, analysis the LACE performances *vs.* flight state is necessary. Fig. 5 shows curves of the liquefaction ratio *vs.* the flying height and Mach number. Below the height of 20 km, the liquefaction ratio λ_g changes little. Above the height 20 km, the liquefaction ratio λ_g decreases with the height increasing. However, the curves of the liquefaction ratio λ_t *vs.* the flying height have a different discipline. The liquefaction ratio λ_t gets the peak value at the height of 20 km. According to calculation results, liquefaction ratio of the LACE subsystem is very high, and the performances of the LACE subsystem are excellent. That means the LACE subsystem could supply a lot of liquid oxygen for LH_2/LO_X rocket engines.

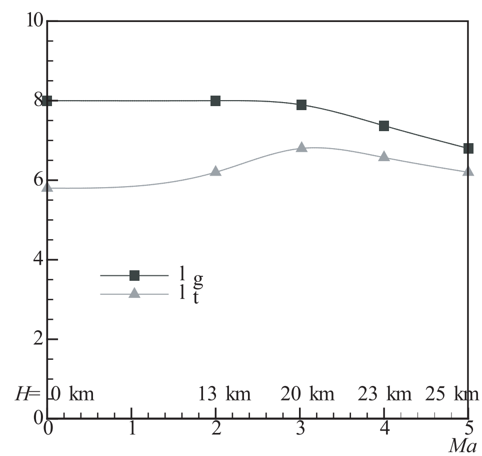

Fig. 5 Liquefaction ratio *vs.* the flying height and Mach number

4 ARCC performance analysis

Whether the performances of ARCC engine are good or not, it should be judged by the performance data. By the thermodynamic cycle modeling and performance cycle analysis, the performances of the turbojet and ramjet are given out. Fig. 6 shows the specific impulse of turbojet *vs*. the height. Fig. 7 shows the specific impulse of turbojet *vs*. the Mach number. Fig. 6 indicates that the specific impulse of the turbojet increases from 0 to 11 000 m height, and above the 11 000 m height, the specific impulse keep the same. Fig. 7 shows that with the Mach number increasing, the specific impulse of the turbojet decreases.

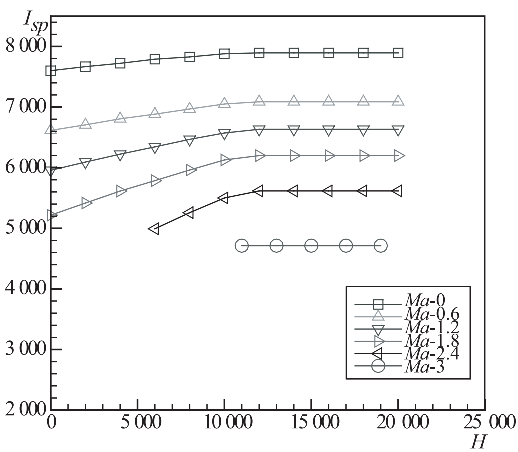

Fig. 6　Specific impulse of turbojet *vs*. the height

Fig. 8 shows the specific impulse of ramjet *vs*. the height. As the height increases, the specific impulse of ramjet changers little. Fig. 9 shows the specific impulse of ramjet *vs*. the Mach number. With the Mach number increasing, the specific impulse of ramjet first increases, and then decreases. At about 3.2 Mach, the specific impulse of ramjet reaches the peak value.

By the research on the specific impulse of ARCC, it can be concluded that the ARCC engine has very excellent specific impulse performance at most of the flying conditions.

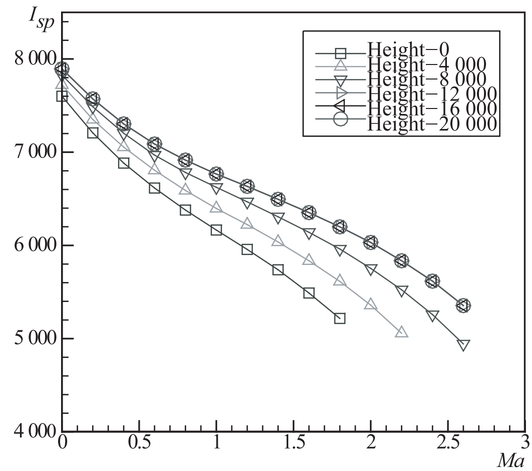

Fig. 7　Specific impulse of turbojet *vs*. the Mach number

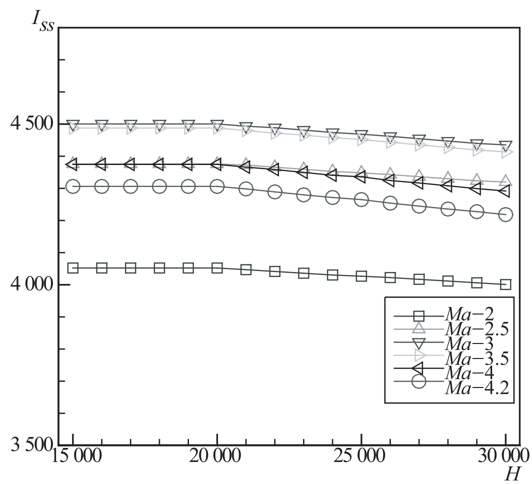

Fig. 8　Specific impulse of ramjet *vs*. the height

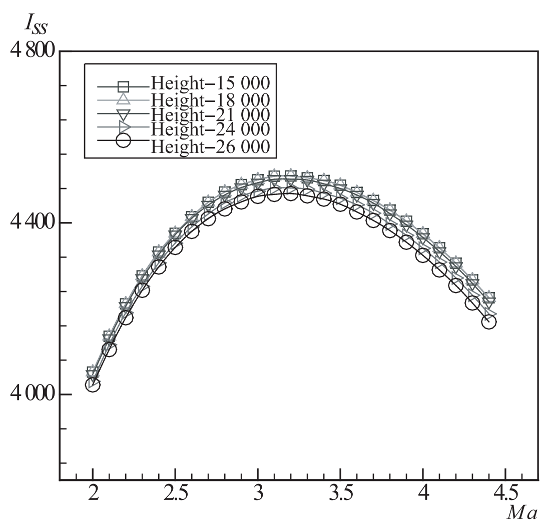

Fig. 9　specific impulse of ramjet *vs*. the Mach number

5 Conclusions

1) A new concept air-breathing rocket combined cycle with LACE subsystem is presented to overcome the propulsion difficulties of the future space vehicle. According to the working mode analysis of the ARCC, the combined engine has excellent performances at most of the working process.

2) A LACE subsystem is designed, with several measures adopted to enhance the liquefaction ratio, such as choosing slush hydrogen as coolant, coolant return tank cycle, compressing air with ram-rotor and expansion cycle.

3) According to the LACE thermal process, the performances calculation methods are listed out. The liquefaction ratio of the LACE subsystem is very high at most of the air-breathing flight states, it indicates that the LACE subsystem has excellent performances.

4) The ARCC engine has excellent specific impulse performance at most of the flying conditions.

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Research on Air-breathing Rocket Combined Cycle with Liquefied Air Cycle Engine Subsystem

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[**Abstract**] To overcome the propulsion difficulties of aerospace plane, a new concept air – breathing rocket combined cycle (ARCC) with LACE subsystem is presented. This combined engine integrates the turbojet, ramjet and rocket engines into one propulsion system. When the air – breathing propulsion works, the LACE subsystem liquefies the oxygen from the atmosphere and stores it in a liquid oxygen tank as propellant of the liquid hydrogen/liquid oxygen rocket. As it takes a little liquid oxygen or even none from ground, the aerospace plane is much economical. To enhance the LACE subsystem liquefaction ratio, a new cycle of LACE subsystem is designed with several measures adopted. The thermal processes of the LACE subsystem and the specific impulse performance of ARCC are calculated. The results show that the liquefaction ratio of the LACE subsystem is very high at most of the air-breathing flight states and the specific impulse performance of ARCC is excellent at most of the flying conditions.

[**Key words**] ARCC LACE liquefaction ratio thermal analysis