Proceedings of the 4rd International Conference on Mechatronics and Smart Systems
DOI: 10.54254/2755-2721/2026.32440

Study on the Influence of Combustion Reaction in the Tail Nozzle of Air Turbine Rocket Engine on Thrust Performance

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Abstract. Air turbo rocket engine (ATR) is a combined cycle power device that mixes turbine and rocket technology. It has many good features, such as a wide working range, high thrust-weight ratio, good specific impulse and strong mobility. It is an ideal power source for near-space high-speed aircraft, tactical missiles and two-stage-to-orbit aerospace transportation systems. This paper, based on five core research aspects, explains the ATR engine's working principle, core component optimization methods, variable working condition performance and control rules, sorts out the current core technical challenges, and looks forward to the future development trend. It provides theoretical reference and technical support for the ATR engine's engineering application and performance improvement. The rapid development of high-speed aeronautical and aerospace technologies in recent years has put forward higher requirements for the performance of air-breathing power devices, and ATR has received extensive attention from academia and industry around the world due to its unique advantages in transonic and hypersonic flight conditions. Different from traditional gas turbine engines that rely entirely on atmospheric oxygen for combustion and pure rocket engines that carry all oxidants, ATR uses a rocket gas generator to pre-generate high-temperature gas, then introduces atmospheric air through an inlet to mix with the pre-generated gas for secondary combustion, and finally expands the mixed gas through a turbine to output thrust. This special working mode makes it avoid the problems of the low thrust-weight ratio of turbine engines and the low specific impulse of pure rocket engines, filling the performance gap between the two traditional power schemes in the flight Mach number range of 3 to 6.

Keywords: air turbine rocket engine, afterburner mode, mixed combustion, adjustable nozzle

1. Introduction

Since Robert Goddard put forward the air turbo rocket (ATR) engine in 1932, ATR technology has developed for almost a hundred years, evolving from an idea into real engineering tests. ATR is an important part of the TBCC engine; it uses gas from a gas generator to drive the turbine and compressor, then the fuel gas and air burn again in the combustor, and finally produce thrust through the nozzle. This working method enables ATR to have the advantages of both turbine engines and rocket engines. It can work stably at an altitude of 0~30km and a speed of Ma0~4.5, which fixes the weaknesses of traditional engines. Many powerful countries such as America and Japan conducted extensive research and tests on ATR engines early. America achieved thrust control from 70N to 1525N and a specific impulse of 527s, while Japan developed the ATREX engine and solved key technologies [1]. China started ATR research in the 1980s, and has achieved many results in modeling, design and combustion, but still faces many problems in solid fuel combustion, control and practical application. This paper summarizes the key technologies of ATR from four aspects, provides a comprehensive analysis, and offers assistance for future research.

2. The working principle and configuration characteristics of ATR engine

The core working cycle of the ATR engine is defined as "gas drives the turbine – the turbine drives the compressor – secondary combustion releases energy – nozzle expansion produces work", and its core components include the inlet, compressor, and so on. Propellant burns in the gas generator to drive the turbine; after being processed, outside air mixes with the fuel-rich gas and undergoes secondary combustion in the afterburner, ultimately generating thrust through the nozzle.Classified by fuel form, ATR engines are divided into two types: liquid and solid. Liquid-fuel ATRs offer easy adjustability, serving as an early test scheme; solid-fuel ATRs feature a simple structure and high safety, making them a key research focus for tactical missiles in recent years [2]. To enhance thrust, an afterburning ATR scheme has been proposed, which adds an afterburning propellant channel within the afterburner to increase thrust by introducing additional propellant. This afterburning design offers three advantages: a simplified inlet, straightforward system integration, and wide-thrust adjustability. Simulation results indicate that while the afterburning mode can boost thrust, it concurrently leads to a reduction in specific impulse [3].Under the design conditions, injecting an equivalent volume of afterburning propellant can result in a 33.6% increase in thrust.See Figure 1 for details.

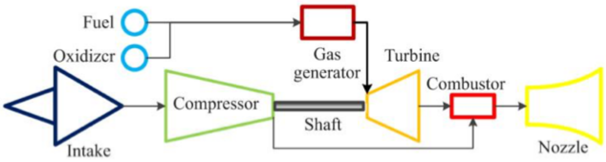

Figure 1. Engine schematic diagram

3. Design and performance optimization of ATR engine core components

The overall performance of the ATR engine is determined by the working performance and matching characteristics of each core component. The combustor, nozzle and turbocharging device are key components; they are also the focus of optimization. The combustor is used for mixing and combustion to release chemical energy, but the normal mixing effect is poor. Using a C-shaped trailing edge lobe mixer can enhance mixing; two pairs of this structure can make the combustion efficiency reach 96.9%, balancing mixing effect and flow resistance. In the afterburner, a dual-mode structure can expand the working speed range. The nozzle converts the gas heat energy into kinetic energy; the ATR engine adopts a two-dimensional asymmetric adjustable nozzle, which is designed by the polynomial function method, with single-degree-of-freedom adjustment, adapts to the dual-flow system, and has engineering value [4]. The turbocharging device determines the engine stability and performance limit; the turbine and compressor need accurate matching. Increasing the turbine pressure ratio and reducing the compressor pressure ratio can improve the specific impulse, and the turbine inlet temperature must be controlled within 1450K. See Table 1 for relevant data [5]. See Figure 2 for details of the above content.

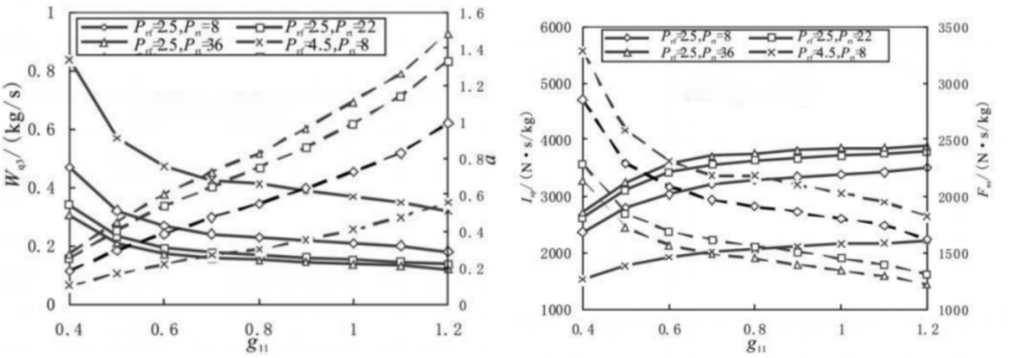

Figure 2. Performance change curve

Table 1. Performance of ATR in dry- and augmented mode at design- and off-design point

number	boost ratio, drop ratio	Air flow rate, vortex flow rate, and boost flow rate (kg/s)	wing drive, boost, adiabatic combustion temperature k of the afterburner	Generator, afterburner pressure/MPa	specific impulse/ (N•s/kg)	Visater go/N	specific impulse variation range	amplitude of thrust variation
1-1	2.5/20	1.40/0.32/0.0	1421/3616/2368	15.75/0.748	5 032	1 610		
1-2	2.92/19.75	1.32/0.37/0.22	1425/3616/2491	18.1/0.875	3 384	1 997	−32.7	24.0
2-1	2.5/20	1.40/0.32/0.19	1421/3616/2582	15.75/0.748	4 199	2 151		
2-2	2.75/19.56	1.37/0.34/0.34	1424/3616/2656	16.93/0.823	3 428	2 352	−18.3	9.3
2-3	2.24/20.31	1.43/0.29/0.058	1418/3616/2511	14.32/0.670	4 767	1 669	13.5	−22.4
2-4	2.11/20.04	1.43/0.27/0.0	1416/3616/2489	13.35/0.633	5 543	1 505	32	−30.0

4. The working process characteristics and regulation control of ATR engine

The working process of the ATR engine includes the design point, off-design point, and start-up transition state; regulatory control determines its stability and adaptability. The performance at the design point is affected by the oxygen-fuel ratio of the gas generator. The rule of performance change is the same in both afterburning and non-afterburning modes, but the afterburning mode has higher thrust and lower specific impulse. At the off-design point, changes in afterburning flow will jointly affect thrust and specific impulse. See Table 2 for relevant data. Adjusting the afterburning flow can realize continuous thrust adjustment, and it is necessary to optimize parameters according to the flight task. Start-up is a key link because the compressor state is difficult to control and prone to failure.

Table 2. Thermodynamic cycle parameters of SP-ATR engine in design point

Parameter	Numerical value
Flying height H/km	0
Flying mach number Ma	0
Air flow mair/(kg/s)	20
Compressor pressure ratio πC	3.0

Table 2. (continued)

Compressor efficiency ηC/%	86
Rich fuel gas flow mgas/(kg/s)	3.18
Turbo expansion ratio πT	10.2
Turbine efficiency ηT/%	82
Combustion efficiency ηCOM/%	90
Combustor outlet temperature T*COM	1600
Gas generator chamber pressure P*GG/MPa	3.04
Gas generator outlet temperature T*GG/K	1200
Thrust F/N	2100
Specific impulse Isp/s	675

$$V\frac{d\rho}{dt}=m_{in}-m_{out} \tag{1}$$

$$V\frac{d\rho_{out}}{dt}=\frac{V}{kRT_{out}}\frac{dP_{out}}{dt}=m_{in}-m_{out} \tag{2}$$

$$\frac{m_{air}\sqrt{T_{in}}}{P_{in}}=f_C\left(\frac{n}{\sqrt{T_{in}}},\pi_C\right) \tag{3}$$

$$h_{t4}=\frac{h_0+\gamma_{of}h_f}{\gamma_{of}+1} \tag{4}$$

$$\frac{dn}{dt}=\frac{\eta_M W_T-W_C}{J\left(\frac{\pi}{30}\right)^2 n} \tag{5}$$

5. Technical challenges and development trends of ATR engine with solid fuel

The solid fuel ATR engine is a hot spot in ATR research, but it has five major challenges in engineering application. It is difficult to achieve high-efficiency combustion and control of solid fuel, improve secondary combustion efficiency, maintain the reliability of high-speed rotating components, match the inlet and exhaust system in a wide speed range, and achieve high precision in multi-physics coupling simulation. In the future, research will focus on six directions. We need to develop new high-energy solid fuel, create new combustion technology in the combustor, improve the reliability of high-speed rotating components, use intelligent methods to optimize the inlet and exhaust system, adopt a multidisciplinary design method, and promote the development of combined power systems with other engines.Details of the above content: Figures 3 and 4.

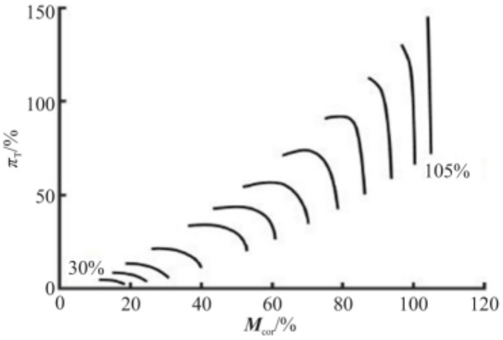

Figure 3. Total pressure ratio-mass flow

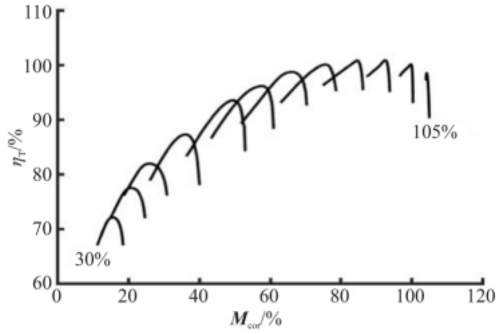

Figure 4. Effciency-mass flow

6. Conclusion

The air turbo rocket engine (ATR) is a combined cycle power device with good performance, and it has broad application prospects in tactical missiles, near-space high-speed aircraft and aerospace transportation systems. The afterburning configuration can increase thrust by 33.6%, the C-shaped trailing edge lobe mixer can raise combustor efficiency to 96.9%, and the two-dimensional asymmetric adjustable nozzle designed by the flow priority principle can achieve a flow coefficient of more than 0.967 and a ground axial thrust coefficient of 0.924 in the full flight trajectory. The cooperative adjustment strategy of propellant supply and nozzle area can realize fast and safe start-up of the engine, and also avoid compressor surge and blockage faults. At present, ATR technology has made great progress, but there are still many technical bottlenecks to break through. In the future, we need to focus on core directions to break through key technologies, promote the ATR engine from theoretical research and laboratory verification to engineering application, and provide core support for the development of China's aerospace power technology.

Propellant supply rate and nozzle throat area are core influencing factors for engine start-up. The cooperative method of "faster supply rate + throat area increase with rotation speed" can achieve fast and safe start-up. The afterburning ATR needs to adjust the flow of the turbine-driven generator and afterburning generator; the liquid type is controlled by a valve, and the solid type is adjusted by a throttle valve. During flight in a wide speed range, it is also necessary to perform cooperative adjustment of the inlet (adopting a variable geometry design) and the nozzle to realize stable and efficient operation in the full flight envelope.

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