# Experimental Investigation on the New 100N Bipropellant Space Rocket Engine

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**Abstract.** This paper developed experimental research on the new 100N bipropellant space rocket engine. The bi-centrifugal swirl injector with high degree of technological maturity, high reliability and properties is used on this engine. The cold flow test, steady-state hot firing, pulse–mode firing, long life hot firing and deflection firing test are carried out. The results show that, the flow and spray characteristics of injector keep stable; during the steady-state hot firing, the structure of engine is intact; the impulse is good and the heat back temperature can up to 220.2 °C; during the different pulse-mode firing, the engine response time (t90) is lower than 38 ms; after the 45000 s long life firing, the structure temperate is not high which can fit the demand of long life; the heat back temperature of weld can up to 232.0 °C.

**Keywords:** Bipropellant space rocket engine · 100N engine · cold flow field test · hot fire test · test condition

## 1 Introduction

At present, the common bipropellant space rocket engines mainly perform tasks such as attitude adjustment and orbital maneuvering. The major international manufacturers include AMPAC-ISP, Aerojet, EADS, Northrop Grumman, etc. [1]. Typical products include: Aerojet's R-4D engine developed for the early Apollo moon landing project. This series of engines has been developed from R-4D-7 to R-4D-16. After more than 40 years of development, through continuous improvement, the engine structure design and material selection, as well as the selection of new propellants, the specific impulse performance of the engine have been improved by more than 10% [2–4]. EADS' Astrium division's 10N bipropellant thrusters S10-01, S10-02, S10-18, etc. This series of thrusters uses swirling injectors and can work continuously in steady state or pulse mode [5–7]. Northrop Grumman has developed apogee engines such as TR-306, TR-308, TR-312, etc., with pintle injectors and MON-3/$N_2H_4$ as propellant, suitable for dual-mode propulsion systems [8–10]. The attitude control thrusters of our country's bipropellant satellites all use the 10N series thrusters [11] and the bipropellant 25N thrusters developed by Beijing Institute of Control Engineering [12]. In addition, Shanghai Institute of Space

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Propulsion developed the attitude control thrusters on the propulsion compartment of the "Shenzhou" manned spacecraft, with the thrusts of 150N and 25N respectively. Both are long-life and high-reliability bipropellant space rocket engines, which can be used for orbit control, attitude control and adjustment, orbit maintenance, etc. These engines have been successfully applied to the SZ1~SZ10 flight missions. Furthermore, Shanghai Institute of Space Propulsion has also developed a 120N bipropellant space engine, a 490N orbit control engine, etc. [13–15].

According to the requirements of the propellant system, and for the requirements of future missions, the bipropellant 100N engine needs to work under a wide range of inlet pressure, with high performance, long life, fast response and high reliability, which can provide orbit control and attitude control power for the spacecraft. Referring to the previous experience, combined with the needs of the mission, the development and test work of the new bipropellant 100N space rocket engine was carried out. The cold test and hot fire test were carried out. During the working period, the heat load is low and the working stability is high, and its performance and reliability meet the requirements of the mission.

## 2 Design Scheme

The bipropellant 100N space rocket engine consists of three parts: injector, nozzle, and solenoid valve, as shown in Fig. 1. The high-performance injector is bi-centrifugal swirl style; the liquid forms a high-speed rotating motion in the nozzle; after leaving the injector, it develops into a thin film under the action of centrifugal force, and the atomization

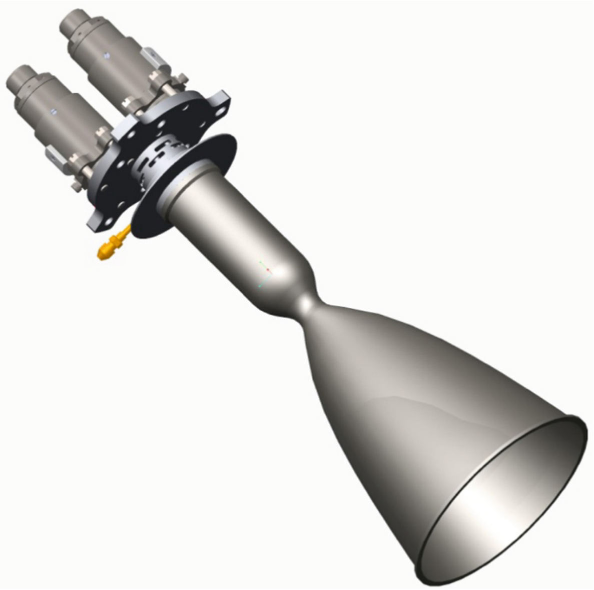


**Fig. 1.** The New 100N Bipropellant Space Rocket Engine

condition is good, the atomized droplet size is small. In addition, the injector has good flame sustaining ability and can ignite stably in a wide range of equivalence ratio; it has the characteristics of high maturity, good reliability and good atomization performance. The nozzle adopts high temperature alloy system material, which has the characteristics of light weight, good high temperature resistance and mature technology. The solenoid valve adopts the main structure of the solenoid valve, which has the characteristics of high reliability and fast response. The design thrust of the new engine is 100N, the rated chamber pressure is 0.9 MPa, and the rated inlet pressure is 1.6 MPa; the propellant is methyl hydrazine/nitrous tetroxide (MMH/NTO); the total length of the engine is 392 mm, the diameter is 130 mm, the total weight of the engine is 1.73 kg.

## 3 Experiment Study

### 3.1 The Cold State Test

Before the hot fire test of the new bipropellant 100N space rocket engine, a cold state test needs to be carried out to determine the parameters of the engine such as pressure drop, spray quality, swirl stability, and spray particle size distribution. During the test, a special spray test system is built, including a simulated propellant supply system, a flow test system, a spray particle size test system, and a water tank. The high-purity nitrogen is used to pressurize the simulated propellant to simulate engine conditions. The high-speed camera and a Phase Doppler Particle Analyzer (PDA) are equipped during the cold state test. The PDA system is a particle dual-mode dynamic analyzer (Dual PDA) from DANTEC, Denmark. The system consists of a dual-pulse laser, a camera, and a software system. It can measure the fogging field at a sampling frequency of 1 kHz. Using the laser generator, receiver and signal processing system in the image system and PDA system, the spray cone angle of the injector, the particle size and particle size distribution of the injector's jet can be obtained. The high-precision pressure sensor is used to measure the pressure of the simulated propellant with an accuracy which is higher than 2‰; a flow meter is used to measure the flow rate of the simulated propellant with an accuracy which is higher than 5‰. The test data is calculated to obtain the flow and pressure drop of the oxidant path and the fuel path. At the same time, the atomization of the injector, including the atomization angle and particle size distribution are obtained. During the test, orifice plates of different specifications are also selected to adjust the flow and pressure drop of the engine to obtain different working conditions and equivalence ratios.

### 3.2 The Hot Fire Test

After the cold state test, the new bipropellant 100N space rocket engine carried out the hot fire test research. The hot fire test system is shown in Fig. 2. The system consists of synchronous control system, data acquisition system, oxidant/fuel supply system, thrust measurement system, pressure measurement system, temperature measurement system, imaging device, etc. The synchronous control system and data acquisition system in the test system adopts the Pacific 6000 system; the oxidant/fuel supply system adopts the

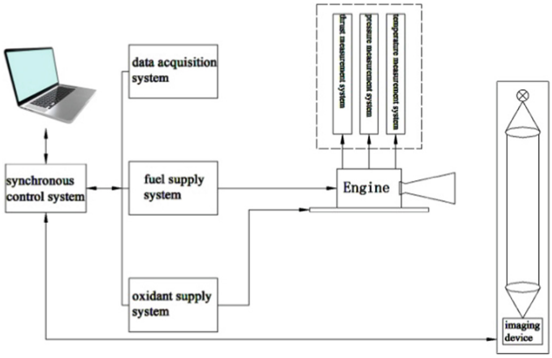


**Fig. 2.** The Hot Fire Test System

CMF025 Micro Motion mass flow meter to measure the flow rate, and the accuracy is better than 0.5%; the pressure measurement system adopts the GE UNIK-5000 series pressure transmitter, and the sensor accuracy is better than 0.1%; the temperature measurement system uses A-grade wire thermocouples, and the measurement accuracy is ±1.5 °C. The entire hot fire test system has been verified on many same type engines, and the system works reliably. During the test, the engine is installed on the thrust sensor in the vacuum chamber, and the test data is transmitted to the test system outside the vacuum chamber through cables for processing and recording. The hot fire test procedure includes steady-state hot firing, pulse-mode firing, long life hot firing and deflection test, etc. Measurement parameters include oxidant flow, fuel flow, vacuum thrust, nozzle pressure, oxidant inlet pressure, fuel inlet pressure, nozzle throat temperature, nozzle body temperature, etc., to comprehensively assess engine performance and working conditions.

## 4 Results and Discuses

Figures 3 and 4 are the product schematic diagram of the new bipropellant 100N space rocket engine, and the installation of the engine on the hot fire test system.

### 4.1 The Cold State Test Results

The cold state test of the new bipropellant 100N space rocket engine mainly includes the cold flow test of the injector and the atomization test of the injector. The test photos are shown in Fig. 5.

During the test, two injectors were tested, numbered 100N-1 and 100N-2, and the test data are shown in Table 1. It can be seen from the table that the flow consistency of the two injectors is very good. The flow rates of oxygen are around 19.7 g/s; the flow rates of fuel are around 14.5 g/s. After installing the orifice plate for throttling, the flow rate of the oxygen fuel circuit of the two injectors decreased slightly, and the flow characteristics of the two engines remained the same after adjustment.

**Fig. 3.** The Picture of Space Rocket Engine

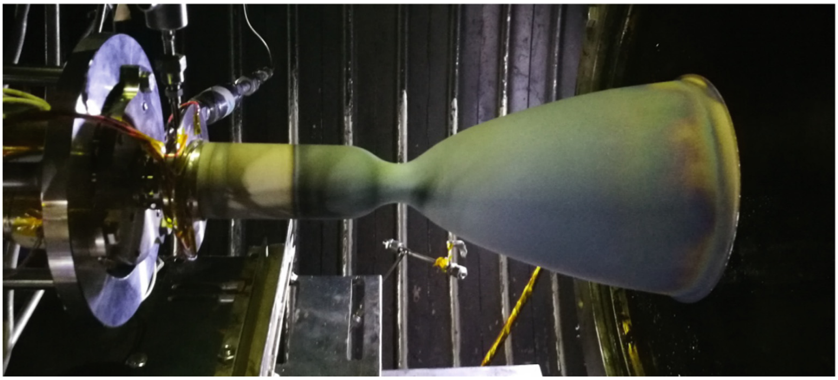


**Fig. 4.** The Space Rocket Engine on the Hot Fire Test System

In the cold state test process, the imaging method and PDA were used to measure the atomization state of the two injectors. The test results show that the inner and outer nozzles of the injectors are in the atomization state of typical swirling nozzles. The inner atomization cone angle is about 73°; and the outer atomization cone angle is about 123°. The consistency is very good. Table 2 shows the atomization distribution data and velocity distribution data tested by PDA. The figure shows the particle number distribution of the 100N-1 and 100N-2 injectors and the droplet velocity distribution in three directions. The cloud map is drawn according to the particle number and velocity of the 24 measured points. It can be seen from the figure that the atomization of the injector is relatively uniform, the maximum number of atomized particles on the test

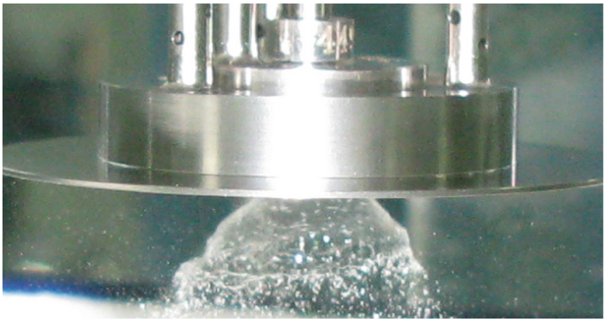


**Fig. 5.** The Cold State Testing of the New 100N Bipropellant Space Rocket Injector

**Table 1.** The Cold State Testing Data of Injector

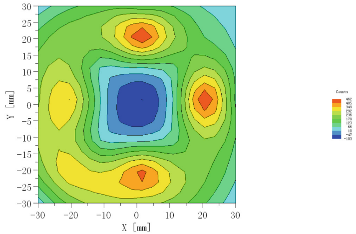
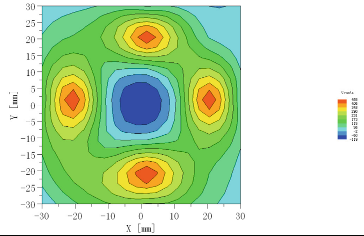
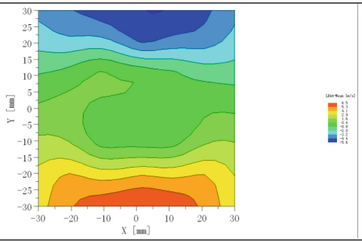
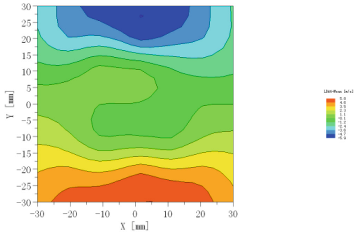
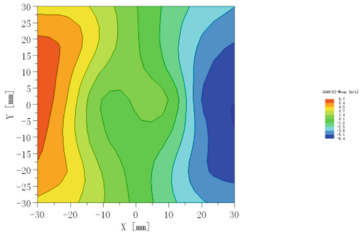
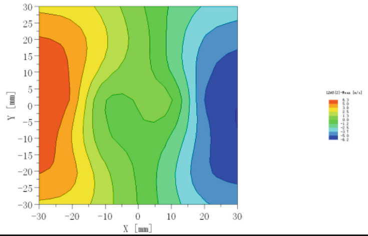
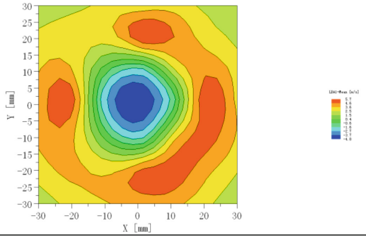
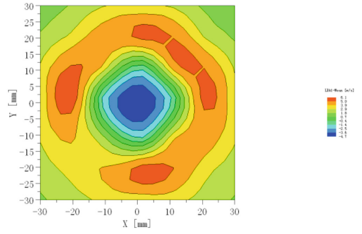
| Numbers | Injector oxygen fuel circuit water flow (g/s) | The re-measured value of the water flow of the oxygen-fuel road after installing the orifice plate (g/s) |
|---|---|---|
| 100N-1 | Oxygen: 19.5<br>Fuel: 15.5 | Oxygen: 18.0<br>Fuel: 14.5 |
| 100N-2 | Oxygen: 19.9<br>Fuel: 15.5 | Oxygen: 18.0<br>Fuel: 14.5 |

section reaches 405, and the number of particles in the circumferential direction exceeds 349. At the same time, the atomization distribution of the two injectors is also relatively consistent. For the velocity distribution of atomized particles, since the droplets atomized by the injector are distributed on a cone, the particles mainly move in the circumferential direction in the X and Y directions, and the X-direction velocities in the opposite position are relatively close. In the opposite direction, the velocity distribution in the Y direction is the same value as the velocity distribution in the X direction. It can be seen from the figure that in the circumferential position, the particle motion velocity is between 4.4 and 5.3 m/s, and the distribution is relatively uniform. For the Z direction velocity, the Z-direction velocity of the droplets is on in the same direction, and its distribution characteristics are quite different from the X-direction and Y-direction. It can be seen from the figure that the Z-direction velocity of the droplets atomized by the injector is 5.0–6.1 m/s, the velocity distribution is relatively uniform.

### 4.2 The Hot Fire Test

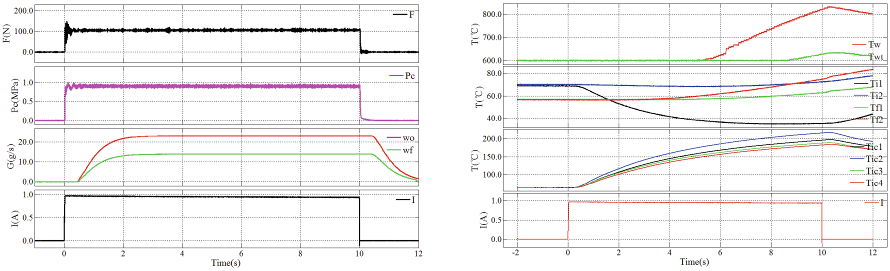
During the development of the new bipropellant 100N space rocket engine, the hot fire test was carried out. The test procedures included steady-state hot firing, pulse-mode firing, long life hot firing, etc., and the test record and analysis of the engine's working reliability and temperature changes were carried out.

**Table 2.** The Testing Result of Injector's Spray Pattern by PDA

| Injector number | **100N-1** | **100N-2** |
|---|---|---|
| Particle number distribution |  |  |
| X speed |  |  |
| Y speed |  |  |
| Z speed |  |  |

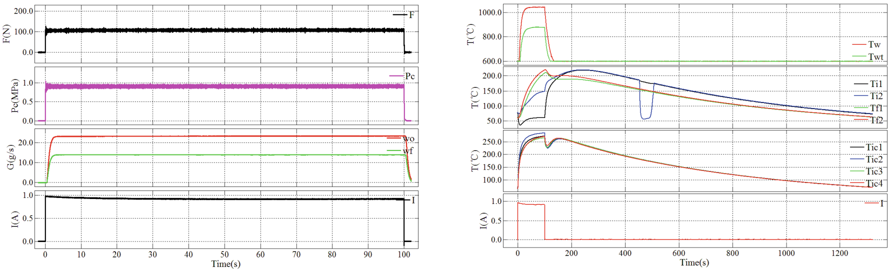
### 4.2.1 The Steady State Hot Firing

Figure 6 shows the test conditions of 10 s steady state, 100 s steady state and 1800 s steady state, all of which are rated working conditions. The curves include the change of engine thrust (F), chamber pressure (Pc), flow (wo, wf), current (I) and temperature (T). Among them, the current signal (I) records the current of the solenoid valve. After the control system issues an instruction, the solenoid valve is energized and turned on; the propellant enters the combustion chamber through the injector and burns to generate high temperature and high pressure gas; the pressure measurement system records the chamber pressure. As can be seen from the figure, the change of the chamber pressure is relatively rapid, and it rises to the working pressure in a very short time; the engine



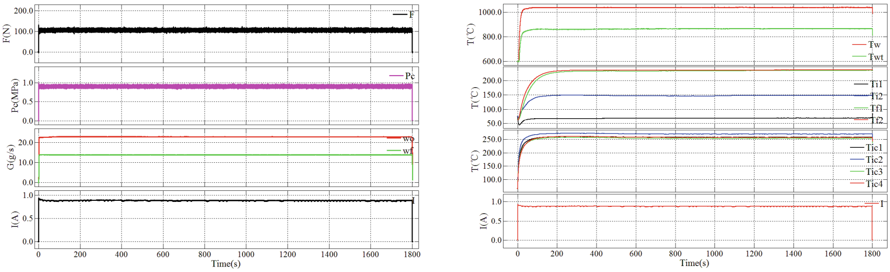
(a)10s rated working condition chamber pressure, thrust, flow and current curve

(b)10s rated working condition temperature curve



(c)100s rated working condition chamber pressure, thrust, flow and current curve

(d)100s rated working condition temperature curve

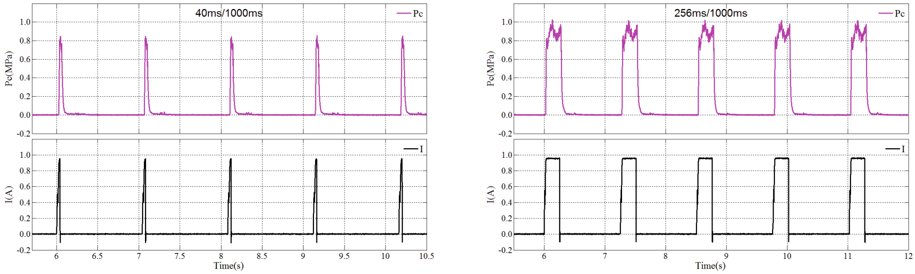


(e)1800s long-life working condition chamber pressure, thrust, flow and current curve

(f)1800s long-life working condition temperature curve

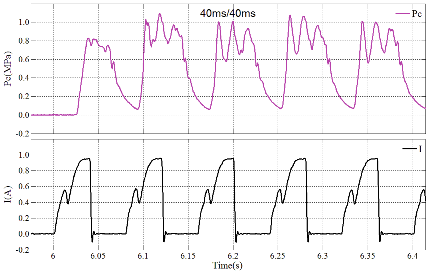
**Fig. 6.** The Hot Fire Test Curves of the New 100N Bipropellant Space Rocket Engine

thrust (F) is measured by the thrust sensor in the test system. Because of the thrust sensor's certain elasticity, the thrust shows a certain degree of vibration when the engine is turned on, and then quickly returns to the working thrust of the engine. Due to safety considerations, the oxidant/fuel supply system is far away from the engine, and they are connected by pipelines. Therefore, the flow rates rise relatively slowly. During the test, the temperature changes of the engine were also recorded. The test results show that the engine works normally under steady-state working conditions; after the test, the engine structure is checked which is intact; and the engine performance is good.



(a)40ms/1000ms pulse performance curve

(b)256ms/1000ms pulse performance curve



(c)40ms/40ms pulse performance curve

**Fig. 7.** The Chamber Pressure and the Electric Current Curves of the New 100N Bipropellant Space Rocket during the Impulse Operations

### 4.2.2 The Pulse-Mode Fire Test

Figure 7 shows the variation curve of chamber pressure and solenoid valve current in the pulse conditions in the hot fire test of the new bipropellant 100N space rocket engine. During the hot fire test, the working conditions of three pulse types of 40 ms/1 s (that is, 40 ms on and off for 1 s in each cycle), 256 ms/1 s, and 40 ms/40 ms were investigated. Table 3 shows the statistics of engine response speed. In pulse-mode operations, the response time (t90) of the engine is less than 38 ms, which can meet the requirements of the propulsion system for the engine to be used for attitude control of the spacecraft. During the pulse-mode operation of the engine, the working pressure is often lower than the rated chamber pressure due to the incomplete combustion of the propellant. In this hot fire test, it can be seen that under the 256 ms/1000 ms pulse-mode test firing, the engine working pressure reaches 1.0 MPa, which exceeds the rated chamber pressure; while under the 40 ms/1000 ms and 40 ms/40 ms working conditions, the engine working pressure reaches 0.8 MPa, slightly lower than the rated chamber pressure. During the 40 ms pulse-mode test, the incomplete combustion of the engine is more obvious.

### 4.2.3 The Long Life Test

According to the mission needs, the new bipropellant 100N space rocket engine has carried out a 45,000 s long-life firing test. Due to the limitation of test system, four 10800 s long-life firing tests and one 1800 s long-life firing test were carried out in the

**Table 3.** The Response Time of Engine during the Impulse Operations

| Pulse Type | t0 (ms) | t90 (ms) | t100 (ms) | t10 (ms) |
|---|---|---|---|---|
| 40 ms/1 s | 25.5 | 38.0 | 22.0 | 46.0 |
| | 25.5 | 38.0 | 22.5 | 46.5 |
| | 26.0 | 38.0 | 22.0 | 45.5 |
| 256 ms/1 s | 25.0 | 36.5 | 22.5 | 60.0 |
| | 25.0 | 37.5 | 22.0 | 55.5 |
| | 25.0 | 38.0 | 23.0 | 57.0 |
| 40 ms/40 ms | 25.5 | 37.0 | 14.5 | 48.0 |
| | 17.5 | 21.5 | 27.5 | 48.5 |
| | 16.0 | 21.0 | 26.5 | 49.5 |

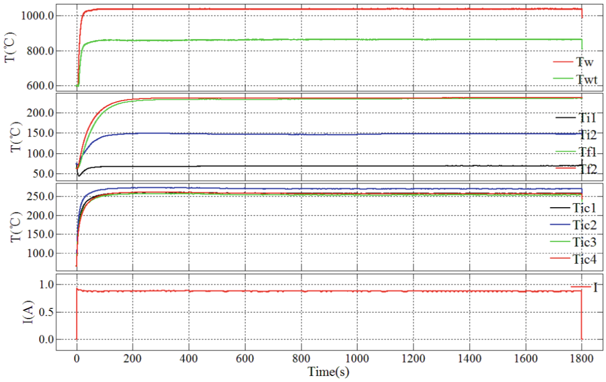
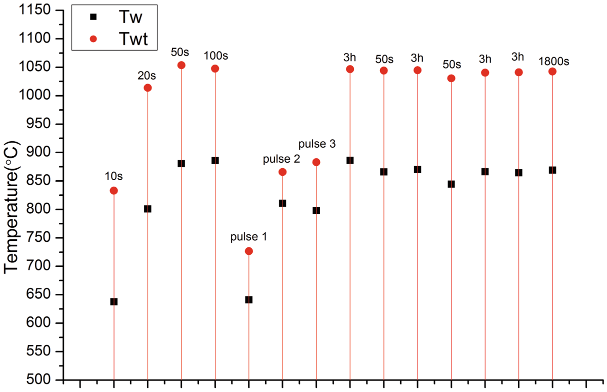


**Fig. 8.** The Temperature Curve of the New 100N Bipropellant Space Rocket during the 1800 s Long Life Hot Fire Test

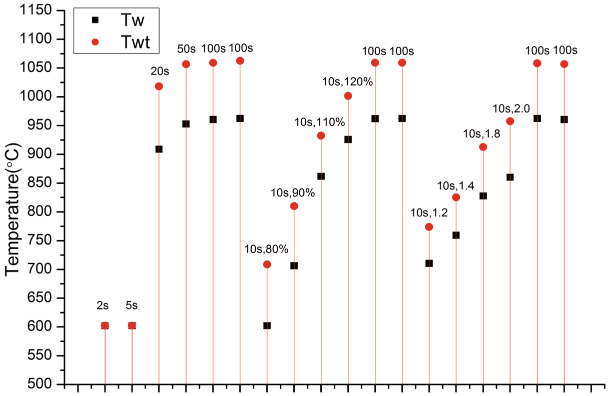
actual test, and the accumulative long-life conditions of 45000 s were obtained. The test conditions are all steady state. During the long-life firing test, the engine needs to undergo a long-term high-temperature condition, which has a great impact on the structural reliability. Figure 8 shows the variation curves of the throat temperature (Twt), nozzle body temperature (Tw), injector temperature (Ti), injection surface flange temperature (Tf), and injector weld temperature (Tic) with the test run process in the 1800 s long life steady-state life assessment of the engine. The test results show that the temperature of each part of the engine has no abnormal fluctuation, the performance is stable, the engine works normally, the maximum temperature of the body position reaches 1044.25 °C, and the temperature of the engine structure is low, which can meet the needs of long-life use.

### 4.2.4 The Temperature Change

The bipropellant engine uses the high-temperature and high-pressure gas generated during the working process to generate thrust. The temperature of the gas has a direct impact on the performance of the engine, as well as the performance of the engine. In the hot fire test of the new bipropellant 100N space rocket engine, in order to comprehensively investigate its temperature change, the temperature of the two engines was tested and counted. The engine numbers are 100N-1 and 100N-2, and the two engines are in exactly the same state, as shown in Fig. 9, the figure lists the maximum temperature of the engine during the hot fire test under each condition, which are the throat temperature (Twt) and the nozzle body temperature (Tw); the abscissa is the operating condition number. The graph lists the operating times of the engine for each operating condition.



(a) 100N-1 engine maximum temperature



(b)100N-2 engine maximum temperature

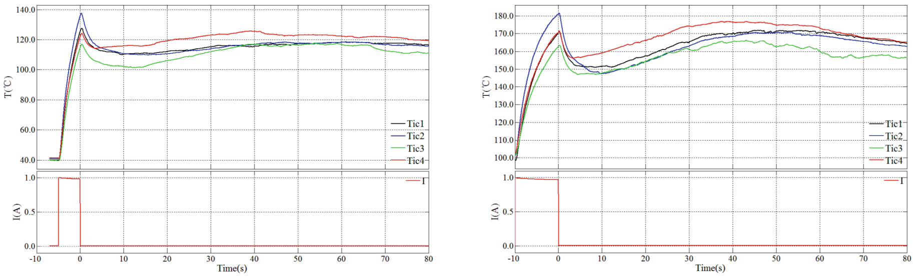
**Fig. 9.** The Highest Temperatures of the Space rocket engine during the High Altitude Simulation Hot Fire Test

For the 100N-1 engine, the maximum temperature of Tw is 886.28 °C (rated condition, 10800 s long-life firing test), and the maximum temperature of Twt is 1046.60 °C (rated condition, 10800 s long-life firing test), which is slightly higher than that in the 1800 s long-life firing test. The engine also tested the maximum temperature under pulse conditions (pulse-1, pulse-2, pulse-3). It is clear that due to insufficient combustion, the temperature is significantly lower than the steady conditions. For the 100N-2 engine, the maximum temperature of Tw is 962.43 °C (rated condition, 100 s steady state test), and the maximum temperature of Twt is 1062.62 °C (rated condition, 100 s steady state test); the engine also tested the temperature changes in the low condition (80%, 90% working conditions) and high working conditions (110%, 120% working conditions); because the working time is only 10 s, the temperature is lower than the steady state working conditions. Indicating that the working time of the engine has more significant effect on the temperature.

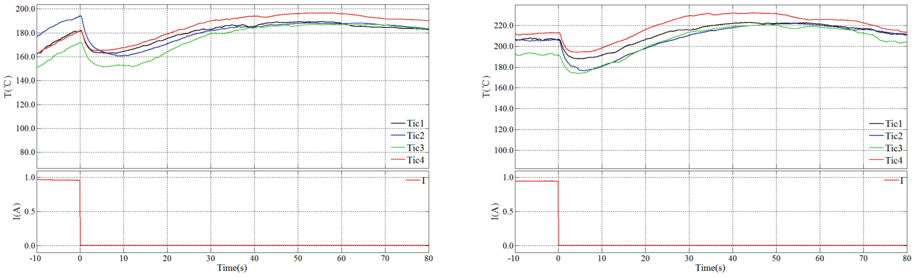
### 4.2.5 The Heat Back Temperature

During the hot fire test process of the new bipropellant 100N space rocket engine, heat back immersion often occurs, that is, the temperature of the welding seam between the engine injector and the nozzle increases after the engine is shut down. During the steady state hot firing of the engine, the highest temperature of the nozzle is located at the throat and the body close to the throat; while at the engine weld position, due to the evaporation and heat absorption of the incoming propellant, the temperature is significantly lower than that of the engine body. After the engine is shut down, the incoming propellant is cut off, the heat absorption effect of evaporation stops, and the heat of the engine body is transferred to the welding seam, causing the temperature of the welding seam to gradually increase. The heat back temperature gradually decreased after increasing to a certain extent. Because the welds between the engine injector and the nozzle need to withstand high structural strength in a complex thermal environment, as well as a complex mechanical environment during pulse operation, it needs to be paid attention to.

Figure 10 shows the change of the heat back temperature at the weld position (Tic) under different engine test state. In the figure, the change of the heat back temperature in the interval from 10 s before shutdown to 80 s after shutdown is selected. Under different steady-state test procedures, the heat back temperatures reached 125.9 °C, 176.9 °C, 196.7 °C, and 232.0 °C respectively. Obviously, with the extension of the steady-state test procedure, the heat back temperature is gradually increased. It can be seen from the figure that when the engine working time reaches 100s, the temperature of the welding seam position has also reached a stable level, that is, it will not rise continuously when the engine is turned on. Due to the temperature value, when it is turned on, the highest temperature reaches 232.0 °C. By analyzing the structural strength of the weld, it can be considered that the structure of the engine is reliable under this condition.



(a)5s steady-state (b)10s steady-state



(c)20s steady-state (d)100s steady-state

**Fig. 10.** The Changing Conditions of the Heat Back Temperature of Weld of the Bipropellant 100N Engine

# 5 Conclusion

During the development of the new bipropellant 100N space rocket engine, cold test and hot fire test were carried out. Cold flow field, steady-state hot firing, pulse-mode firing, long life hot firing and deflection were investigated.. The main conclusions are:

1) In the cold test, the injectors of two engines were tested, and the flow characteristics of the engines were relatively stable; the inner atomization cone angle was about 73°, and the outer atomization cone angle was about 123°; the droplet velocity distribution of the injector remains stable;
2) In the hot fire test study of the engine, the changes of the engine thrust (F), chamber pressure (Pc), flow rate (wo, wf), current (I) and temperature (T) in the steady state hot firing were measured. The test results show that the engine works normally under steady state conditions. After the test, the engine structure is intact and the engine performance is good;
3) The working conditions of three pulse types of 40 ms/1 s, 256 ms/1 s and 40 ms/40 ms were investigated respectively. The response time (t90) of the engine is less than 38 ms, which can meet the requirements of attitude control;
4) The engine has undergone four 10800 s long-life tests and one 1800 s long-life test, and accumulated 45,000 s long-life conditions. The maximum temperature of the engine body position reaches 1044.25 °C, and the temperature of the engine structure is relatively low, which can meet the needs of long-life use;

5) Investigate the heat back of the engine weld position, it can be seen that after the steady-state engine shutdown, the weld temperature gradually increases, and then decreases after reaching a certain level. After the steady-state working time reaches 100 s, the heat back temperature immersion exceeds the temperature during the start-up operation, and the maximum can reach 232.0 °C.

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