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Model optimization method and connected-pipe experiment of a liquid fuel ramjet engine

MA Qian-rong[1,2], GUO Xin[2], WU Hu[1], CHOU Qian[2]

(1. School of Power and Energy,
Northwest Polytechnical University, Xi'an 710072, China;
2. Aero-Engine Altitude Simulated Key Laboratory,
China Gas Turbine Establishment, Aviation Industry Corporation of China,
Jiangyou Sichuan 621703, China)

Abstract: The optimization method of a mathematical model and connected-pipe experimental technique for a test in altitude test facility (ATF) of a liquid fuel ramjet engine was researched. The optimization of the simple mathematical model was divided into two steps. Firstly, using the test engine's geometry configuration size data, a preliminary adjustment was done. Secondly, using experimental test data, the components' experiential coefficients were modified appropriately. Emphasis was laid on the simulation technique of flight condition and parameters measurement method. The experimental technique was applied to a ramjet ATF test successfully. The comparison results show that the optimized-model has higher precision and the nozzle gross thrust difference drops from 12% to about 4%.

Key words: ramjet engine; model optimization; altitude test facility (ATF);
connected-pipe experiment; simulation technique

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Nomenclature

H	Flight height	p_{t3}	Total pressure at combustor inlet section
Ma	Flight Mach number	T_{t3}	Total temperature at combustor inlet section
q_m	Air mass flow rate		
W_f	Fuel flow rate	T_{cw}	Combustor wall temperature
F_g	Gross thrust	2-D	Two-dimensional
α	Excess air coefficient	3-D	Three-dimensional

Subscripts

dp	Supersonic cruise design point	3	Combustor inlet
ref	Reference value	8	Nozzle throat
0	Free stream	9	Nozzle exit
1	Aircraft-engine interface		

Introduction

Ramjet engines have been researched at many countries, such as America, Russia, Germany etc. in 1950', and they have been used in supersonic cruise missiles successfully[1-2]. The liquid fuel ramjet engines have many advantages, such as high speed and specific impulse, comparative simple configuration and low cost. It has more promising prospect that liquid fuel ramjet engines are applied to propulsion device for supersonic cruise missiles and aerospace vehicles.

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E-mail: kingworm@yahoo.cn

As a result, the development of ramjet engines are increasing more interests in the world and becoming a hot topic renewedly in recent years[3].

The ramjet engine configuration and control system have become more complex to fulfill the wider operating regime (Mach number up to 10.0 and altitude up to 35 km) and engine-vehicle integrative design demands. Numerical analysis with engine mathematical model and experiential research with ground test facilities play increasingly important role during the whole periods of one ramjet engine development[3]. Ramjet engine mathematical model can be used to design engine, to analyze performance of the engine and its components, to improve control system[4-11]. The ground test of ramjet engine can be divided into connected-pipe experiment and free-jet experiment. The connected-pipe experiment usually aims to study engine thermodynamics characteristic, to reveal combustor burning principle, to obtain engine and its components steady performance[12-14]. The free-jet experiment can examine engine operational characteristics, matehing and maneuverability. It is necessary to combine numerical simulation with experiment, that will improve the accuracy of the model, and increase the effectiveness of the test.

Based on the individual components characteristic and experiential coefficients, authors developed a simple thermodynamic model of a liquid fuel ramjet engine. Using this model, the influence of the change in engine configuration size and components experiential coefficients on engine performance was analyzed in detail[15]. According to detailed performance analysis, optimization method of the mentioned simple model and connected-pipe experimental approach for a liquid fuel ramjet engine testing in the continuous-air-offered ATF are proposed. The experimental approach is applied to high altitude starting and performance tests of a developing liquid fuel ramjet engine successfully. Comparison between calculation performance and experimental data shows the feasibility and effectiveness of the proposed model optimization method.

1 Study engine specification

The study engine is a liquid fuel ramjet engine that can be used repeatedly. The schematic diagram and station number of the study ramjet engine are shown in Fig. 1. The study engine has a subsonic rectangle combustor with heat shield, a 2-D rectangle convergent-divergent nozzle, a set of fuel system and a set of control system. The mixed-compression supersonic inlet for matching design is a 2-D multi-shock inlet. The geometry of inlet and nozzle are fixed.

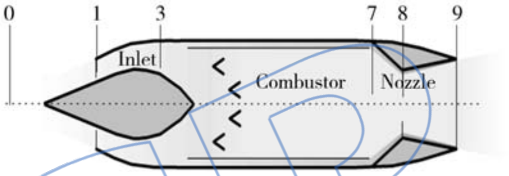

Fig. 1 Schematic diagram of the study ramjet engine

The altitude of in-flight fire point was designed at 23 km. Engine in-flight fire point is an altitude at which engine ignites and then generates thrust. The altitude of supersonic cruise point was designed at 28 km. Flight Mach number increased 0.2 following the flight track form in-flight fire point to supersonic cruise point, and the total temperatures at inlet intake are in excess of 400 ℃ within the range of the engine operating envelope. Aero-kerosene was chosen as engine fuel. This engine uninstalled the supersonic inlet when it was tested in ATF.

2 Experimental test setup

The experimental test setup for this work is in an ATF which locates at China Gas Turbine Establishment. It is a connected-pipe altitude test facility that was designed primarily for the altitude simulation test of 120 kg/s-class gas turbojet and turbofan engines. This facility can simulate flight altitudes from sea level to 25 km and flight Mach number from 0 to 2.5. It can be operated continuously for 5 hours at least[16].

ATF is one of the most complicated facilities. As shown in Fig. 2, this facility consists of cell, air supply system, air exhaust system, facility control system and synthetic information management system. Air supply system consists of compressors and heater or cooler can offer the non-vitiated requirement air which total temperature and total pressure can match the desired flight condition.

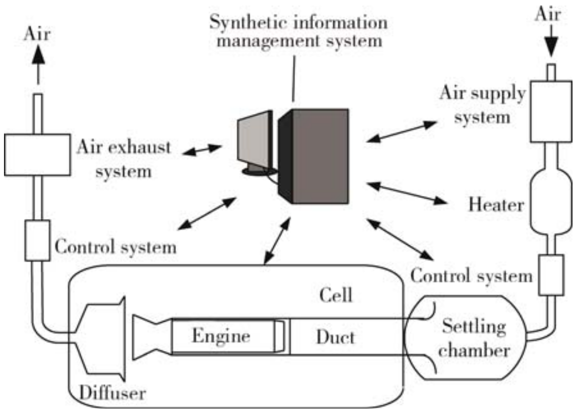

Fig. 2 Sketch map of the ATF

The heater has a capacity of 500 ℃，but the pipeline and valve of air supply system can only survive about 200 ℃. In order to obtain the altitude pressure environment，air exhaust system with diffuser and compressors capture and pressurize the high temperature gas exhausted from the engine nozzle. The ramjet engine is installed on the cell's thrust stand. The ATF is also equipped with many sensors，pressure probes and thermocouples to measure temperature，pressure，axial-force，air flow rate，fuel flow rate and vibration etc. The maximum of the axial-force and fuel flow rate are 196 kN and 45 000 kg/h，respectively. The synthetic information management system is available for acquiring，processing，monitoring and displaying data continuously in real time during testing.

In order to meet with the demands of the ramjet engine test，the upgrade had been completed before experiment study，including adding a set of high temperature pipelines and valves in the supply stream，replacing the cell's thrust stand and engine-installed rig，fixing a settling chamber in the cell to improve the aerodynamic flow field uniform at the combustor inlet，designing a new connect-duct to measure the air flow rate.

3 Model optimization method

3.1 Simulation model

A simple thermodynamic model is programmed for the cycle design calculation and the performance analysis of a liquid fuel ramjet engine. In this program，the specific heat is a function of the temperature. This model is a equivalent one-dimensional tool based on following hypotheses：

1) The thermodynamic process is adiabatic without energy exchange between the ramjet engine and the environment.

2) Some components' coefficients are setup by experience，such as the combustion efficiency and the pressure loss coefficients.

3) The inlet characteristics is calculated based on one-dimensional chock theory and set a appropriate coefficient to take into account the pressure loss inducing by the complicated three-dimensional interaction of the multiple shock and expansion waves and boundary-lay when the supersonic airflow passes through the whole inlet.

4) The rectangular combustor is a duct with constant area.

5) The pressure loss coefficient of the divergent part of the nozzle is determined based on one-dimensional chock theory when a shock occurs in this part.

3.2 Model optimization

Usually，the configuration sizes of the test engine are generally different from the design values predefined by the thermodynamic cycle simulation because of manufacture errors. So the mentioned simple thermodynamic model is optimized by taking following two steps in this paper based on the performance analysis of this test ramjet.

Firstly，using the actual geometry configuration size data of the test engine，a preliminary adjustment has been done. It is the major work that adjusting the inner wall outline dimension of the inlet to match with the test ramjet. To redesign the inlet，the actual values of the test engine are replaced for the throat area，the exit area of the nozzle and the combustor area of the simple thermodynamic model. Secondly, using experimental test data, the components' experiential coefficients are modified appropriately. The results of the combustor performance tests are used to modify the experiential coefficients of the combustor, such as the combustion efficiency and pressure loss due to heat addition. The results of the air-start tests of the ramjet are used to modify the pressure loss coefficient before the ramjet ignited. The results of the ramjet performance tests are used to adjust the experiential coefficients of the nozzle, such as the thrust coefficient and the pressure loss. After completing the mentioned modifications, the geometry configuration size is redesigned and then the new inner wall outline dimension of the ramjet inlet is obtained.

Fig. 3 shows the flow chart of the model optimization, and the optimization model is developed from the primary simple one with the modified components' experiential coefficients and the new inlet outline dimension.

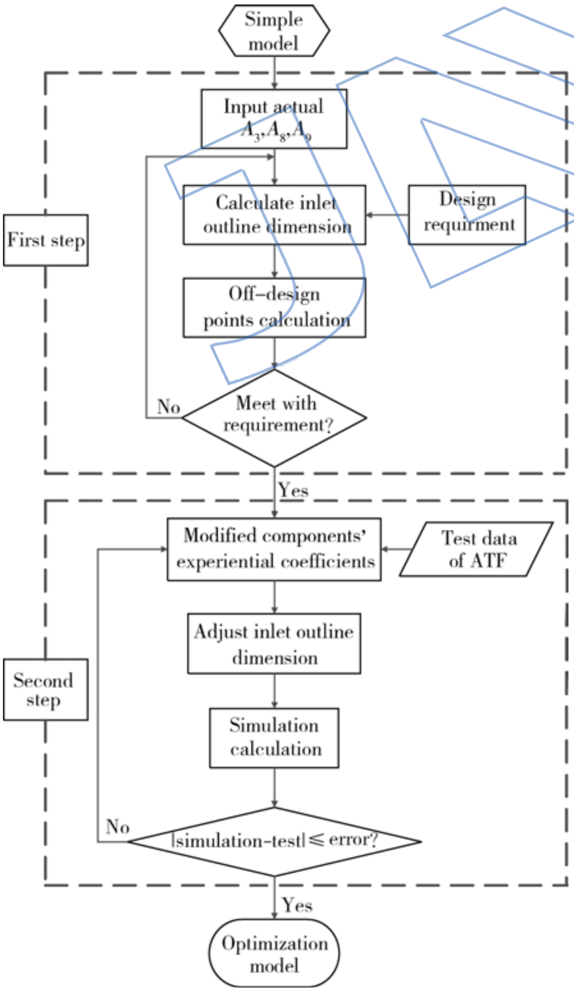

Fig. 3 Flow chart of the model optimization

4 Experimental approach

The connected-pipe experiment of ramjet engine in ATF simulates the engine inner flow by controlling the flow field of combustor inlet section and engine exhaust pressure to correspond with the expected flight condition[17]. In this way, the engine performance of the chosen test points in the operating envelope can be obtained.

4.1 Test challenges

Because the altitude and Mach number in the operating envelope are high and engine net thrust is small, the connected-pipe experiment of the study ramjet in ATF faces the following three challenges:

1) How to simulate the flight altitude, which exceeds the design capacity of the ATF?

2) The mass flow rate is an indirect simulation parameter. At some given flight conditions, during the whole process from ignition and starting engine to shut down, how to keep air mass flow rate unchanged?

3) Some parameters, such as air mass flow rate and thrust etc. are very small. How to improve test accuracy and measure them accurately?

4.2 Altitude simulation approach

The altitude of the supersonic cruise point of the study ramjet engine is at 28 km, and corresponding pressure is 1586 Pa. But the designed maximum altitude that the ATF could simulate is at 25 km and corresponding pressure is 2 511 Pa. In the past tests, the altitude had reached beyond 22 km and corresponding pressure is 4000 Pa. In other words, the lowest exhaust pressure that had been verified is more higher than the expected value.

To reduce pressure of the cell, the method of altitude simulation is taken as follows:

1) Chose the pressurization scheme of

series-parallel connection three stages. This scheme is optimized by reasonably matching the volume flow and pressurization ratio of every stage, thus it is ensured that the compressors of air exhaust system could run normally accompany with very high pressurization ratio.

2) Design a new diffuser of air exhaust system, based on numerical analysis of integrating the ramjet, cell and diffuser. This diffuser is used as the first-stage pressurizer to further raise the total pressurization ratio.

3) Control the secondary flow rate in the cell by dealing with the holes at the cell wall to decrease the leakage as much as possible. The secondary flow rate should meet with the requirement of cooling the measure instruments and equipments in the cell.

4.3 Air mass flow rate simulation approach

At a certain flight condition, the performance is different between ramjet engine with fixed geometry and turbojet and turbofan engine. The air mass flow rate of the former remains unchanged with fuel flow rate increase but the invariable parameter of the latter is entry total pressure. According to the study ramjet operating characteristic, the combustor entry total pressure increases with the temperature rise at nozzle throat section. The change of the combustor entry total pressure is estimated before tests using the thermodynamic model.

Air mass flow rate is usually an indirect control parameter when engine is tested in ATF while total pressure can be changed directly. Mass flow rate meets with the demand through adjustment the pressure. Unfortunately, the numerical analysis could not estimate the exact total pressure at combustor entry as well as the variety rate of this total pressure. A new combination control scheme is used to fulfill the simulation requirement of the constant air mass flow rate. The schematic diagram is shown in Fig. 4.

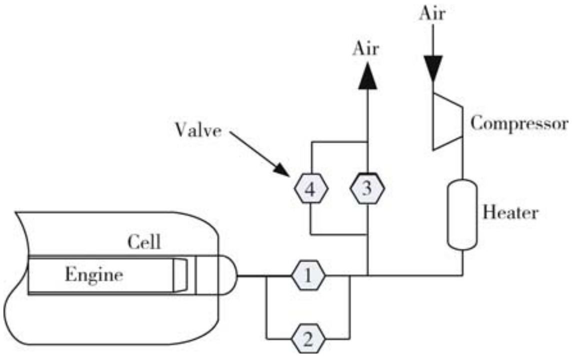

Fig. 4 Control scheme of the mass flow rate at combustor intake

The combination control scheme install four valves at the channel of the ATF air supply system. No. 2 and No. 4 are bypass valves and allow a little air to pass through. Valve No. 1 and No. 3 are first set at the suitable valve position with reference to the estimate value of the total pressure before igniting. Then the two bypass valves are adjusted to make the air mass flow rate getting into engine consistent with the requirement. When the engine runs at steady states, the automatic adjustment pattern based on feedback control technique is used to keep engine entry total pressure. Before changing excess air coefficient, the valves' control pattern switches to manually operate and maintain the valves' position. The upstream pressure of valves No. 1 and No. 2 should be high enough to keep them supercritical state during the whole test process. Only this could ensure that air mass flow rate should not change with fuel flow rate increase or decrease.

4.4 Measure improvement

To get the performance of the study ramjet engine, a lots of sensors, pressure probes and thermocouples are equipped which are used to measure temperature, pressure, axial-force, air flow, fuel flow and vibration etc. But because thrust and fuel flow rate of the test engine are very small as well as the cross sections' shape is rectangle, it is necessary to improve measure precision. The main measure improvements included:

1) A axial-force stand of very small range is installed to replace the 196 kN one in the cell of the ATF. Based on the analysis and calculation,

the thrust influence coefficient is determined by tests.

2) A new circular duct is designed to measure engine airflow. Because the section area of the new duct is smaller than that of the combustor entry section, Mach number of the flow is higher. The circular duct linked to the rectangle combustor by means of a connecting duct that its' generating line is designed utilizing 3-D graphics software.

3) Two turbine flowmeters of small range are installed to measure the fuel flow. The maximums of the two flowmeters are 234 kg/h and 286 kg/h. Comparing with the original measure instrument that the maximum is 45 000 kg/h, their range is very small.

5 Result analysis

5.1 First step adjustment results

The first step adjustment is completed by inputting the actual width, combustor section area and nozzle throat area of the test engine into the simple thermodynamic model. The combustion efficiency, excess air coefficient and pressure loss coefficient of inlet of design point are constants. Comparing with the primary design parameters, the relative change of the geometry configuration sizes and the performance of design point is shown in Table 1.

From Table 1, it is known that an increase of the nozzle throat area means a raise of circulation capacity when pressure loss coefficient is constant, so the capture area and minimum section area of the inlet also increase. As the result, the air mass flow and net thrust increase corresponding. The change of nozzle outlet area is remarkable because the nozzle of the test engine is cut short. The primary nozzle is designed at full expansion mode while actual nozzle work at incomplete expansion mode.

Table 1 Results of first step adjustment

Parameters		Relative change/%
Width of the test engine/m		2.08
Inlet	Capture area/m^2	8.61
	Height/m	6.11
	Minimum section area/m^2	8.62
Combustor	Section area/m^2	4.73
	Height/m	2.09
Nozzle	Throat area/m^2	8.83
	Outlet area/m^2	−19.24
Design point	Air mass flow rate/(kg/s)	8.62
	Net thrust/daN	6.48
	Specific impulse/s^{-1}	−1.96

5.2 Test results

A combustor test and three engine tests are completed successfully in the upgraded ATF. The flight conditions and the simulation fidelity of the typical air-start and performance test points are shown in Table 2. The last point is the supersonic cruise design point. Fig. 5 gives the changes of air mass flow rate of two performance test points with the excess air coefficient.

From the Table 2, it is known that the differences of the flight height and total temperature at combustor inlet section are smaller than

Table 2 Flight condition and their simulation fidelity of the test points

Case	Flight condition		Difference between the simulation and remand		Test item
	H/km	$Ma-Ma_{dp}$	ΔH/km	ΔT_{t3}/K	
1	23	−0.2	⩽0.2	⩽3.0	Start
2	25	−0.2	⩽0.2	⩽3.0	Start
3	23	−0.2	⩽0.2	−7	Performance
4	28	0	−1.3	−88	Performance

the simulation tolerance error for the cases 1, 2 and case 3, but the simulation fidelity of the case 4 does not reach the demand. The simulated total temperature and flight height of the design point drops 88℃ and 1.3 km comparing with the demand. The Fig. 5 shows that the air mass flow rate are almost invariant with the change of the fuel flow rate for the performance test points.

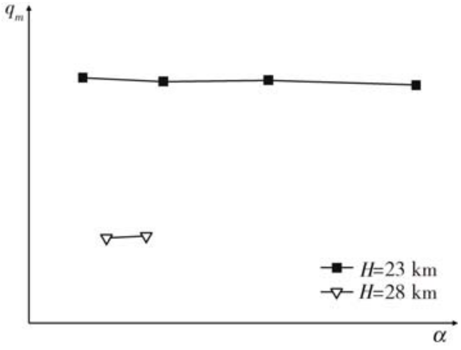

Fig. 5　Air mass flow change with α

For the case 2, the Fig. 6 gives the variable trends of the parameters such as combustor inlet total pressure p_{t3}, engine air mass flow rate q_m, fuel flow rate W_f and combustor wall temperature T_{cw} when excess air coefficient α is 10. The calculated combustor inlet pressure $p_{t3,c}$ based on optimized model is also given. Fig. 6 shows that q_m is fluctuating and p_{t3} is increasing suddenly when combustor is lighted successfully and the increase degree of p_{t3} is consistent with the calculated results.

The performance test states are shown in Table 3. The Fig. 7 shows the variable trends of q_m, W_f, p_{t3} and gross thrust F_g with the change of α. Fig. 8 and Table 4 give the difference between the test results and prediction values based on the simple primary model, and the gross thrust difference ΔF_{g2} between the calculated values based on optimized model and test results are also shown in Fig. 8 and Table 4. The difference in Fig. 8 and Table 4 is calculated according to the following formula.

$$\text{difference} = \frac{\text{calculation value} - \text{test data}}{\text{calculation value}} \times 100\%$$

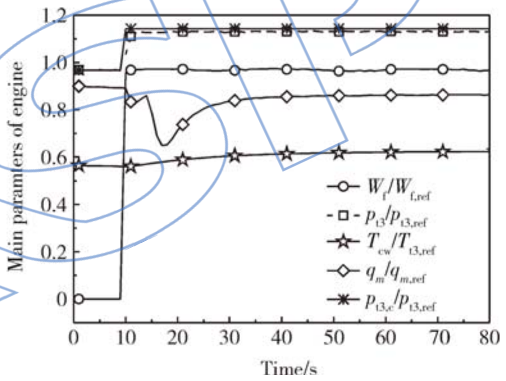

Fig. 6　Change of paramenters during start process

Table 3　Performance test points

Flight condition case	3				4	
State No.	1	2	3	4	5	6
Excess air coefficient α	3.18	2.58	2.15	1.82	2.079	1.917

From the Fig. 7, the parameters such as W_f, p_{t3} and F_g decrease with the increase of α when q_m is almost kept constant. The change tends of these parameters agree with the analysis results.

The Fig. 8 shows that, comparing with the calculation values based on the simple primary model, the test datas of q_m and W_f are less, and the test p_{t3} is higher in the three test states (2, 3 and 4), and the test F_g is apparently less. The maximum difference of F_g is beyond 12% and it mainly owes to q_m and W_f being error. The difference between the calculation values and test data drops down to about 4% after the model optimization. The decrease of difference depends on the following model adjustments:

1) Modifying model structure and using test data of q_m, W_f, p_{t3} and T_{t3} as model input to diminish the influence by the error of q_m and W_f.

2) Adjusting combustor characteristic parameters. Combustor efficiency is modified appropriately. Moreover, the cool drag coefficient

obtained by the combustor air-start test is used to replace the unchanged one of original program. Cool drag coefficient is caused by the pressure loss when the combustor isn't ignited.

3) Adding the influence correction of nozzle throat area caused by temperature change.

4) Decreasing appropriately the nozzle thrust coefficient in consideration of the influence of the wall cool air on the nozzle heat transfer.

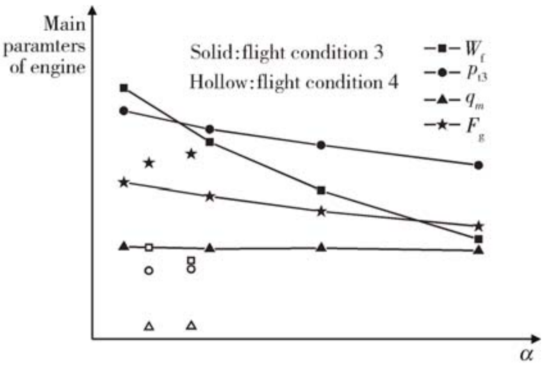

Fig. 7 Changes of parameters with α

Table 4 Difference between prediction values and test results

State No.	ΔW_f/%	Δp_{t3}/%	Δq_m/%	ΔF_{g1}/%	ΔF_{g2}/%
1	3.86	1.2	3.87	11.32	3.56
2	2.34	−0.55	2.33	10.33	4.10
3	2.03	−0.92	2.56	9.42	3.67
4	1.36	−1.98	1.38	9.14	4.67
5	0.38	3.87	0.35	6.8	1.00
6	1.23	7.19	1.28	12.21	3.27

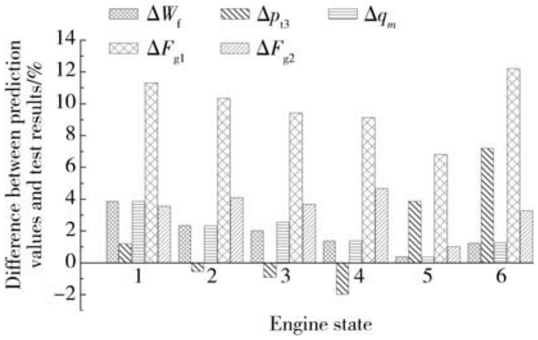

Fig. 8 Difference between prediction values and test results

6 Conclusions

The model optimization method and relative test technique are researched to satisfy the connected-pipe experiment demand of a liquid fuel ramjet engine testing in one ATF. The study outcome is applied successfully to the air-start and performance tests of a ramjet engine. The important results included:

1) The simulation method of flight altitude and air mass flow rate can be applied directly to connected-pipe experiment of ramjet engine test in ATF, and four sets of flight conditions required by the study engine are also almost simulated exactly.

2) The measure improvements of air mass flow rate, thrust and fuel flow rate enhance the experimental parameters precision of a low velocity and airflow engine.

3) The prediction values of the simple model optimized by numerical analysis, actual geometry configuration sizes and the ATF experimental data are in good agreement with the test data. The nozzle gross thrust difference drops from 12% down to about 4% after the model optimization.

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