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RESEARCH AND VALIDATION OF SYSTEM MODELING AND SIMULATION OF INTAKE AIR MIXER ALTITUDE TEST BED

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Abstract:

High precision simulations of intake condition and flight environment are practical as well as important issues in simulated altitude test facility. Although numerous researches have been published to examine the characteristics on control component modeling simulation technology, very limited studies focused on dynamic system modeling of large-complex test facility, which is of vital importance for performance evaluation of aero-engine. This paper reports the intake air mixer dynamic behaviors by using object-oriented modeling method for better feasibility. A system simulation mathematical model including valves, flame extinguishing and ejector of altitude test bed was established, and a simulation model of the test bed which is consistent with the actual test bed was built. The simulation results indicate that the simulation system could reflect the dynamic behavior effectively of the actual test bed, the mathematical models of the system were reasonable. The influence of mixer temperature change on the front chamber temperature was simulated. With the increase of mixer temperature, the front chamber could reach a higher temperature. The largest relative error of the intake air pressure is less than 1%, and the largest relative error of the temperature is less than 5% at the whole simulation process. The system modeling and simulation method in this paper can provide a significant reference for virtual test bed.

Key words:

Altitude Test Bed; System Simulation; Experiment and Simulation; Modeling Technology

1 Introduction

With the rapid development of modern aviation science and technology, the requirements of aeroengine in performance, reliability and airworthiness are higher and higher, and higher requirements for high altitude simulation test are put forward [1]. On the one hand, with the continuous development of test subjects, the requirements of increasing test complexity and reducing test cost are put forward for the test; on the other hand, with the increase of test difficulty, the requirements of reducing test risk are further put forward for the test. Through the system modeling and simulation technology, we can evaluate the performance of each subsystem in the test, optimize the test technology and process effectively, reduce the test cost and risk, and improve the test efficiency[2][6].

In some countries, modeling and simulation methods of high altitude simulated test facility started earlier and developed at a higher level, as well as many technologies have entered the stage of engineering application. AEDC[7](American Engineering Development Center) carried out the research on modeling simulation and simulation technology of high-altitude test system around

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2000, developed the real-time mathematical simulation model of test equipment, formed a simulation system that can carry out virtual test on PC, shortened the integrated debugging time of new equipment from several months to several weeks, and effectively improved the test efficiency. NASA Green Center [8]carried out a full set of system modeling and simulation work on the new high altitude simulation equipment of the US Army laboratory, carried out a lot of model analysis and research, optimized the system parameters, balanced the performance of each part before the final scheme was determined, and saved the test cost. A real-time system simulation model of high altitude simulation test bed is developed for the ATF high altitude platform of the Institute of Aeronautical propulsion system (ILA) of Stuttgart University in Germany[9]. The model can design and verify the control system and control algorithm without damaging the test equipment and engine, thus reducing the test risk. In China, research on simulation and modeling technology of large-scale and complex equipment system mainly focuses on missile, aircraft, ship and other fields [10]-[12]. Research on the system modeling and simulation method of aero-engine altitude simulation test facility is less. Sichuan Gas Turbine Research Institute of China Aviation Development Corporation has carried out theoretical modeling research on some subsystems of altitude simulation test bed, but it is outstanding with foreign industries There is still a gap between the results.

The simulated test facility is complex and has the characteristics of interdisciplinary "physics" and "information" cross fusion. The results of system simulation directly depend on the accuracy of simulation model. Therefore, it is of great significance for the development of aero-engine to establish the accurate mathematical simulation model of each system of the high-altitude simulated test facility, to analyze the model as well as to study the complex coupling process within each component. In this paper, a complete virtual simulation system corresponding to the actual test system is built through the self-built basic model base and parts of the standard base for the basic components, such as intake system, exhaust system and each pipe valve of a domestic aero-engine altitude simulation test bed. The simulation results are compared with the test data to verify the correctness of the system model. On this basis, the parameters of the front chamber and mixer are considered when the outlet temperature of the mixer is 220 ℃. Through the research of system modeling and simulation, we can make full use of system simulation technology to promote the development of virtual test and improve the level of simulation technology.

2 The test facility system

The main composition of a typical altitude test facility system is shown in Fig.1, which includes intake system, test bed system and exhaust system. During the test, the intake air is obtained by the supply unit, and it is divided into multiple streams with different conditions. After that, several streams are mixed in a mixer and flow through the flow tubes to the engine in test. At last, the high temperature and pressure off gas exhaust from the engine and the second flow are all discharged by the exhaust system. The temperature and pressure are adjusted by the mixer, and finally enter the test cabin through the pipeline. In the high-altitude simulation test-bed system, the intake parameters of the engine can be adjusted by controlling the valve state to change the air flow resistance. The gas discharged from the engine enters the flameout section of the cooler for cooling. The cooled gas is pressurized by the air extraction unit and then discharged to the atmosphere. The cabin pressure is adjusted by controlling the valve status in the test bench system. In this way, the altitude test facility can provide flight conditions of the aero-engine on the ground.

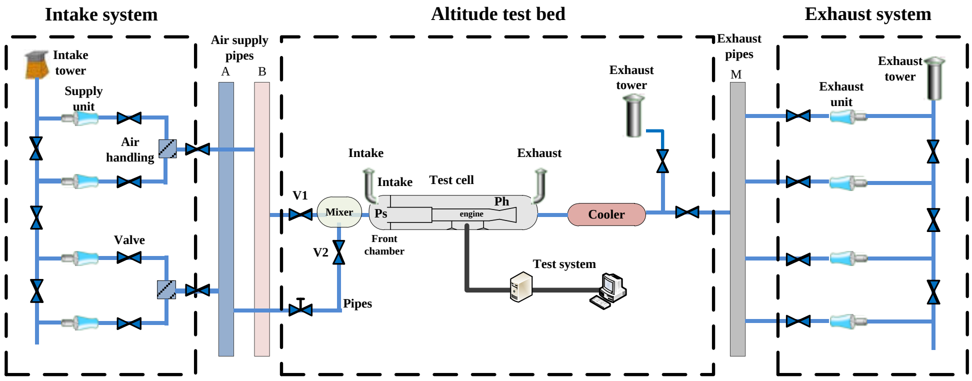


Fig.1 Sketch of a typical altitude test facility

3 Mathematical Modeling of system

In the system simulation, the accuracy of the mathematical model is of crucial importance The high-altitude simulation test facility is composed of basic components such as pipes, valves, ejectors, flame extinction sections, etc. Therefore, in this paper we first establish a corresponding mathematical model based on the basic principles of the components, through the respective control equations. Then through the established component model, the virtual simulation system corresponding to the actual test system is built. Finally, the simulation and verification of the system are carried out to obtain the working characteristics of typical valves.

3.1 Valve

The valve is an important component of the high-altitude simulation test facility system. The flow of fluid can be adjusted by the movement of the valve core. For the high-altitude simulation test facility system, there are mainly two kinds of valves, plunger valve and butterfly valve, which can be regarded as the combination structure of variable orifice and closed chamber. In this case, the basic mathematical equations describing the two kinds of valves can be obtained by using the continuous equation and isentropic relationship.

3.1.1 Plunger valve

There are many valves in the high-altitude simulation test system. At different pressure and flow regulating positions, flow coefficients of the same valve may be different. According to the conservation equation, the plunger valve model equation is obtained as follows:

$$W_a = \begin{cases} \alpha A\sqrt{\dfrac{p_1\left(p_1 - p_2\right)}{RT}} & \dfrac{p_1}{p_2} \le 1.89,\ \text{Subcritical} \\ C_m \alpha A \dfrac{p_1}{\sqrt{T}} & \dfrac{p_1}{p_2} > 1.89,\ \text{Supercritical} \end{cases}$$

Where：

α : the flow coefficient

A: circulation area

p_1: Inlet pressure

p_2: Outlet pressure

R: Gas constant

T: Total temperature

According to different engine working conditions, the required air supply flow is not the same. In high-altitude simulation test, the air supply pipe network should be reasonably equipped to meet the needs of engine test. In the pipe network system, the diameter of the gas supply pipeline is not equal, so the valve diameter connecting different pipelines is not the same, and the valve flow coefficient of different diameters is different. The diameter of the plug valve described in this paper can be divided into three sizes: 400mm, 800mm and 1400mm. The corresponding empirical formulas of flow coefficient are as follows:

$$\alpha = \begin{cases} 0.0004CF + 0.4077 & d = 400\text{mm} \\ -0.0051CF + 1.0347 & d = 800\text{mm} \\ 0.0015CF + 0.4077 & d = 1400\text{mm} \end{cases}$$

Where CF is the valve opening.

3.1.2 Butterfly valve model

The butterfly valves in the pipe network of air simulation test bench are mainly hydraulic butterfly valves and electric butterfly valves, of which working principles are basically the same. The air flow can be opened, closed or regulated through the reciprocating rotation of the disc type opening and closing parts. The basic principles are shown in Figure 2.

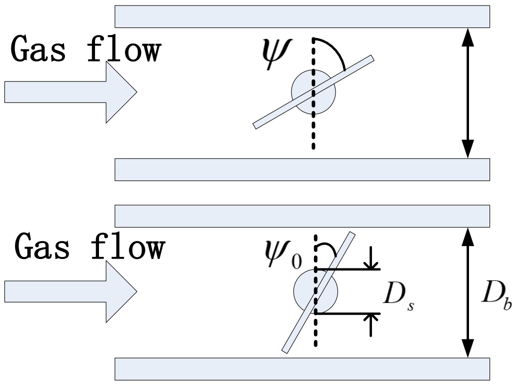


Fig.2 working principle of butterfly valve

The main parameters of butterfly valve model include: pipeline diameter, butterfly valve diameter and dynamic characteristics of opening / closing. According to the working mode of butterfly valve, the mathematical model is established as follows:

$$\frac{4A}{\pi D_b} = \left(1 - \frac{\cos\psi}{\cos\psi_0}\right) + \frac{2}{\pi}\left(q + r - s - t\right)$$

Where：

$$q = \frac{a}{\cos\psi}\left(\cos^2\psi - a^2\cos^2\psi_0\right)^{1/2}$$

$$r = \frac{\cos\psi}{\cos\psi_0}\sin^{-1}\left(\frac{a\cos\psi_0}{\cos\psi}\right)$$

$$s = a\left(1 - a^2\right)^{1/2}$$

$$t = \sin^{-1} a$$

$$a = \frac{D_s}{D_b}$$

3.2 Flame extinguishing section

The working principle of the flameout section is shown in Fig. 3. The direct injection of water is used to reduce the gas temperature of the engine to about 50 ℃ and enter the air extraction unit. In the modeling, the partial pressure of water vapor in the mixed gas is calculated by Antoine equation according to the working principle of flameout section, and then the mole fraction of water vapor in the mixed gas is calculated by Dalton's law of partial pressure, and then the mass ratio of water vapor to air can be deduced, at last the mass flow of water vapor can be calculated.

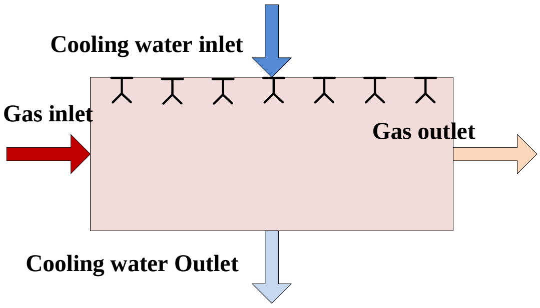


Fig 3 Working principle of flameout section

The Antoine equation is:

$$\log p = A - \frac{B}{C+T}$$

When t is 1 ℃ ~ 100 ℃, a = 8.07131, B = 1730.63, C = 233.426; when t is 99 ℃ ~ 374 ℃, a = 8.14019, B = 1810.94, C = 244.485. Where p is the saturated vapor pressure at the corresponding temperature T, in mmHg.

For the ideal gas, the total pressure of the gas mixture is equal to the sum of the partial pressures of the gas components, as well as the flameout section gas is close to this ideal state. According to Dalton's law of partial pressure:

$$x_i = \frac{p_i}{p} = \frac{n_i}{n}$$

According to the calculated mole fraction of water vapor in the mixed gas, the mass fraction of water vapor relative to air is converted as follows:

$$m_i = \frac{x_i}{1-x_i}\frac{n_i}{n_{air}}$$

Where, m_i is the mass fraction of water vapor relative to air and n_{air} is the molar mass of air.

According to the law of conservation of energy, the energy (internal energy of gas and cooling water) entering the flameout section is equal to the sum of latent heat of gasification, internal energy of liquid water, internal energy of water vapor and internal energy of air after cooling. According to thermodynamics theory:

$$\dot{m}_{air}c_{pair}T_1 + \dot{m}_w c_{pwl}T_w = \dot{m}_{wgas}c_l + \left(\dot{m}_w - \dot{m}_{wgas}\right)c_{pwl}T_2 + \dot{m}_{wgas}c_{pwgas}T_2 + \dot{m}_{air}c_{pair}T_2$$

Where, $\dot{m}_{air}$ is the mass flow of gas, c_{pair} is the specific heat of gas, $\dot{m}_w$ is the mass flow of water spray, c_{pwl} is the specific heat of water, $\dot{m}_{wgas}$ is the mass flow of water vapor, c_l is the latent heat of water, T_1 is the temperature of gas, T_W is the temperature of water, T_2 is the temperature of mixed gas.

3.3 Ejector model

The ejector is located at the rear end of the down flow direction of the high-altitude chamber. When the engine is running, the high-speed air jet from the nozzle is discharged through the ejector. At this time, due to the ejector action, part of the test cabin gas will be taken away, resulting in the pressure reduction in the test chamber. The test chamber has two stream intake valves, and the outside air flows into the test cabin through the intake valve to ensure the pressure balance in the chamber. The relationship is established to describe the amount of air flow taken away by the injection. The mathematical model equation is:

Then mass conservation: $m_1 + m_2 = m_3$

The momentum conservation: $m_1 u_1 + p_{s1} A_1 + m_2 u_2 + p_{s2} A_2 + m_3 u_3 + p_{s3} A_3 + F_{friction} = 0$

The Conservation of energy: $m_1 c_{p1} T_{t1} + m_2 c_{p2} T_{t2} = m_3 c_{p3} T_{t3} + Q$

The area relation: $A_1 + A_2 = A_3$

Where, subscript 1 is the main flow, subscript 2 is the secondary flow and subscript 3 is the mixed flow. m is the gas flow rate, u is the air flow rate, a is the area, $F_{friction}$ is the momentum loss of wall friction, p_s is the static pressure, Tt is the total temperature, Q is the heat exchange.

3.5 Simulation model of test bed

On basis of the above component model, according to the principle of high-altitude simulation test system, combined with self-built model base, pneumatic base, signal base and other relevant components, the simulation model of test bench is as shown in Fig 4. The working principle of the simulation system is consistent with that of the actual test bench. During the calculation, the parameters of each component are set according to the characteristics of the model, in which the input and output boundaries are the pressure-temperature boundary conditions of the test point, the valve opening is controlled by the external function, the initial pressure and temperature of each system cavity are the same as the local atmospheric conditions, and the components are set according to the test data and the standard library model. The characteristic parameters are corrected and calibrated, as well the simulation system parameters are input. By the simulation model of test facility, the temperature, pressure and flow parameters of each component in the system can be calculated. Meanwhile, by adjusting the valve opening, we can get the air intake and environmental conditions which are requisite for engine test, as well as we can complete the simulation of the virtual test system in the high-altitude facility.

Mathematical models give an insight into the test bed characteristics and model physics during simulation. The conservation laws and equations of motion act as starting point to develop this dynamic math-model. The simulation model of test bed system is shown in Fig.4

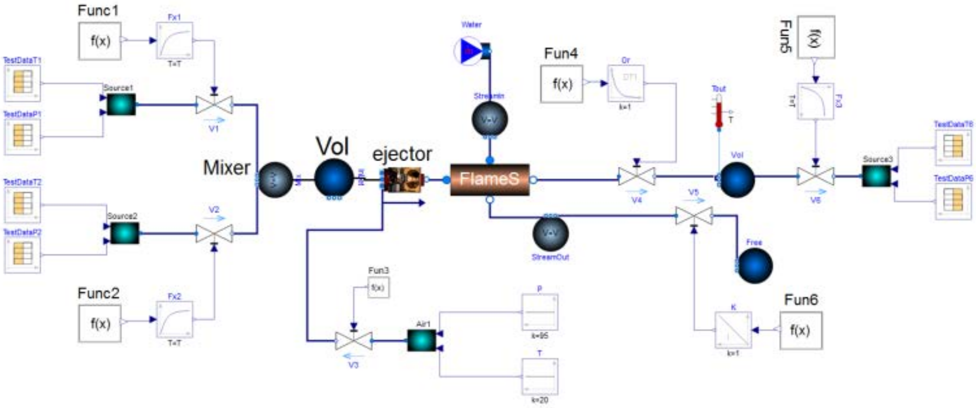


Fig.4 Simulation model of test bed system

4 Results and discussion

4.1 Model validation

In order to check the accuracy of the aforesaid model, according to the actual behavior and properties of the test-bed system, the valve, flameout section and ejector model established in this paper are respectively verified by using typical pressure change curve and test points.

4.1.1 valve

In order to meet the requirements of the parts model universality of aerial platform, the valve model is built as well the simulation verification model, as shown in Fig 5. The valve inlet pressure function is set as P (T) = 95 + 60t (kPa), where, t is the time, the valve outlet pressure is set as 95kPa, and the simulation time is 6s. The simulation results of different diameter plunger valves and butterfly valves are shown in Fig. 6 ~ Fig. 9. From Fig. 6 ~ Fig. 8, it can be seen that the simulation results of plunger type regulating valve and standard reservoir throttle valve established in this paper are very consistent. Under the same valve opening, the valve flow decreases with the increase of the pressure ratio between the inlet and the outlet, and the calculated flow error of the self-built valve in the whole simulation process is less than 1% compared with the standard valve, as well as the current pressure ratio, etc. at 1. The pressures at the inlet and outlet of the valve are equal, and the flow is 0. There are differences in the flow rate of valves with different diameters, which is caused by different flow area and flow coefficient. The larger the flow area is, the larger the flow rate is under same pressure ratio, as well as the flow characteristic change curve is consistent with the change rule of the simulation results in the standard model. The three kinds of plunger valve models established in this research are all meet the engineering requirements.

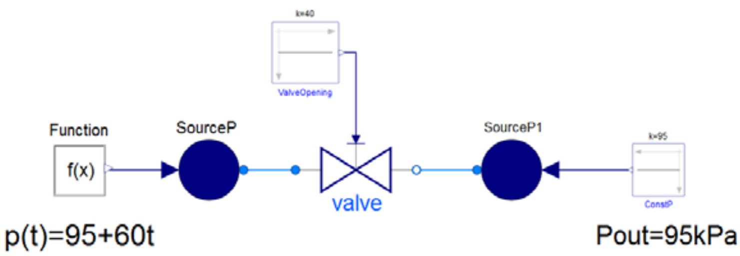
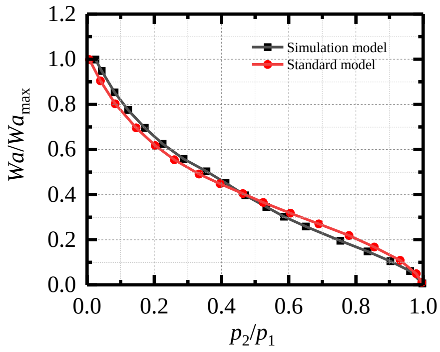
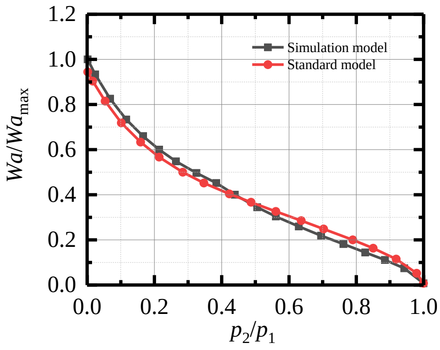


Fig 5 Valve model verification loop

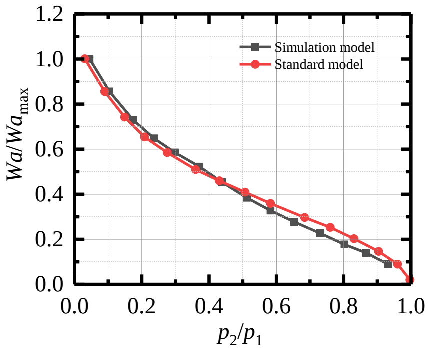


(a) valve opening (40%)

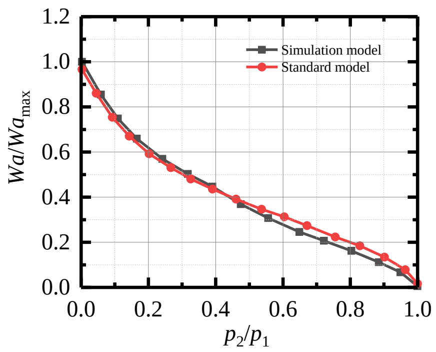


(b) valve opening (100%)

Fig.6 Pressure ratio flow characteristic curve of plunger valve with diameter of 400mm

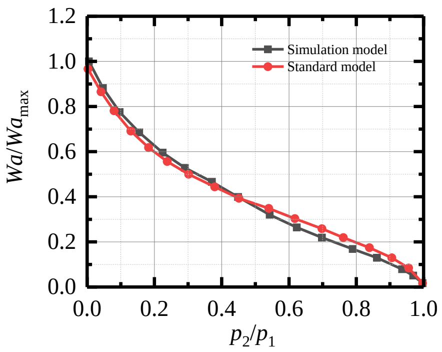


(a) valve opening (40%)

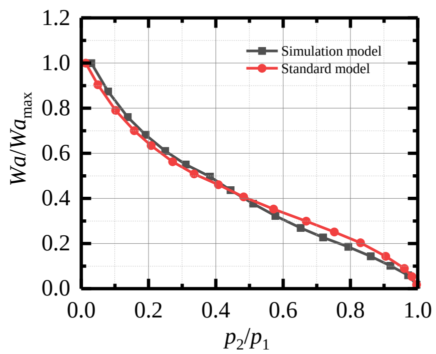


(b) valve opening (100%)

Fig.7 Pressure ratio flow characteristic curve of plunger valve with diameter of 800mm

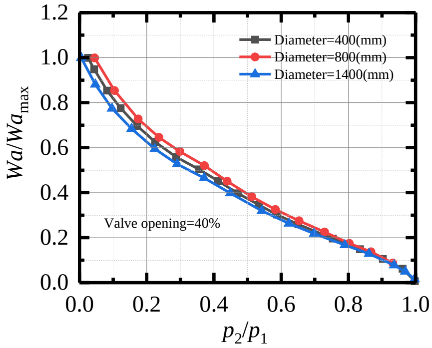


(a) valve opening (40%)

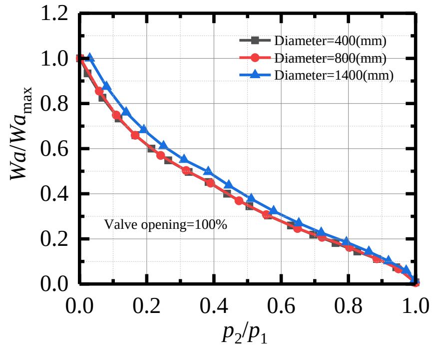


(b) valve opening (100%)

Fig.8 Pressure ratio flow characteristic curve of plunger valve with diameter of 1400mm



(a) valve opening with formula modeling (40%)



(b) valve opening with formula modeling (100%)

Fig.9 Pressure ratio flow characteristic curve of different diameter plunger valve

Fig.10 shows the differential pressure flow curves of butterfly valves with different valve openings, such as the openings of 1.4 rad and 0.4 rad respectively. The valve opening area is calculated by input angle, and then the flow can be calculated. It can be seen from Fig.10 that under the same valve opening, the larger the pressure difference is, the larger the flow is. When the opening is 1.4 rad, the valve is close to full open. At this condition, the valve flow reaches its maximum value. When the opening is 0.4 rad, it is in the common working range of altitude facility butterfly valve.

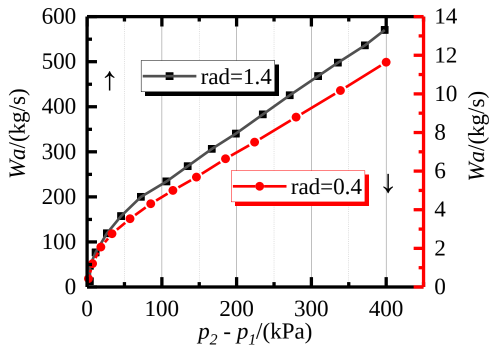


Fig.10 Differential pressure flow characteristic curve of butterfly valve

4.1.2 Flameout model

According to the basic theory of flameout section, the established verification circuit of flameout section is shown in Fig.11. The inlet and outlet conditions of the flameout section are input by the standard boundary condition model, the cooling water is driven by the pump, and the valve opening remains unchanged.

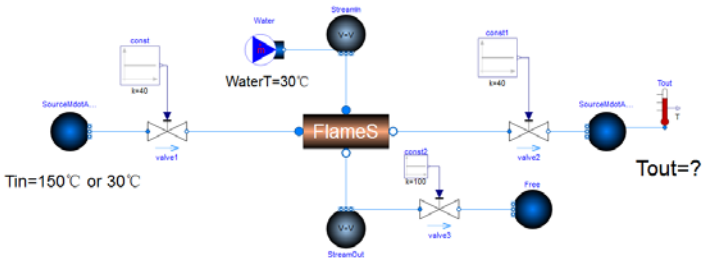


Fig .11 Model verification circuit of flameout section

The main simulation conditions are shown in Table 1. The air mass flow at the model inlet is 160kg/s, the air inlet temperature are 150 °C and 30 °C, the water inlet temperature is 30 °C, as well the relative humidity are 50% and 0%, respectively.

Table 1 main working conditions of flameout section model

number	Intake air temperature (°C)	Inlet water temperature (°C)	relative humidity (°C)
Case1	150	30	50
Case2	150	30	0
Case3	30	30	0

Fig.12 shows the change of outlet temperature after heat exchange in the flameout section under three different conditions. According to the simulation model of case 1, the outlet temperature is 35 (°C), the outlet temperature is 51 (°C) in case 2, and the outlet gas temperature is 30 (°C) in case 3. It can be seen from Fig.12 that the simulation results are in good agreement with the actual working conditions, and the steady-state temperature error is not more than 3%, indicating that the flameout section model can meet the simulation requirements of the aerial platform system.

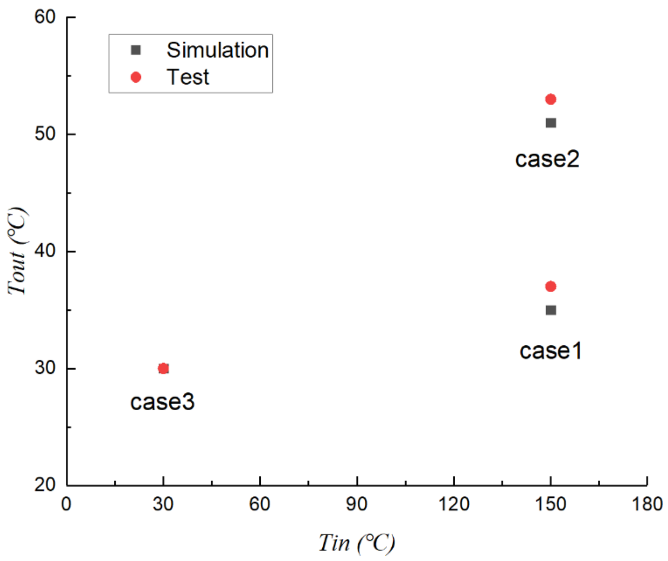


Fig.12 Simulation results of outlet temperature of flameout section model under three working conditions

4.1.3 Ejector model

In order to verify the function and characteristics of ejector model, the verification model is built as shown in Figure 11. A group of typical test conditions are selected for verification. The initial total pressure of main flow is 65kpa, the temperature is 525 ℃, the extraction pressure is 32 kPa, the opening of secondary flow valve is 24°, the atmospheric pressure is 95kPa, and the atmospheric temperature is 20 ℃. Under the same test condition, the ejector flow is about 2.5kg/s, as well as the error is about 5%, which proves that the ejector model established in this paper has high precision.

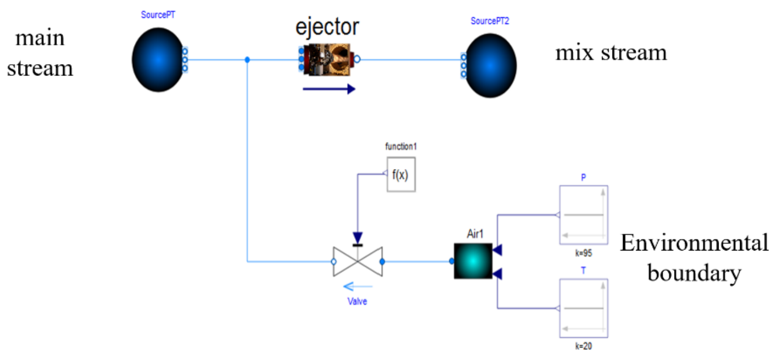


Fig 10 Ejector verification model

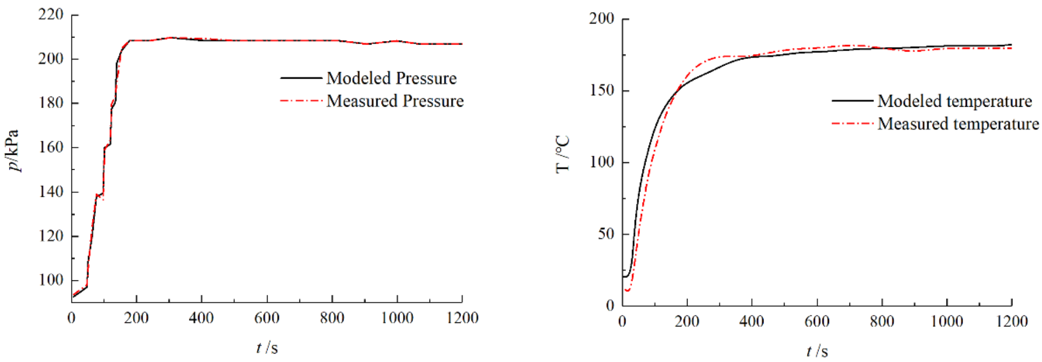
4.2 Analysis of simulation results

In this paper, two groups of test data are selected for simulation analysis of the test system, which are the test conditions of mixer outlet temperature 220 ℃ (test point 1) and mixer outlet temperature 130 ℃ (test point 2). The simulation time is 1200s, and the system simulation model is shown in Figure 4. During the simulation, according to the test data, the pressure, temperature and valve position signals in front of the valve are input into V1 and V2 valves dynamically. The flow of the front chamber is calculated through V1 and V2 valves, and the two flows are calculated through V3 valve. The air flow into the test chamber can be controlled by adjusting the opening of V1 and V2.

Fig.14 shows the variations of temperature and pressure in the front chamber of test point 1. It can be seen from Figure 14 that when the outlet temperature of mixer reaches to 220 ℃, the maximum pressure and temperature of front chamber can reach 210 kPa and 180 ℃, respectively. The simulation starts from t=0s, and both V1 and V2 have air flow through; when t = 400s, the pressure and temperature of the front chamber reach a balance state, and the simulation pressure and temperature values are consistent with the test results. During the whole simulation process, the maximum pressure error of the front chamber is less than 1%, and the maximum temperature error is less than 5%.

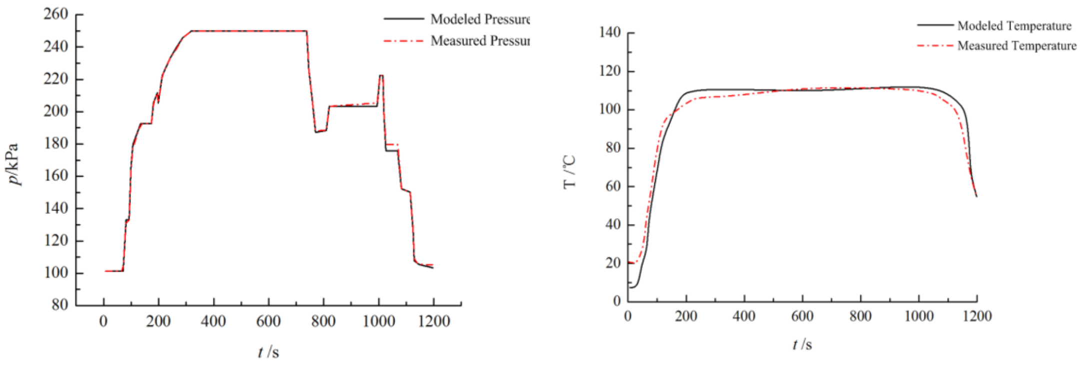
Fig.15 shows the pressure and temperature variations of the front chamber air with time. It is clearly that the simulation results are very close to the measured results. The largest relative error of the intake air pressure is less than 1%, and the largest relative error of the temperature is less than 5% at the whole simulation process. It indicates that the system modeling in this paper is reasonable.

Figure 15 shows the variations of temperature and pressure in the front chamber of test point 2. It can be seen from Fig.15 that when the outlet temperature of mixer is 130 ℃, the maximum pressure and temperature of front chamber can reach 250kPa and 110 ℃ respectively, and the temperature and pressure of front chamber tend to be stable at t=300s. During the test, according to the different working conditions of the engine, the air supply parameters need to be adjusted to meet the air intake requirements of different test points. According to Fig.15 (a), the front chamber pressure drops to 185kPa at the time of t=800s, and then the pressure and temperature values are automatically adjusted according to the engine states. The dynamic change trend reflected by the simulation is the same as the actual process. Because the mixer outlet and the front chamber are connected by pipeline, there are friction loss and heat exchange in the pipeline, so the front chamber temperature is lower than the mixer outlet temperature under the two calculation conditions, which is the same as the actual physical law. Compare Fig. 14 to Fig. 15, it can be seen that the mixer outlet temperature is in direct proportion to the stable temperature of front chamber, and the time to stabilize temperature is short. For different test points, the simulation results of the pressure and temperature in the front chamber show high accuracy, among which the maximum error of the steady-state pressure is not more than 1%, as well the maximum error of the steady-state temperature is not more than 4%. It shows that the model established in this paper can meet the simulation requirements of the high-altitude simulation test bed system, and has high reliability. By using the model, the system parameters of the test bed under different conditions can be effectively simulated the law of variation.



（a） pressure （b） temperature

Fig.14 pressure and temperature change of front chamber (test point 1)



（a） pressure （b） temperature

Fig.15 pressure and temperature change of front chamber (test point 2)

5 Conclusion

In this paper, the system simulation model of the test bench including valve, flameout section and ejector is established. According to the working principle of the components, the theoretical model of each component is established. At the same time, a complete simulation system model of the test bench is built. The model is consistent with the actual working process of the real high altitude simulation test bench system. The research results of this paper show that the simulation results of the simulation model of the high-altitude simulation test-bed system are in good agreement with the test results, the simulation system can reflect the real working process of the test-bed, and the model accuracy is high. The effectiveness of the modeling method and the model is verified by comparing with the test data. Under two groups of typical test point conditions, the maximum error of the front chamber pressure in the simulation process is Less than 1%, the maximum error of temperature is less than 5%. The modeling ideas and methods in this paper can be used for reference for the development of simulation and virtual test of high-altitude simulation test system.

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