Control-Oriented Study on Modeling for Scramjet

YU Bingqiang[1], *LIAN Zhiqiang*[1], *ZHOU Xin*[1*], *QIU Xiaojie*[2], *LU Feng*[1], *HUANG Jinquan*[1]

1. Jiangsu Province Key Laboratory of Aerospace Power System, Nanjing University of Aeronautics and Astronautics,
Nanjing 210016, P.R. China;
2. AECC Aero Engine Control System Institute, Wuxi 214063, P.R. China

(Received 10 May 2023; revised 30 August 2023; accepted 1 October 2023)

Abstract: First, a one-dimensional steady model of the scramjet is established. Particularly for the combustion with three modes, the one-dimensional gas dynamic governing equations are introduced to describe the axial distribution of the flow. Second, a one-dimensional dynamic model is derived by considering the volume effect based on the steady model. The model running results show that the results of the model are in good agreement with the experimental data. Further, a three-input-one-output proportional-integral (PI) controller is designed. The simulations show that the model can meet the requirements of scramjet control system design.

Key words: scramjet; one-dimensional model; dynamic model; volume dynamics

CLC number: V233.7 **Document code:** A **Article ID:** 1005-1120(2023)S2-0018-08

0 Introduction

In recent years, hypersonic flight ($Ma>5$) have gradually attracted the attention of researchers all over the world. Since the rocket engine must carry oxidant during hypersonic flights, the load is increased, while the specific impulse of fuel is decreased. The traditional air-breathing engine can directly obtain air from the external environment, and the fuel specific impulse is higher. However, due to the limitation of the material and structure, it cannot solve the problem of the huge entropy increase when slowing down the hypersonic incoming flow to subsonic, so that it cannot work properly in hypersonic flights[1]. Under this case, the scramjet can be a good choice for hypersonic vehicles because of its ability to achieve supersonic combustion. The extensive research on scramjet is known as the third revolution of aviation propulsion technology.

Since the concept of supersonic combustion was proposed, the research of scramjet has gone through theoretical analysis, numerical simulation, ground test and other stages. Early in the 1960s, many countries have carried out a large number of flight plans with scramjet as the power device, such as the X-43A and X-51A flight tests of the United States Hyper-X Program[2-4], Russia's Kholod flight test[5-8], and Australia's HY-Fire Program[9-13]. These flight tests have made some progress in the scramjet design and manufacture, fuel research and development, performance analysis and other aspects, but the research of the control system is still blank. And the design of the engine control system depends on the engine model.

The research of mathematical model of scramjet has started since the concept of supersonic combustion was proposed, including the modeling of the physical effects of supersonic flow and combustion and the modeling of the whole engine. Heiser et al. developed a scramjet model HAP[14]. However, the model is not accurate at high Mach numbers due to the assumption of isobaric combustion, the single point injection of fuel, and the empirical determination of the starting point of heat release and the re-

---

*Corresponding author, E-mail address: zhouxin_203@nuaa.edu.cn.

How to cite this article: Yu Bingqiang, LIAN Zhiqiang, ZHOU Xin, et al. Control-oriented study on modeling for scramjet [J]. Transactions of Nanjing University of Aeronautics and Astronautics, 2023, 40(S2): 18-25.

http://dx.doi.org/10.16356/j.1005-1120.2023.S2.003

connection point of the flow.

Many researchers in China have also proposed one-dimensional models for scramjets. Cao[15] analyzed the scramjet combustion mode transition boundary, studied the interaction between the combustion and the isolator, and established the one-dimensional steady model of the combustion. Existing literature is mainly on the study of scramjet steady model, and the study of the dynamic models for control system design is less. A few studies concentrated on component-level dynamics real-time model. For example, Liu et al.[16] established a real-time model of scramjet component level considering the combustion volume effect and conducted closed-loop simulation tests. In terms of scramjet control, LYU et al.[17] introduced the basic issues of scramjet control and gave the basic task framework of the system, which included thrust control, inlet control and combustion mode control. Although the component-level dynamic model of scramjets can describe the dynamic characteristics of scramjets, it cannot be used to control the distributed parameters of scramjets. Therefore, it is necessary to establish a one-dimensional dynamic model of scramjets.

Aiming at the control requirements of the one-dimensional dynamic model, a steady mathematical model of the scramjet based on the numerical simulation data and ground test data is established in this paper. Based on the one-dimensional steady model of the combustion, a one-dimensional dynamic calculation model of the combustion is further established by using the volumetric dynamics modeling method. The proposed model can calculate the changes of axial flow field parameters of combustion quickly, thereby assisting the design of the control system.

1 One-Dimensional Steady Model of Scramjets

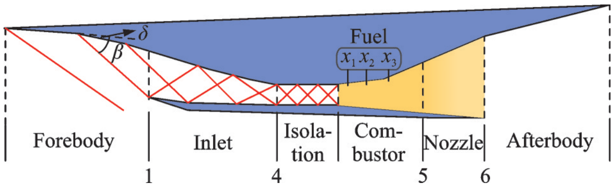


Fig.1 Scramjet structure diagram

The modeling object of this paper is a scramjet mainly composed of an inlet, an isolator, a combustion and a nozzle. The structure and the position number of each part are shown in Fig.1. Since the characteristics of the inlet and nozzle of the scramjet are similar to that of the conventional turbofan engine, component-level modeling method is adopted. The isolator and the combustion have a strong distribution parameter characteristic, which should be considered as a one-dimensional model. Given the engine's geometry, the flow condition and fuel injection condition, by solving one-dimensional gas dynamic governing equation of the flow of the engine combustion parameters along the axial distribution of engine, the performance parameters of the engine can be estimated by the flow parameters. The specific procedures are as follows.

1.1 Inlet model

According to the operation principle of the scramjet, the oblique shock model is the basis for the inlet modeling.

Given the shock front Mach number Ma_{f} and the deflection angle of air flow δ, the shock angle β is calculated as

$$\beta = \arctan\left(\frac{Ma_{\mathrm{f}}^{2}-1+2a\cos\left[(4\pi+\arccos b)/3\right]}{3\left[1+(k-1)/(2Ma_{\mathrm{f}}^{2})\right]}\tan\delta\right) \tag{1}$$

where

$$a=\left[(Ma_{\mathrm{f}}^{2}-1)^{2}-3\left(1+\frac{k-1}{2}Ma_{\mathrm{f}}^{2}\right)^{2}\tan^{2}\delta\right]^{\frac{1}{2}} \tag{2}$$

$$b=\frac{1}{a^{3}}\left((Ma_{\mathrm{f}}^{2}-1)^{3}-9\left(1+\frac{k-1}{2}Ma_{\mathrm{f}}^{2}\right)\cdot\left(1+\frac{k-1}{2}Ma_{\mathrm{f}}^{2}+\frac{k+1}{4}Ma_{\mathrm{f}}^{4}\right)\tan^{2}\delta\right) \tag{3}$$

The three oblique shock wave parameters can be solve referring to the Ref.[18]. Further, the inlet parameters of the isolator can be calculated from the inlet atmospheric parameters.

1.2 Combustion model

The scramjet combustion is treated as a one-dimensional pipeline, thus the one-dimensional gas dynamics governing equation can be used to describe the flow inside the scramjet combustion. Given the changes in the combustion area, inlet conditions and fuel addition conditions, the flow parameters along the combustion axis are obtained by solving the one-dimensional gas dynamics governing equation, and then the performance parameters of the scramjet combustion are estimated.

In this section, the total temperature distribution along the whole flow direction is given by polynomial fitting method based on the experimental data

$$\frac{T_t(x)}{T_{t2}}=1+(\tau-1)\left[\frac{\theta\chi}{1+(\theta-1)\chi}\right] \quad \theta>1 \tag{4}$$

where x is the axial position of the engine combustion(m); $T_t(x)$ the total temperature at the position x(K); T_{t2} the total temperature at the inlet of the isolator(K); τ the total heating ratio; θ the rate of heat release, which is an empirical constant from 1 to 10; χ the dimensionless axial position, $\chi=\frac{x-x_i}{x_4-x_i}$; x_i the fuel injection point location; and x_4 the outlet position of combustion.

In the hypersonic engine test, the drag caused by wall friction accounts for about 80%—90% of the total drag of the engine. Therefore, the estimation accuracy of friction is crucial to the scramjet combustion modeling. The following equation is used to predict the friction coefficient

$$C_f=\frac{0.472}{\left(\log Re_x\right)^{2.58}\left(1+\frac{k-1}{2}Ma^2\right)^{0.467}} \tag{5}$$

where C_f is the local friction coefficient; Re_x the local Reynolds number, $Re_x=\frac{\rho Vx}{\mu}$; ρ the local density; V the local velocity; μ the local gas dynamic viscosity, which is calculated by the Sutherland formula

$$\mu=\mu_0\left(\frac{T}{T_c}\right)^{1.5}\frac{T_c+T_s}{T+T_s} \tag{6}$$

where μ_0 is the viscosity coefficient under standard atmospheric conditions; T_s the Sutherland constant, which is related to the gas properties; $T_c=273.16$ K, and T the local temperature.

The one-dimensional governing equation of the flow field in the scramjet combustion can be derived from the basic governing equation of the gas dynamics. The relationship between Mach number and total pressure with one-dimensional coordinate x is

$$\frac{\mathrm{d}Ma}{Ma}=\frac{1}{Ma^2-1}\left(1+\frac{(k-1)}{2}Ma^2\right)\cdot \left[\frac{\mathrm{d}A}{A}-\frac{kMa^2+1}{2}\frac{\mathrm{d}T^*}{T^*}-\frac{kMa^2}{2}4C_f\frac{\mathrm{d}x}{D}\right] \tag{7}$$

$$\frac{\mathrm{d}p^*}{p^*}=-\frac{kMa^2}{2}\left(\frac{\mathrm{d}T^*}{T^*}+4C_f\frac{\mathrm{d}x}{D}\right) \tag{8}$$

On the basis of the Mach number and the total pressure, other parameters can be calculated from the gas dynamics function.

There are three different combustion modes in the scramjet combustion: The sub-combustion mode, the shock-free mode and the oblique shock mode. The transition boundary between the shock-free mode and oblique shock mode is as follow: When the lowest Mach number of the combustion is larger than 0.762 times of the Mach number at the inlet of the isolator, the combustion works in the shock-free mode. The transition boundary between the oblique shock mode and the sub-combustion mode is as follow: When the lowest Mach number of the combustion is larger than or equal to 1, the combustion operates in the oblique shock mode.

When the scramjet is in the shock-free mode, the whole flow passage is supersonic, and there is no boundary layer separation between the isolator and the combustion. The distribution of aerodynamic parameters in the isolator and the combustion can be obtained by directly solving the ordinary differential equations.

When the scramjet operates in the oblique shock mode, the whole flow passage is supersonic, and the isolator is separated from the combustion by a boundary layer. Firstly, for the modeling of the oblique shock mode, the interaction model between the isolator and the combustion is established. In the case of boundary layer separation of combustion, the inlet pressure p_3 and peak pressure $p_{\max}$ has the following relationship

$$p_3 = \delta p_{\max} \tag{9}$$

where δ is the dimensionless similarity criterion.

Secondly, the shock compression section model of the isolator is established. Obtaining the outlet pressure of the isolator, the outlet Mach number Ma_3 of the isolator can be calculated as

$$Ma_3 = \left[\frac{k^2 Ma_2^2 \left(1 + \dfrac{k-1}{2} Ma_2^2\right)}{\left(1 + k Ma_2^2 - \dfrac{p_3}{p_2}\right)^2} - \frac{k-1}{2} \right]^{-\frac{1}{2}} \tag{10}$$

where Ma_2 is the inlet Mach number of the isolator, and p_2 the pressure at the inlet of the isolator.

Thirdly, the length of the shock train in the isolator is calculated as

$$\frac{L_s (Ma_2^2 - 1) Re_\theta^{\frac{1}{4}}}{D^{\frac{1}{2}} \theta_2^{\frac{1}{2}}} = 50\left(\frac{p_3}{p_2} - 1\right) + 170\left(\frac{p_3}{p_2} - 1\right)^2 \tag{11}$$

where Re_θ is the Reynolds number at the inlet of the isolator; D the inlet equivalent diameter of the isolator (m); L_s the shock wave string length(m); and θ_2 the momentum thickness of boundary layer at the entrance of isolator(m)

$$\theta_2 = 0.664 * 0.652 / \sqrt{\rho V^* 0.652 / \mu} \tag{12}$$

Fourthly, the axial distribution of pressure inside the shock train is calculated by

$$\frac{p(x)}{p_2} = 1 + \left(\frac{p_3}{p_2} - 1\right)(3 - 2\chi)\chi^2 \tag{13}$$

where χ is the dimensionless axial position, $\chi = \dfrac{x - x_2}{x_3 - x_2}$.

Finally, the combustion separation section model can be modeled by the calculation of the internal parameters of the shock train. The axial pressure distribution of the combustion separation section can be calculated by the quadratic polynomial

$$\frac{p(x)}{p_3} = 1 + \left(\frac{p_{\max}}{p_3} - 1\right)(2 - \chi)\chi \tag{14}$$

where χ the dimensionless axial position, $\chi = \dfrac{x - x_3}{x_{\max} - x_3}$; x_3 the inlet position of combustion; and $x_{\max}$ the outlet position of the separation section of the combustion, namely the highest pressure position.

By replacing the pressure value in Eqs. (13, 14) with Mach number, the axial distribution of Mach number between the inner shock train and the separation section of combustion can be calculated. Once obtaining the pressure and Mach number, other aerodynamic parameters can be calculated from the gas dynamics equation.

For the scramjet sub-combustion mode modeling, the location of the critical sound velocity point is determined. For Eq. (7), when $Ma = 1$, since the flow field parameters are continuous at the sound velocity point, ignoring the influence of friction force, the following equations exist

$$\begin{cases} Ma_*^2 - 1 = 0 \\ \left(\dfrac{1}{A}\dfrac{\mathrm{d}A}{\mathrm{d}x}\right)_* - \dfrac{k+1}{2}\left(\dfrac{1}{T_t}\dfrac{\mathrm{d}T_t}{\mathrm{d}x}\right)_* = 0 \end{cases} \tag{15}$$

The position of the critical sound velocity point can be calculated from the above equations. According to the operation principle of scramjets, the Mach number increases when the air flow accelerates from subsonic to supersonic in the combustion. Therefore, the positive solution should be taken to calculate the Mach number before and after the sound speed point

$$Ma_u = 1 - \Delta x * \left(\frac{dMa}{dx}\right)_* \tag{16}$$

$$Ma_d = 1 + \Delta x * \left(\frac{dMa}{dx}\right)_* \tag{17}$$

Finally, through Eq. (7), let Ma_u be the initial value condition, the critical sound velocity point is integrated forward along the combustion axial direction, and the parameter distribution in the subsonic region of the combustion is calculated. Let Ma_d be the initial value. The parameter distribution in the supersonic region of the combustion is calculated by integrating backward from the critical sound velocity point along the combustion axis. The parameter distribution in the isolator can be calculated from Eqs. (11—14).

1.3 Nozzle model

The high temperature and high pressure air flow out of the combustion expands through the nozzle to generate thrust. This thermodynamic process can be considered as adiabatic and isentropic. According to the continuous equilibrium equation of the flow at the throat and nozzle outlet sections is

$$\dot{m}=K_5\frac{P_{t5}}{\sqrt{T_{t5}}}q(Ma_5)A_5=K_6\frac{P_{t6}}{\sqrt{T_{t6}}}q(Ma_6)A_6 \tag{18}$$

where $K=\sqrt{\frac{k}{R}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}}$.

The nozzle outlet static pressure P_6, speed V_6 and flow rate $\dot{m}_6$ can be calculated from Eq.(19) so as to obtain the total thrust of the engine

$$F=(P_6A_6+\dot{m}_6V_6)-(P_1A_1+\dot{m}_1V_1) \tag{19}$$

2 One-Dimensional Dynamic Model of Scramjet

2.1 Volume Dynamics modeling principles

The combustion structure of the scramjet dynamic model established in this paper is shown as Fig.2.

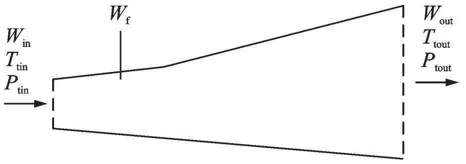


Fig.2 Combustion structure of the scramjet

The one-dimensional approximate energy equation of heat transfer in the air flow can be written as

$$\frac{\partial(\rho C_VT_t)}{\partial t}-\frac{\partial(\rho Uh)}{\partial x}=0 \tag{20}$$

where h is the specific enthalpy related to the total temperature of the air flow; U the air flow velocity; and x the axial coordinate.

Substituting the flow formula $W=\rho UA$ into Eq.(21), we have

$$A\frac{\partial(\rho C_VT_t)}{\partial t}-\frac{\partial(Wh)}{\partial x}=0 \tag{21}$$

The inlet of the combustion is taken as the volume inlet. Once the volume exit position is determined, Eq.(22) can be changed to

$$\frac{\mathrm{d}(\rho C_VT_t)}{\mathrm{d}t}=\frac{\left[W_{in}h(T_{tin})+W_f(\eta H_f+h_c)-W_{out}h(T_{tout})\right]}{V_c} \tag{22}$$

where V_c is the volume of the cavity (varies with the position of the point to be calculated); h_c the fuel static enthalpy; and H_f the calorific value of fuel.

Equation of continuity is a fundamental equation that must be satisfied by any flow system

$$\frac{\mathrm{d}\rho_{out}}{\mathrm{d}t}=\frac{W_{in}+W_f-W_{out}}{V_c} \tag{23}$$

From Eqs.(23, 24), we can obtain

$$\frac{\mathrm{d}T_{tout}}{\mathrm{d}t}=\frac{\left\{W_f(\eta H_f+h_c)+W_{in}h_{in}-W_{out}h_{out}-C_VT_{tout}(W_3+W_f-W_{out})\right\}}{C_V+T_{tout}\frac{\mathrm{d}C_V}{\mathrm{d}T_{tout}}} \tag{24}$$

Substituting $C_V=C_p/k$, $C_pT_t=h$ into Eq.(24) we have

$$\frac{\mathrm{d}T_{tout}}{\mathrm{d}t}=\frac{R_{out}T_{tout}}{V_cP_{tout}D_{out}}\left\{W_f\left[\eta H_f+h_c-\frac{h_{out}}{k_{out}}\right]+W_{in}\left[h_{in}-\frac{h_{out}}{k_{out}}\right]-W_{out}\frac{k_{out}-1}{k_{out}}h_{out}\right\} \tag{25}$$

where $D_{out}=\mathrm{d}\frac{h_{out}}{k_{out}}\Big/\mathrm{d}T_{tout}$.

Substituting $\rho_{out}=\frac{P_{tout}}{R_{out}T_{tout}}$ into Eq.(23), we have

$$\frac{\mathrm{d}P_{tout}}{\mathrm{d}t}=\frac{R_{out}T_{tout}}{V_c}(W_{in}+W_f-W_{out})+\frac{P_{tout}}{T_{tout}}\frac{\mathrm{d}T_{tout}}{\mathrm{d}t} \tag{26}$$

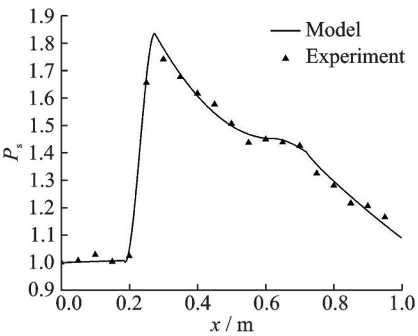
Eqs.(25, 26) are the basic equations of engine volume dynamic modeling.

2.2 Dynamic model of scramjet

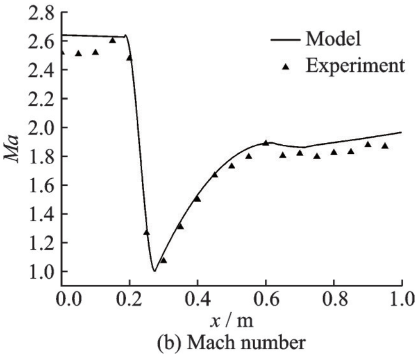
The dynamic model is established considering volume dynamics. On the basis of the steady model established in Section 1, the appropriate volume should be selected. In this paper, the outlet of the isolator is selected as the inlet of the volume. The wall of the combustion is the side of the volume. And the sections after the first injection point are the outlet of the volume. We take the steady outputs as the initial value, then the total temperature and pressure are calculated from Eqs.(25, 26), and the Mach number is calculated from the flow equation, thus the static temperature and static pressures are obtained. Finally, on the basis of these parameters, the mode modeling method of Section 1 is used to solve all the parameters of the flow field at time t. The parameters at time t are taken as the initial values at time $t+1$, and the calculation cycle is carried out until the fuel flow is balanced. During the dynamic process, the one-dimensional steady model from the isolation section exit to the first injection point is replaced by the dynamic equation of the volume, and reflects the mass flow and energy accumulation effects of the combustion.

3 Scramjet Model Simulation

In order to verify the accuracy of the model, the output of model is compared with the experimental data. Fig. 3 shows the comparison between the output of steady model and experiment parameters. It can be seen that the output of steady model is matched with the experiment parameters, which can effectively capture the pressure peak in the combustion and the pressure rise point in the isolator. And the average error is below 3%. The comparison between the output of steady model and experiment parameters can fully prove that the established steady model of scramjets can be used to simulate the changes of axial flow parameters in scramjet combustion.



(a) Static pressure



(b) Mach number

Fig.3 Comparison between outputs of steady model and experiment data

Fig. 4 shows the comparison between the output of dynamic model and experiment parameters. It can be seen that the thrust output of dynamic model is consistent with the change trend of experiment value over time. And the average error is below 5%. Through the comparison between the output of dynamic model and experiment parameters can fully prove that the established dynamic model of scramjets can be used to predict the performance when fuel is changing.

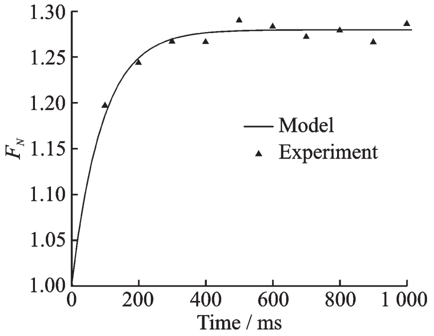


Fig.4 Comparison between outputs of dynamic model and experiment data

The scramjet mathematical model is taken as the controlled plant. The three-point fuel flow rate distributed axially in the engine combustion is used as the control parameters. The engine thrust is the controlled parameter. Thrust tracking control simulations are carried out to verify if the established scramjet can be used in the design of control system. Since the thrust cannot be measured, this paper uses back propagation (BP) neural network to estimate the thrust through measurable parameters[19].

A proportional-integral (PI) controller is designed (Fig. 5) under the atmospheric condition of 27 km altitude and $Ma=6$. Figs. 6, 7 show the results. It can be seen that the established scramjet model can reflect the operation state during the acceleration and deceleration process whether under large step and small step, which can be used in the design of engine control system.

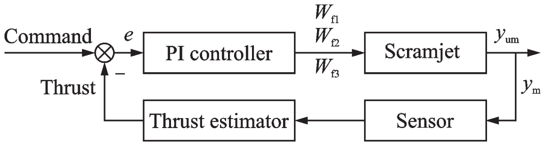


Fig.5 Control system stucture

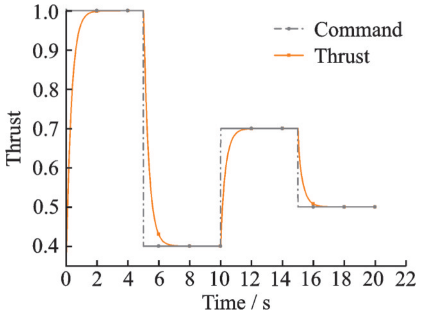


Fig.6 Thrust responses

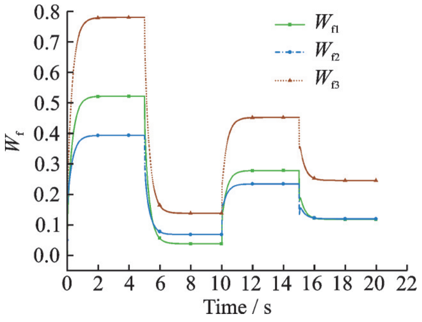


Fig.7 Mass flows of fuel

4 Conclusions

(1) In this paper, a one-dimensional steady model of scramjets is established, including the performance calculation of inlet, combustion and nozzle. On this basis, the one-dimensional models of shock-free mode, oblique shock mode and sub-combustion mode of the scramjet are established. Combined with the experimental data, the steady model is verified. The results show that the steady model of scramjets can accurately describe the axial variation trend of the flow parameters in the engine. And the average error is below 3%.

(2) In view of the influence of fuel dynamics on burner, a one-dimensional dynamic model of engine combustion is established considering volume dynamics. According to the actual fuel dynamics in the experiment, the dynamic model is used to calculate the thrust change during the fuel change process, and the calculation results are compared with the experimental data. The comparison results show that the results of the dynamic model are in good agreement with the experimental data. And the average error is below 5%.

(3) Taking the established scramjet mathematical model as the control plant, we design a PI controller to simulate the acceleration and deceleration process. The results show that the model can quickly calculate the changes of the axial flow field parameters in the combustion, which can meet the requirements of engine control system design.

In this paper, the disturbance wave transfer is not considered in the dynamic modeling process of the scramjet. In future, the disturbance wave transfer factor should be considered in the dynamic modeling process to increase the accuracy of the one-dimensional dynamic model of the scramjet.

References

[1] LUO Shaobin. Research on integrated body/engine and overall multidisciplinary design optimization method for hypersonic vehicle[D]. Changsha: National University of Defense Technology, 2004. (in Chinese)

[2] MCCLINTON C, VOLAND R, HOLLAND S, et al. Wind tunnel testing, flight scaling and flight validation with Hyper-X[C]//Proceedings of the 20th AIAA Advanced Measurement and Ground Testing Technology Conference. Albuquerque, USA: AIAA, 1998.

[3] HARSHA P, KEEL L, CASTROGIOVANNI A, et al. X-43A vehicle design and manufacture[C]//Proceedings of AIAA/CIRA 13th International Space Planes and Hypersonics Systems and Technologies Conference. Capua, Italy: AIAA, 2005.

[4] MCCLINTON C. X-43-scramjet power breaks the hypersonic barrier: Dryden lectureship in research for 2006[C]//Proceedings of the 44th AIAA Aerospace Sciences Meeting And Exhibit. Reno, USA: AIAA, 2006.

[5] TISHKOFF J, DRUMMOND J, EDWARDS T, et al. Future directions of supersonic combustion research-Air Force/NASA workshop on supersonic combustion[C]//Proceedings of the 35th Aerospace Sciences Meeting and Exhibit. Reno, USA: AIAA, 1997.

[6] VOLAND R, AUSLENDER A, SMART M. CIAM/NASA Mach 6.5 scramjet flight and ground test[C]//Proceedings of the 9th International Space Planes and Hypersonic Systems and Technologies Conference. Norfolk, USA: AIAA, 1999.

[7] BOUCHEZ M, ROUDAKOV A, KOPCHENOV V, et al. French-Russian analysis of Kholod dual-mode ramjet flight experiments[C]//Proceedings of AIAA/CIRA 13th International Space Planes and Hypersonics Systems and Technologies Conference. Capua, Italy: AIAA, 2005.

[8] ROUDAKOV A, SEMENOV V, HICKS J. Recent flight test results of the joint ciam-NASA Mach 6.5 scramjet flight program[C]//Proceedings of the 8th

AIAA International Space Planes and Hypersonic Systems and Technologies Conference. Norfolk, USA: AIAA, 1998.

[9] DENG Fan, CHEN Jun, XIE Feng, et al. Research progress of flight test of HIFiRE project based on scramjet[J]. Journal of Aerospace Power, 2018(3): 683-695. (in Chinese)

[10] BOWCUTT K, PAULL A, DOLVIN D, et al. Hifire: An international collaboration to advance the science and technology of hypersonic flight[C]//Proceedings of the 28th International Congress of the Aeronautical Sciences. Leiden, The Netherlands: ICAS Secretariat, 2012.

[11] SCHMISSEUR J D. Hypersonics into the 21st century: A perspective on AFOSR-sponsored research in aerothermodynamics[J]. Progress in Aerospace Sciences, 2015, 72: 3-16.

[12] KIMMEL R, ADAMCZAK D, PAULL A, et al. HIFiRE-1 preliminary aerothermodynamic measurements[C]//Proceedings of the 41st AIAA Fluid Dynamics Conference and Exhibit. Honolulu, USA: AIAA, 2011.

[13] LI F, CHOUDHARI M, CHANG C L, et al. Transition analysis for the HIFiRE-1 flight experiment[C]//Proceedings of the 41st AIAA Fluid Dynamics Conference and Exhibit. Honolulu, USA: AIAA, 2011.

[14] HEISER W H, PRATT D T. Hypersonic airbreathing propulsion. aiaa education series[M]. Washington DC, USA: American Institute of Aeronautics and Astronautics, 1994.

[15] CAO Ruifeng. Study on controlling-oriented one-dimensional modeling of scramjet[D]. Harbin, China: Harbin Institute of Technology, 2011. (in Chinese)

[16] LIU M L, ZHANG H B. Study on real-time model simulation of hypersonic scramjet[J]. Journal of Aerospace Power 2017, 32(6): 1447-1455. (in Chinese)

[17] LYU C, CHANG J, BAO W, et al. Recent research progress on airbreathing aero-engine control algorithm[J]. Propulsion and Power Research, 2022, 11(1): 1-57.

[18] ANDERSON J D. Modern compressible flow[M]. New York, USA: McGraw-Hill Publishing Company, 2002.

[19] LI Qiuhong, LI Yebo, WANG Qianyu. Direct thrust control of aeroengine[J]. Journal of Nanjing University of Aeronautics & Astronautics. 2010, 42(5): 557-561. (in Chinese)

Authors Mr. **YU Bingqiang** received his B.S. degree in aircraft power engineering from Nanjing University of Aeronautics and Astronautics in 2022. From 2022, he is currently a doctor candidate at Nanjing University of Aeronautics and Astronautics. His research interests are aerospace engine modeling and control technology.

Dr. **ZHOU Xin** received his Ph.D. degree in aeronautical and astronautical propulsion theory and engineering from Nanjing University of Aeronautics and Astronautics, China in 2021. Her current research interests include aero-engine modeling and intelligent control.

Author contributions Mr. **YU Bingqiang** and Mr. **LIAN Zhiqiang** designed the study, complied the models, conducted the analysis, interpreted the results and wrote the manuscript. Mr. **ZHOU Xin** and Mr. **QIU Xiaojie** contributed to data and components for the model. Mr. **LU Feng** and Prof. **HUANG Jinquan** contributed to the discussion and background of the study. All authors commented on the manuscript draft and approved the submission.

Competing interests The authors declare no competing interests.

(Production Editor: ZHANG Bei)

面向控制的超燃冲压发动机建模研究

于兵强[1]，廉志强[1]，周　鑫[1]，仇小杰[2]，鲁　峰[1]，黄金泉[1]

(1.南京航空航天大学江苏省航空动力系统重点实验室，南京 210016，中国；
2.中国航发控制系统研究所，无锡 214063，中国)

摘要：建立了超燃冲压发动机的一维稳态模型。特别是对于三模态燃烧，引入一维气体动力学控制方程来描述流动的轴向分布。在稳态模型的基础上，推导出考虑体积效应的一维动态模型。模型运行结果表明，模型结果与实验数据吻合较好。最后，设计了三输入一输出比例积分(Proportional-integral, PI)控制器。仿真结果表明，该模型能够满足超燃冲压发动机控制系统设计的要求。

关键词：超燃冲压发动机；一维模型；动态模型；容积动力学