Design and experiments of the fuel control method for the scramjet engine

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Abstract. The control method is one of the key application technologies of the engine. And the core of the scramjet control system is the fuel-based control method. The design and the experimental verification of the scramjet fuel-based control method were mainly carried out in this paper. The correlation between the engine thrust, the wall pressure and the equivalence ratio was obtained by means of the numerical simulation. Combined with the results of experiments, the fuel control method and the verification method of the experiment, which chose the wall pressure as the feedback signal, were designed and developed, and the ground test of the fuel control method was carried out. The results of the numerical simulation and the experiment showed that (i) the magnitude of the wall pressure at some axial locations of the combustor was proportional to the fuel flow rate and (ii) the fuel control method based on the feedback signal, i.e., the wall pressure, and the choice of the location of the wall pressure control point were feasible and rational.

Keywords. Scramjet; controlled parameters; fuel control; thrust; wall pressure.

1. Introduction

As the ideal propulsion system for hypersonic vehicles, the scramjet engine is an important system in the aerospace field. The achievement of a functional fuel-based control method with a wide range of Mach number is one of the key techniques for the application of the scramjet engine. There are a great number of differences between the scramjet and other aero propulsion

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systems, such as the turbine engine and the ramjet engine, in terms of the working process. The entire scramjet flight process is characterized by a higher Mach number, wider flight altitude and greater range of Mach number, larger variation of working mode, and surface heat flux. To fulfill the demand of the whole flight mission, multi-fuel injection points are arranged in different regions. The location of the fuel injection and the fuel flow rate change under different flight conditions, which can bring about more control parameters and more complicated control rule; therefore, it is increasingly difficult for the control system to meet all the demands.

In the 1990s, Russian 'Kholod' program carried out five flight tests and the control law for regarding the wall pressure as the controlled parameter was described in detail in the documents (Volland *et al* 1999; McClinton *et al* 1996). However, during the flight, the unexpected non-starting of the air inlet also occurred. In America, as the research on the scramjet has arrived at the flight test stage (Kazmar 2005; Hank *et al.* 2008; Bahm *et al* 2005), the fuel control techniques have developed gradually (Huebner *et al* 2001). In May 1, 2013, the fourth flight test of X-51 aircraft was carried out successfully. However, the documents on its fueling control law were not found. Nowadays the research on the fuel control techniques has attracted more attention in China and many researchers have carried out a large number of researches on it (Lu Cunkan *et al* 2009; Vogel J M *et al* 2009; Adami *et al* 2006; Yu Daren *et al* 2010). There is no definitive conclusion on what kind of control law and control method that shall be adopted by the scramjet engine during its flight path. The main objective of this paper is to provide an advanced research for the scramjet fuel control method by the design and ground verification test.

2. Methodology design

The design of the fuel-based control method mainly depends on the flight mission of the vehicle. This is because the designed fuel control method must fulfill the demand of the specified flight mission, and at the same time, enhance the performance and the efficiency of the engine as much as possible.

To get the baseline of the design, the flight mission is assumed as that of the hypersonic vehicle is first accelerated to Mach number 4.0 by a roll booster, then the engine is separated from the roll booster and starts to work, and after a climbing phase the engine will work at an invariable altitude and speed, i.e., Mach number 6.5.

The choice of the fuel control parameters and controlled parameters is the key for the design of the fuel-control method.

2.1 Choice of the control parameters

For a scramjet whose flow area is invariable, there are simply two parameters, i.e., the fuel flow rate and the location of the fuel injection points, which could be controlled directly. In this research, the fuel flow rate was chosen as the control parameter.

2.2 Choice of the controlled parameters

The following aspects should be considered when the controlled parameters (which are the feedback signals in engine closed-loop control) are chosen:

2.2a Monotonicity: As one of the most important scramjet engine performance parameters, the thrust could not be measured directly. Therefore the feedback signal is required to perfectly reflect the operation condition and the thrust performance of the engine, namely the magnitude of the feedback signal must correspond to the fuel flow rate and the thrust.

2.2b Stability: When the fuel flow rate is constant, the fluctuation of the magnitude of the feedback signal must be stabilized within certain limits.

2.2c Sensitivity: The feedback signal should be sensitive to the change of the fuel flow rate.

2.2d Measurability: The feedback signal should be easy to be measured.

In this paper, the correlation between the engine thrust, the wall pressure and the equivalence ratio were researched numerically first under two different flight conditions, i.e., Mach number 4.0 and Mach number 6.5 at the cruising state. Then combined with the results of the experiment conducted before, a fuel-based control method was designed and a preliminary verification of the engine's ground tests was presented in this paper.

3. Numerical simulation

3.1 Engine configuration

Figure 1 is the configuration of the 2-D scramjet engine simulated in this study. The total length of the engine is 2262 mm and the engine consists of the forebody/inlet, the isolator, the combustor and the nozzle/afterbody. The forebody/inlet is a 3-slope shock wave compression inlet and is 712 mm in length. The length of the isolator and combustor is 850 mm in total, and the height of the isolator is 30 mm. The length of the nozzle/afterbody is 700 mm. A dual-cavity flame holder is used in the combustor. Room temperature hydrogen was injected sonically from the down wall through a single port at 25 mm upstream of the cavity leading edge.

3.2 Grid system and numerical method

The 2-D grid was constructed with the Gambit software. As shown in figure 2, a denseness management was made at the region of sharp divergence and convergence, and the neighbourhood of the injection. The total number of the CFD scramjet model grid was 92775. The Fluent CFD software was used to simulate the combustion. The CFD tools implanted in this study included a coupled-implicit solver, a $k - \omega$ shear stress transport (SST) turbulence model, which was more applicable for the calculation of the supersonic flow. A finite model of the single-step chemical kinetics was implanted to simulate the hydrogen combustion. Apply hydrogen and

Figure 1. 2-D integrated scramjet/airframe configuration.

Figure 2. The scramjet grid.

kerosene as the fuel and the above two both adopt the single-step chemical reaction kinetics model:

The residual criteria for convergence of the simulation are as follows:

- The residual criteria of flow property — When there is no chemical reaction, the residual of each equation is less than 10^{-5} ; When there is chemical reaction, the residual of each equation is less than 10^{-3} .
- The static pressure of wall needs to be stable with the error less than 0.1%.
- The flow mass of inlet and outlet needs to be conserved with the error less than 0.5%.

3.3 Flow condition

In this study, two flight conditions, i.e., the Mach number 4.0 and Mach number 6.5, were simulated, respectively. Table 1 shows the boundary conditions corresponding to different flight conditions.

3.4 Numerical results and discussion

- Results on hydrogen fuel:** In table 2, the scramjet engine performance is summarized under different hydrogen equivalence ratios (ER) at the flight condition of Mach number 6.5 when the engine is fueled solely at inject1. Besides, the pressure distributions of the up and down wall of the combustor are shown in figures 3 and 4, respectively.

As shown in table 2, the engine thrust and the specific impulse are proportional to the equivalence ratios. By analysing the results in table 2, figures 3 and 4 collectively, it can be found that the wall pressure in the combustor rises significantly after the ignition; the magnitude of the

Table 1. Calculation conditions for the numerical simulation.

	Mach number	6.5	4.0
Freestream conditions	Total temperature	1897 K	883 K
	Total pressure	6.1 MPa	1.4 MPa

Table 2. The scramjet engine performance under different hydrogen ER(Ma = 6.5).

Hydrogen ER	0.6	0.8	1.0	1.2
Engine thrust (N)	3360	3843	5344	5755
Specific impulse (Ns/kg)	342	391	543	585

wall pressure is proportional to the engine thrust and the specific impulse. In zone1 (presented in figure 3), there is a monotone relation among the up wall pressure, the engine thrust and the specific impulse. The same relationship among the down wall pressure, the engine thrust and the specific impulse in zone 2 and zone 3 are presented in figure 4.

In table 3, the scramjet engine performance is summarized under different hydrogen equivalence ratios at the flight condition of Mach number 4.0. Besides, the pressure distributions of the up and down wall of the combustor are shown in figures 5 and 6, respectively.

As shown in table 3, figures 5 and 6, the engine thrust, the specific impulse and the magnitude of the wall pressure in the combustor are proportional to the equivalence ratio. In Zone 1 (presented in figure 5), there is a monotone correlation among the up wall pressure in the combustor, the engine thrust and the specific impulse; in zone 2 (presented in figure 5), with the increasing equivalence ratio, the pressure disturbance propagates upstream; therefore, the up wall pressure in zone 2 could be chosen as the signal to judge whether the inlet unstart happens or not. As shown in figure 6, there is also a monotone correlation among the engine thrust, the specific

Figure 3. Up wall pressure distribution under different hydrogen ER (Ma = 6.5).

Figure 4. Down wall pressure distribution under different hydrogen ER ($Ma = 6.5$).

impulse and the down wall pressure in Zone 3 and Zone 4. There are 6 and 3 locations at which the wall pressure could be chosen as the control parameters, in Zone 3 and Zone 4, respectively (the locations of the pressure tap are presented in figures 5 and 6). In Zone 5, the same phenomenon is observed as in Zone 2, and the down wall pressure in Zone 5 could also be chosen as the judgmental signals for the inlet unstart.

- (ii) **Results on kerosene fuel:** In table 4, the scramjet engine performance is summarized under different kerosene equivalence ratios at the flight condition of Mach number 6.5, when the engine is fueled solely at inject1. Besides, the pressure distributions of the up and down wall of the combustor are shown in figures 7 and 8, respectively.

As shown in table 4, the engine thrust and the specific impulse are proportional to the equivalence ratios. Based on the curve shown in figures 7 and 8, it could be found that in Zone 1 (presented in figure 7), there is a monotone relationship between the up wall pressure and the

Table 3. The scramjet engine performance under different hydrogen ER ($Ma = 4$).

Hydrogen ER	0.6	0.8	1.0
Engine thrust (N)	6432	7184	9472
Specific impulse (Ns/kg)	406	459	606

Figure 5. Up wall pressure distribution under different hydrogen ER ($Ma = 4$).

equivalence ratios. And the same relationship between the down wall pressure and the equivalence ratios in Zone 2 (presented in figure 8) could as well be observed. By analysing the results in table 4, figures 7 and 8 collectively, there is a monotone relationship among the wall pressure, the engine thrust and the specific impulse. Therefore, the wall pressure could be chosen as the control parameters in those zones. Besides, there are 7 locations on the up wall and 8 locations on the down wall (the locations of the pressure tap are presented in figures 7 and 8), respectively according to the numerical results.

3.5 Experiment study

The kerosene combustion experiments made in NWPU's directly connected supersonic combustor, and the detailed analysis based on the experiment was presented in terms of the feasibility of the choosing of the wall pressure as the controlled parameter. The results provide an experimental basis for the design and study of the fuel control method.

Supersonic ignition and combustion experiments, simulating the flight condition of Mach number 4.0 and fueled with room temperature kerosene which were ignited by pilot hydrogen, were conducted. The relationship between the combustor wall pressure and the mass flow rate

Figure 6. Down wall pressure distribution under different hydrogen ER ($Ma = 4$).

of the kerosene was examined. The experiment model was the combustor model of the scramjet which is shown in the figure 1. The configuration of the ground model included two parts, i.e., the isolator and the combustor; and the detailed geometry could be found in the above mentioned numerical simulation section. The inflow conditions of the ground model were, 800 K in total temperature, 8 atm in total pressure and $Ma = 2.0$.

The combustor wall pressure distributions with different equivalence ratio of kerosene are presented in figures 9 and 10. With the increase of the equivalence ratio of kerosene, the wall pressure rose on the whole and the disturbance induced by the pressure rose propagated upstream. The up wall pressure in Zone 1 ($x = 270 \sim 520$ mm) and the down wall pressure in Zone 2 ($x = 270 \sim 420$ mm) varied monotonously according to the equivalence ratio of kerosene; thus, the up wall pressures in Zone 1 and the down wall pressures in Zone 2 could be chosen as controlled parameters.

Table 4. The scramjet engine performance under different kerosene ER ($Ma = 6.5$).

Kerosene ER	0.6	0.8	1.0
Engine thrust (N)	3727.6	3892.7	4599
Specific impulse (Ns/kg)	381	398	470

Figure 7. Up wall pressure distribution under different kerosene ER (Ma = 6.5).

Figure 8. Down wall pressure distribution under different kerosene ER (Ma = 6.5).

Under the equivalence ratio 0.44 and 0.53, coincidence and intersect appeared in the up wall pressure and the down wall pressure, respectively at the axial location within $x = 550 \sim 600$ mm. Therefore, it was shown that there was no monotone relationship between the wall pressure and the equivalence ratio within the specified axial location.

3.6 Fuel control method and ground experiment scheme

According to the results of the analysis of the numerical simulation and the experiment, the engine thrust increased monotonously in accordance with the fuel flow rate on the condition of fuel supply at a single point. Meanwhile, in some specific regions of the interior flow path, there was a monotone correlation between the wall pressure and the fuel flow rate.

In order to achieve a successful control of the engine thrust or the internal thrust which is closely related to the wall pressure distribution and magnitude, the wall pressure at specified or controlled points must be proportional and sensitive to the variation of the fuel mass flow rate.

The design of a fuel control method is valuable only when it can allow an existing flight mission to be carried out more effectively or an entire new mission to be accomplished. Therefore, a flight mission, in which the vehicle first accelerated to Mach number 6.5 from Mach number 4.0 and then cruised with the constant Mach number 6.5, was assumed in this study. The configuration of the vehicle was also assumed, and its detailed geometry information is presented in figures 1 and 11. During the acceleration process, to maximize the engine thrust, an open-loop control mode for the fuel was adopted, which chose the fuel mass as a controlled parameter.

Figure 9. Up wall pressure distribution under different ER.

Figure 10. Down wall pressure distribution under different ER.

During the cruising process, a closed-loop control mode for the fuel, in which the wall pressure at axial location 370 mm (presented in figure 11) was chosen as the controlled parameter was adopted. In order to monitor the condition of the inlet, a pressure sensor was installed on the up wall of the isolator which was 150 mm away from the inlet of the isolator, and the fuel mass flow rate would stop increasing when the wall pressure was higher than the critical value (varied with Mach numbers) which corresponded to the boundary of the inlet unstart. During the research for the fuel-based control method, we have also made the comparison study between the engine performance of kerosene fueled and hydrogen fueled on different fuel equivalent ratio. Because the kerosene fuel has the advantages such as easy storage, good security and high heat value in the

Figure 11. Geometry configuration of combustor model for experiment validation.

range of mach number 6–8, the kerosene fuel was utilized for fuel-based control method scheme and the ground verification test.

In order to test the feasibility and capability of the mentioned fuel control method above, the preliminary ground test on the stable point of Mach number 4.0 was conducted based on the available experiment conditions in NWPU. The detailed information and discussion about the experiment is presented in the next section.

4. The ground experiment of the scramjet fuel control method

4.1 Experimental set-up

The experiment was conducted to examine the feasibility and the capability of the fuel control method on the directly connected supersonic combustor model at the scramjet lab of NWPU (presented in figure 12). The inlet air could be heated to a stagnation temperature of 1000 K from 500 K by an electric resistance heater. The range of air mass flow rate was 0.5 to 1.5 Kg/s. The stable operation time could reach more than 200 s, and the maximum flight Mach number simulated was 4.3. In order to fulfill the demands of the fuel control experiment, the fuel driving and control system were rebuilt (figures 13 and 14).

Figure 12. Supersonic combustion test facility of NWPU.

Figure 13. The principle of the open-loop fuel control.

Figure 14. The principle of the close-loop fuel control.

For the open-loop control of the fuel, the actual fuel mass flow rate was adjusted to or maintained in the vicinity of the desired fuel mass flow rate, while the fuel mass flow rate, detected by a flow meter, was regarded as the feedback signal. If the actual fuel mass flow rate was less than that of the desired, for example, the fuel driving system would drive more fuel into the combustor till the difference between the actual fuel mass flow rate and the desired fuel flow rate reach an acceptable magnitude, and vice versa (whose principle is presented in figure 13).

For the fuel closed-loop control, whose principle is presented in figure 14, the actual fuel mass flow rate was adjusted to or maintained in the vicinity of the desired fuel mass flow rate, while the wall pressure, detected by a pressure sensor, was regarded as the feedback signal. If the actual fuel mass flow rate is less than that of the desired, for example, the fuel driving system would drive more fuel into the combustor till the difference between the actual fuel flow rate and the desired fuel flow rate reach an acceptable magnitude, and vice versa.

4.2 Experiment results and discussion

Two different tests, case 1 and case 2, respectively, were operated to test the feasibility and capability of the open and closed fuel control loops. In the tests, the kerosene was ignited by the hydrogen pilot flame which had been ignited by a spark plug. The air mass flow rate is 0.76 Kg/s. The two tests' scheme is shown in table 5.

In case 1, the open-loop control of the fuel was tested, and there were two different desired kerosene mass flow rates, 27 g/s during the first 5 seconds and 31 g/s during the last 3 seconds. The fuel injection pressure and the wall pressure at the x-axial location 330 mm varied with the time, as presented in figure 15. Besides, the curves of the fuel flow rate, the fuel injection pressure and the wall pressure at x-axial location 370 mm, which varied with the time, are presented in figure 16. As the kerosene mass flow changed, the equivalence ratio changed from 0.53 to 0.61,

Table 5. The experimental scheme.

Scheme	Loop type	Pilot hydrogen ER	Kerosene mass flow rate and timing	Kerosene ER
Case 1	Open-loop	0.2	27 g/s+31 g/s 5 s+3 s	0.53+0.61 5 s+3 s
Case 2	Close-loop	0.2	28 g/s+0.31 MPa 5 s+3 s

Figure 15. Variation with the time of the fuel injection pressure and the wall pressure (case 1).

Figure 16. Variation with the time of the fuel flow rate, the fuel injection pressure and the wall pressure at x-axial location 370 mm (case 1).

Table 6. The performance of the fuel open-loop control test (i.e., case1).

Control expectations (g/s)	Rise time (s)	Overshoot (%)	Steady-state value (g/s)	Error (%)
27	0.88	3.89	26.82	−0.67
31	0.60	3.16	30.823	−0.57

which took less than 1s, and the regulating error was less than 1%. Meanwhile, the wall pressure in the combustor was proportional to the fuel flow rate. In addition, the performance of the open-loop control test of the fuel, i.e., case 1, is listed in table 6. At the same time, this test successfully achieved the purpose of controlling and regulating the fuel flow rate as the predetermined control timing.

In case 2, the open-loop control of the fuel was working during the first 5 seconds with a desired or pre-set kerosene mass flow rate 28 g/s, and after the stable kerosene combustion was achieved, the closed-control loop of the fuel started working during the last 3 seconds with a desired wall pressure 0.31 MPa at the specified point, i.e., x-axial location 370 mm. When the kerosene flow rate changed from 28 to 26 g/s, the equivalence ratio changed from 0.55 to 0.51. Under the open-loop control stage, the fuel flow rate achieved the desired value within 1 second and remained constant during the next 4 seconds. The wall pressure of the control point achieved 0.33 MPa when the kerosene burned alone. In the closed-loop control stage, the control point pressure achieved the desired value within 1 second and remained stable during the next 2 seconds. Besides, at the control point, the wall pressure was proportional to the fuel flow rate. The regulating error of it was less than 1%.

Figure 17. In case 2, the variation with the time of the hydrogen and the kerosene injection pressure and the wall pressure.

Figure 18. In case 2, the variation with the time of the kerosene injection pressure, mass flow rate (the open-loop controlled parameter) and the wall pressure (the close-loop controlled parameter).

Table 7. The performance of the fuel close-loop control test (i.e., case 2).

Control expectations	Rise time (s)	Overshoot (%)	Steady-state value	Error(%)
28 g/s	0.92	1.11	27.91 g/s	−0.32
0.31 MPa	0.08	1.29	0.31 MPa	−0.65

The curves of the hydrogen and the kerosene injection pressure and the wall pressure varied with the time (figure 17). The kerosene injection pressure, the mass flow rate (the open-loop controlled parameter) and the wall pressure (the closed-loop controlled parameter) varied with the time, as the curves presented in figure 18. The performance of the closed-loop control test of the fuel, i.e., case 2, is listed in the table 7.

5. Conclusion

We have conducted the design of the scramjet fuel control method, verified it by the ground experiment, and studied the possibility of the fuel-based control method with the wall pressure as the controlled parameter. The open-loop and closed-loop control test of the fuel had been accomplished and the study has revealed following points.

- The result of the open-loop control test of the fuel showed that the fuel driving and control system could work reliably. This test achieved the purpose of regulating and controlling the fuel as the desired timing and the satisfactory control cycle and error.

- (ii) The result of the numerical simulation and the closed-loop control test of the fuel presented that the wall pressure was proportional to the fuel flow rate and the thrust of scramjet in certain x-axial location of the combustor. The control method which chose the wall pressure as the feedback signal was proved feasible and the location of the pressure tap chosen by the numerical results was rational, and both of them were the important contributions of this study.

Moreover, the relationship between the wall pressure and the fuel flow rate with multi-fuel feed points is a complex issue. Therefore, how to design the law of the fuel feeding on multiple points is a difficult issue. To push this research further, the relationship between the wall pressure and the fuel flow rate of the multi-fuel injection points will be the key topic.

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