Ideal performance analysis of the scramjet with Pre-jet fuel

Shengsheng Zhang1,*, Yu Xue2, Yang Yang1, Haoliang Wang1, Yubao He1, Sihang Zheng1, Ya Lv1 and Yong Zhang1
1China Academy of Launch Vehicle Technology, Beijing 100076, China
2China United Gas Turbine Technology Co., LTD, Beijing 102209, China

*E-mail: zhangsshit@163.com

Abstract. In order to research the influence on the overall performance of scramjet with Pre-jet (jetting fuel or water vapor into the isolator) fuel, the governing equations of the different component in scramjet and the ideal performance analysis model with Pre-jet fuel are established. Moreover, Pre-jet fuel is considered based on the ideal Brayton cycle. The results of ideal performance analysis show that Pre-jet fuel doesn’t burn at a given maximum temperature of the combustor exit. Due to the increasing of oil to air ratio with Pre-jet fuel, the outlet temperature of the isolator drops more. However, fuel potential of the combustion, the flux of working fluid and the engine thrust ratio are increased. Meanwhile, the influence of methane and water vapor on the engine performance is similar, because the Pre-jet fuel is small and there are some similarities between methane and water vapor.

1. Introduction
As the most important part of hypersonic vehicle, the scramjet can be applied in hypersonic aircraft, spaceflight aircraft and the future single-stage round-trip transportation system powered by combined cycle. However, there are still many problems and challenges in improving performance [1]. Such as, engine thermal protection and supersonic combustion.

The Pre-jet (jetting fuel or water vapor into the isolator) fuel is designed to realize the multipurpose and maximize the potential of fuel. It can be used for reference to the improvement of engine cooling and other performance, as well as the subsequent development of scramjet technology. Foreign research institutes have done some work in this field, including the central aero engine research institute in Russia and the University of Florida in the United States. But there is very little research on this aspect in China. Only Peiyong Wang et al. Using the results of Hyshot scramjet test for reference and conducted numerical simulation of cold flow and combustion conditions respectively [2]. The initial goal of the Pre-jet fuel was to develop an effective aspirating propulsion cycle on a dual-mode scramjet using conventional hydrocarbon fuel when flight Ma>3.5 [3]. The main hypersonic aerodynamic problems including pressure loss caused by injection, mixing efficiency between fuel and main flow, interaction between intake system and combustion chamber, and flame stability [4-5].

Previous foreign researches mainly focus on the injection of liquid and gas fuel into the main flow of the inlet and the isolation section of supersonic or hypersonic, the location of the jetting tower bridge is either in the upstream of the combustion chamber or in the isolation section. Spraying fuel on the rear wall of the jetting tower bridge can improve mixing, flame stabilization and combustion efficiency. By fully considering fuel penetration depth, residence time, operating conditions, fuel physical and chemical properties, etc., the non-start phenomenon caused by combustion moving to the
inlet can be avoided, as shown in figure 1 and figure 2 [6-15]. Therefore, a more flexible system is obtained with Pre-jet fuel, and the interaction between fuel and air occurs throughout the entire system of the inlet, isolator, and combustor. Despite the complexity of system is increased, the following advantages can be achieved:

1) Reduced the length of isolator and combustor, decreased the engine weight and cooling pressure;

2) Get a more flexible fuel control system, it is due to the possibility of distributing fuel in the pre-injection and direct injection into the combustor, moreover, achieving liquid and gaseous fuel injection through the placement of different injectors [16-17].

Figure 1. Tower-bridge installed inside the compression surface of inlet.

Figure 2. Mixing efficiency of ethylene injection at Ma=6.

A series of key problems need to be solved to realize the application with Pre-jet fuel in actual flight, for example, the variation of angle of attack and sideslip-offset cause the flow structural change and mechatronics.

Previous researchers have mostly focused on the study of improving combustion performance with Pre-jet fuel. However, few studies have been conducted to assess the impact with Pre-jet fuel on the inlet temperature of combustor, the ultimate heating capacity and the overall performance of scramjet. Based on the ideal Brayton cycle, a one-dimensional analysis method of scramjet with Pre-jet fuel was developed, in order to improve analysis efficiency, avoid a lot of simulation and test work, and realize the rapid prediction of the overall performance in the scramjet with Pre-jet fuel. It provides important reference and basis for the application in the scramjet with Pre-jet fuel technology.

2. Analysis of the thermodynamic process in the scramjet with Pre-jet fuel technology

2.1. Physical model
The effect on the overall performance of scramjet with Pre-jet fuel were researched, as shown as figure 3, the physical model of scramjet with Pre-jet fuel was established, containing equivalent isolator, expansion chamber and nozzle.

Figure 3. Schematic diagram of scramjet with Pre-jet fuel.

Cross section 2 — entrance of the isolator without or with Pre-jet fuel;  
Cross section 3—exit of the isolator (or inlet of the combustor) without Pre-jet fuel;  
Cross section 4—exit of the combustor without Pre-jet fuel;  
Cross section 6—exit of the nozzle without Pre-jet fuel;  
Cross section 3’ — exit of isolator (or inlet of the combustor) with Pre-jet fuel;  
Cross section 4’ — exit of the combustor with Pre-jet fuel;  
Cross section 6’ — exit of the nozzle with Pre-jet fuel.

2.2. Analyses of thermodynamic cycle

According to mass, momentum, energy conservation and state equations, the governing equations of the working process of the scramjet with or without Pre-jet fuel are established respectively, as follow:

1) Entrance and exit of the isolator without Pre-jet fuel:

\[ m_2 = m_3 \]
\[ P_2 A + m_2 u_2 = P_3 A + m_3 u_3 \]
\[ m_2 \left( C_p T_2 + \frac{u_2^2}{2} \right) = m_3 \left( C_p T_3 + \frac{u_3^2}{2} \right) \]
\[ P = \rho R_g T \]

2) Entrance and exit of the isolator with Pre-jet fuel:

\[ m_2 + m_{j1} = m_3 = \rho \dot{m}_f A \]
\[ P_2 A + m_2 u_2 + m_{j1} u_{j1} \cos \theta = P_3 A + m_3 u_3 \]
\[ m_2 \left( C_p T_2 + \frac{u_2^2}{2} \right) + m_{j1} \left( C_p T_{j1} + \frac{u_{j1}^2}{2} \right) = m_3 \left( C_p T_3 + \frac{u_3^2}{2} \right) \]
\[ P = \rho R_g T \]

\( m \) — mass flow rate (kg/s), the subscript numbers represent different sections, the same below;  
\( m_{j1} \) — mass flow rate of Pre-jet fuel (kg/s), \( m_{j1} = m_2 \cdot f_1 \);  
\( P \) — pressure (N/m²);  
\( A \) — cross-sectional area (m²);  
\( u \) — flow rate (m/s);  
\( C_p \) — specific heat at constant pressure (J/kg.K);  
\( T \) — specific heat at constant pressure (K);  
\( \rho \) — density (kg/m³);  
\( R_g \) — gas constant (J/kg.K);  
\( \theta \) — the Angle between the spray direction and the axial direction (°).

It is assumed that the compression process of air flow is completed within the inlet, the compression in the isolation section is negligible. It can be seen from the formula, there is no parameter change in the inlet and outlet of the isolation. Supposing that Pre-jet fuel is unburned, only
reduced the inlet temperature of the combustor. The above formula (5)–(8), except for $\rho_i$, $u_i$, $P_i$ and $T_i$, the rest parameters are known that can be directly given or calculated by formulas (1) ~ (4). Four equations and four unknown parameters, the equations are closed and can be solved.

In general, some airflow properties kept constant in the scramjet, such as Mach number, flow area and static temperature, it is not difficult to modeling the combustion or heat addition process. But the main reasons for the preference of constant pressure processes are as follows: Firstly, from the perspective of aerodynamics, constant pressure process eliminated the possibility of boundary layer separation and the need for structure to withstand peak pressure; Secondly, the internal static pressure can be approximately regarded as a constant because the velocity of the combustor decreases to a small level for the scramjet; Thirdly, when chemical energy release an equal-area combustor operates at constant pressure processes due to separation of the boundary layer. This paper chooses constant pressure processes.

3) Entrance and exit of the combustor with Pre-jet fuel:

$$P_3 = P'_4$$  \hspace{1cm} (9)

$$m_i + m_{f_2} = m'_4$$  \hspace{1cm} (10)

$$m_i u_i - C_f A_i / (2A_i) \rho_i u_i A_i = m'_4 u_i$$  \hspace{1cm} (11)

$$m_i (C_p T_i + u_i^2 / 2) + m_{f_2} \times \left( \eta_f H_f + C_p T_{f_2} + u_{f_2}^2 / 2 \right) = m'_4 (C_p T'_4 + u'_4^2 / 2)$$  \hspace{1cm} (12)

$$C_f A_i / A_i = \text{drag} / \left( \rho_i u_i^2 A_i \right)$$ — effective resistance coefficient of combustor, command $C_f A_i / A_i = 0$; $H_f$ — heat value of methane(kJ/kg), command $H_f = 50010$ kJ/kg [18]; $\eta_f$ — combustion efficiency, command $\eta_f = 1.0$; $m_{f_2}$ — fuel mass flow of combustor (kg/s), command $m_{f_2} = m_2 \times f_2$.

The equations (5), (10) and (11) are obtained simultaneously:

$$u'_4 = u_i \left( 1 + f_1 \right) / \left( 1 + f_1 + f_2 \right)$$  \hspace{1cm} (13)

The maximum temperature $T_{\text{max}}$ at outlet of the combustor is 2300K, meantime, outlet temperature of the combustor ($T'_4$) is equal to $T_{\text{max}}$. Pre-jet fuel can reduce inlet temperature of the combustor without burning. The oil to air ratio $f_2$ of the combustor can be applied to explain the maximum energy injection of the combustor. Two equations (11) and (12) can be solved with two parameters.

4) Entrance and exit of the nozzle with Pre-jet fuel, the process is equivalent to the static pressure and frictionless. The specific equations are as follows:

$$T_{is} = T_{is}$$  \hspace{1cm} (14)

$$P_{is} = P_{is}$$  \hspace{1cm} (15)

$$P_{s} = P_{s}$$  \hspace{1cm} (16)

$$m_i (C_p T_i + u_i^2 / 2) = m'_s (C_p T'_s + u'_s^2 / 2)$$  \hspace{1cm} (17)

3. Simulation of effect on the performance of the scramjet with Pre-jet fuel

3.1. Boundary condition

The hypersonic vehicle usually designs at the isodynamic pressure $q_0$. If the dynamic pressure ($q_0$) is too high, the structure stress and resistance on the vehicle is very heavy; on the other hand, if the dynamic pressure ($q_0$) is too low, the wing space required to maintain flight may be immense [19]. It is generally acknowledged the hypersonic vehicle must be designed in a relatively narrow dynamic pressure range, approximately 20000~90000N/m$. Designing at the isodynamic pressure $q_0 = 50000N/m^2$ in this paper, the compression efficiency, combustion efficiency and
expansion efficiency are given in accordance with the literature [20], relevant parameters are shown in table 1.

Table 1. Summary table of correlation parameters.

| Numerical order | Parameters                               | Unit   | Value        |
|-----------------|------------------------------------------|--------|--------------|
| 1               | flight altitude                          | km     | 22.45        |
| 2               | Mach number                              | -      | 6            |
| 3               | compression efficiency                    | -      | 0.88         |
| 4               | combustion efficiency                     | -      | 1.0          |
| 5               | inlet Mach number of the isolator        | -      | 2.8 (Ma0=6) 2.4 (Ma0=5) |
| 6               | heat ratio of free flow                   | -      | 1.36         |
| 7               | heat ratio of compressive flow            | -      | 1.34         |
| 8               | heat ratio of the combustion              | -      | 1.238        |
| 9               | heat ratio of expansion                   | -      | 1.238        |
| 10              | calorific value of gaseous methane        | J/kg   | 50010        |
| 11              | gas constant of mixed gas, calculate      |        |              |
| 12              | inlet area of the isolator               | m²     | 0.15         |
| 13              | inlet area of the combustor              | m²     | 0.15         |
| 14              | outlet area of the combustor              | m²     | 0.225        |
| 15              | total temperature of Pre-jet fuel         | K      | 300          |
| 16              | area of Pre-jet fuel                     | m²     | 0.001        |

The gas is regarded as ideal gas, the heat capacity of common gases under constant pressure is calculated as follows:

\[ C_p = C_v + C_0 \theta + C_1 \theta^2 + C_2 \theta^3 \text{ kJ/(kg} \cdot K) \theta = \{T \}/1000 \quad (18) [20] \]

Application range of equation (18): 250~1200K, the constant pressure specific heat capacities of methane and water vapor at constant pressure at 300K were calculated respectively, the results are shown in table 2.

Table 2. Constant pressure specific heat capacities of methane and water vapor.

| Parameter           | \( C_0 \) | \( C_1 \) | \( C_2 \) | \( C_3 \) | \( C_f \text{[kJ/(kg} \cdot K)} \) |
|---------------------|--------|--------|--------|--------|-----------------------------|
| Methane             | 1.2    | 3.25   | 0.75   | -0.71  | 2.22333                    |
| Water vapor         | 1.79   | 0.107  | 0.586  | -0.2   | 1.86944                    |

The gas constants of mixed gas of methane and mainstream air in the isolator are calculated according to equation (19).

\[ R = \frac{1.9857117\text{Btu}/(\text{lbm} \cdot R)}{28.97 - f_c \times 0.946186} \quad (19) \]

The unit conversion in equation (19) is as follows, when calculate outlet air flow parameters of the isolator with Pre-jet fuel, the oil to air ratio here refers \( f_c \) specifically.

\[ \frac{\text{lbm}}{\text{lbm} \cdot R} = 4.1868 \text{kJ}/(\text{kg} \cdot K) \quad (20) \]

\[ F_s = (1 + f_1 + f_2)V_0^2 - V_0 \quad (21) \]

\[ I_{\text{sp}} = F_s / g_0/(f_1 + f_2) \quad (22) \]

\[ W = 0.5 \times \left[(1 + f_1 + f_2)V_k^2 - V_0^2 \right] \quad (23) \]

\[ \eta_a = \frac{W}{f_3(H_u n_0 + u_2^2/2)} \quad (24) \]

\[ \eta_c = \eta_a / n_0 \quad (25) \]
\[ \eta = \frac{F V_w}{W} \]  
\[ \eta_b = \eta_a \eta_p \]  

- \( W \) — mechanical power of scramjet (unit mass);  
- \( f_i, f_l \) — oil to air ratio of isolator and combustor;  
- \( \eta \) — thermal efficiency of scramjet;  
- \( \eta_a \) — thermodynamic cycle efficiency of scramjet;  
- \( \eta_p \) — propulsion efficiency of scramjet;  
- \( \eta_o \) — total efficiency of scramjet.

3.2. Simulation study

Setting up the simulation platform based on the scramjet model at Matlab environment. Spray Angle is 300. The effects of methane and water vapor on the overall performance of the scramjet were investigated when there is Pre-jet fuel in isolator with inlet flow Mach number 5.0 and 6.0.

As shown in figure 4, because methane has more enthalpy than water vapor per unit mass \( (C_{pf}/T_f) \), when same Mach number and same oil to air ratio of isolator, outlet air static temperature of the isolator is reduced more by injecting methane gas. It can be seen that methane has more cooling capability. With the increasing of oil to gas air ratio, the difference of cooling effect between the methane and water vapor on the main stream becomes larger, this is mainly caused by the larger enthalpy difference between the methane and water vapor. Static temperature is shown in table 3.

| Table 3. The influence of different oil to air ratio on the isolator outlet static temperature reduction with Pre-jet fuel. |
|---------------------------------------------------------------|
| \( f_l \) | 0 | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 |
| \( T_i \) temperature reduction comparing without Pre-jet fuel \( (K) \ (M_a=5 \text{ methane}) \) | 0 | 5.66 | 13.21 | 22.22 | 32.34 | 43.21 | 54.53 |
| \( T_i \) temperature reduction comparing without Pre-jet fuel \( (K) \ (M_a=5 \text{ water vapor}) \) | 0 | 2.74 | 7.34 | 13.46 | 20.80 | 29.06 | 38.00 |
| \( T_i \) temperature reduction comparing without Pre-jet fuel \( (K) \ (M_a=6 \text{ methane}) \) | 0 | 3.40 | 10.41 | 20.15 | 31.79 | 44.64 | 58.02 |
| \( T_i \) temperature reduction comparing without Pre-jet fuel \( (K) \ (M_a=6 \text{ water vapor}) \) | 0 | 0.1 | 3.66 | 9.96 | 18.33 | 28.18 | 38.94 |

Figure 4. The relationship between the isolator outlet static temperature and oil to air ratio with Pre-jet fuel (or water vapor to air ratio).
As shown in figure 5, jetting methane or water vapor into isolator. It is assumed that the fuel jetted in the isolator didn’t burn, due to its cold gas ($T_f=300K$), outlet static temperature of isolator (or inlet static temperature of combustor) reduced. Supposing that the combustor outlet temperature limit kept constant. The Pre-jet fuel can increase the temperature difference between the inlet and outlet of the combustor. Meanwhile, the combustion outlet is close to maximum mass flow with the temperature reached to maximum.

The results show that inlet static temperature of the combustor is low when the Mach number ($M_{a0}=5$) is low. As a result, the maximum capacity of jetting oil to air ratio ($f_2$) is relatively large. Under the same Mach number and the oil to air ratio of isolator, the combustion maximum oil to air ratio are close either jetting methane or water vapor. It can be seen from table 3, jetting methane only decreases about 20K more than water vapor when the maximum oil to air ratio $f_1$ is equal to 0.06. On the basis of $\eta f H mC T \eta\Theta f$ $f H mC T \eta\Theta f$ , Because the high heat value of methane and the similarity of constant pressure specific heat, the oil to air ratio change is very small. The oil to air ratio (or water vapor to air ratio) with Pre-jet fuel increases, while the difference between methane and water vapor temperature increases, the oil to air ratio (or water vapor to air ratio) difference between methane and water vapor in the combustor is also increased. As shown in table 4, compared without Pre-jet fuel, the case that oil to air ratio is 0.06 at $M_{a0}=6$ (the oil to air ratio was 0.05825 when the equivalence ratio was 1.0), the maximum oil to air ratio of the combustor was increased by 6.76%. And as $f_1$ increases, $f_2$ increases almost linearly.

### Table 4. Influence of different oil to air ratio with Pre-jet fuel on the ultimate oil to air ratio of combustor (taking methane as an example).

| $f_1$ | 0   | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 |
|-------|-----|------|------|------|------|------|------|
| $f_2$ growth rate with Pre-jet fuel ($M_{a0}=5$) | 0 | 1.05% | 2.16% | 3.34% | 4.56% | 5.81% | 7.09% |
| $f_2$ growth rate with Pre-jet fuel ($M_{a0}=6$) | 0 | 0.921% | 1.97% | 3.10% | 4.3% | 5.53% | 6.76% |

![Figure 5](image)

Figure 5. The relationship between the limiting oil to air ratio of the combustor and oil to air ratio with Pre-jet fuel (or water vapor to air ratio).

As shown in figure 6, the unmounted specific thrust increases with the increasing of oil to air ratio (or water vapor to air ratio). The main reason is increasing the flow rate of working medium, meanwhile, cooling can also play a role by increasing the oil to air ratio of the combustor, both functions increase propulsion. According to the analysis, the process of jetting methane or water vapor is similar, the detailed comparison between different oil to air ratio (or water vapor to air ratio) with or without Pre-jet fuel is shown in table 5.
Figure 6. The relationship between the unmounted specific thrust and oil to air ratio with Pre-jet fuel (or water vapor to air ratio).

Table 5. Influence of different oil to air ratio with Pre-jet fuel on the unmounted specific thrust (taking methane as an example).

| f1  | 0   | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.06 |
|-----|-----|------|------|------|------|------|------|
| $F_s$ growth rate with Pre-jet fuel $(M_a=5)$ | 0   | 1.88%| 3.77%| 5.65%| 7.54%| 9.43%| 11.33%|
| $F_s$ growth rate with Pre-jet fuel $(M_a=6)$ | 0   | 2.29%| 4.70%| 7.23%| 9.87%| 12.63%| 15.52%|

As shown in figure 7, the specific impulse defined is the specific thrust of unit weight propellant, the propellant contains methane or water vapor with Pre-jet fuel. Although the Pre-jet fuel lowers the inlet temperature of the combustor, it can accommodate more fuel. However, the flow rate of the propellant is lower with Pre-jet fuel that this part of the propellant does not combust, but only plays a cooling role. With increasing of oil to air ratio (or water vapor to air ratio) with Pre-jet fuel, the specific impulse naturally decreases and fuel economy decreases.

As shown in figure 8, with increasing of oil to air ratio (or water vapor to air ratio) with Pre-jet fuel, the total engine efficiency is improved. In equation (25) the fuel only refers to the fuel injection to the combustor, and does not include the fuel with Pre-jet fuel. From the effect of input and output, the definition is flawed and the amount of Pre-jet fuel should be included.

Figure 7. The relationship between the specific impulse and oil to air ratio with Pre-jet fuel (or water vapor to air ratio).
Figure 8. The relationship between the engine overall efficiency and oil to air ratio with Pre-jet fuel (or water vapor to air ratio).

4. Conclusion
The effect on the performance of the scramjet with Pre-jet fuel was analysed in this paper. Governing equations of the different component in scramjet and an ideal performance analysis simulation platform were established. Meantime, methane and water vapor with Pre-jet fuel was compared at different Mach number. There were combustion, shock wave, friction and fuel thermal dissociation losses in the actual scramjet with Pre-jet fuel. The following conclusions could be obtained based on ideal situation.

1) Compared with the scramjet without Pre-jet fuel, with increasing of the oil to air ratio, the outlet static temperature of isolator was reduced more tempestuously, by contrast, the total engine efficiency was improved.

2) Compared with the scramjet without Pre-jet fuel, when the oil to air ratio of isolator was 0.06 at Ma0=6 (the oil to air ratio was 0.05825 when the equivalence ratio was 1.0), the maximum oil to air ratio of the combustor was increased by 6.8%, and the unmounted specific thrust was increased by 15.5%.

3) Compared with the scramjet without Pre-jet fuel, because the mass flow of working fluid increased with Pre-jet fuel, the specific thrust increased, meanwhile, the specific impulse and the fuel economy also reduced.

4) Compared with the scramjet without Pre-jet fuel, the effect of methane on scramjet performance with Pre-jet fuel was similar to water vapor.

References
[1] Ning Li, Xuchang Li, Hongyu Xiao. A review of new technologies of scramjet [J]. Winged Missiles Journal. 2013, 7(7): 86-93.
[2] Peiyong Wang, Ming Chen, Fei Xin. CFD numerical simulation of Hyshot scramjet [J]. Journal of Aerospace Power, 2014, 29(5): 1020-1028.
[3] Vinsgrads V A, Prudnikov A G. Injection of liquid into the strut shadow at supersonic velocities [R]. SAE Technical Paper, 1993.
[4] Seiner J M, Dash S M, Kenzakowski D C. Historical survey on enhanced mixing in scramjet engines [J]. Journal of Propulsion and Power, 2001, 17(6): 1273-1286.
[5] Sisilian J P, Parent B. Hypervelocity fuel/air mixing in a scramjet inlet [J]. Journal of propulsion and power, 2004, 20(2): 263-272.
[6] Schwartzentruber T E, Sisilian J P, Parent B. Suppression of premature ignition in the premixed inlet flow of a scramjet [J]. Journal of propulsion and power, 2005, 21(1): 87-94.
[7] Arai T, Kasahara J, Mukai K, et al. Experiments of Pre-Mixing Shock-Induced Combustion Scramjet with Forebody-Wall Fuel Injection [J]. AIAA Paper, 2002 (2002-5243).
[8] Star JB, Edwards, J R, Smart, MK, Baurle RA. Numerical Simulation of Scramjet Combustion in a Shock Tunnel. AIAA Paper No. 2005-0428, Jan. 2005.

[9] Shikhman Y M, Vinogradov V A, Yanovskiy L S, et al. The Demonstrator of Technologies—Endothermic Hydrocarbon Fueled Dual Mode Scramjet [J]. AIAA Paper, 1787-2001, 2001.

[10] Buriko Y, Vinogradov V, Goltsev V, et al. Influence of Active Radical Concentration on Self-Ignition Delay of Hydrocarbon Fuel/Air Mixture. Journal of Propulsion and Power, 2002, 18(5): 1049-1058.

[11] Livingston T, Segal C, Schindler M, et al. Penetration and spreading of liquid jets in an external-internal compression inlet [J]. AIAA Journal, 2000, 38(6): 989-994.

[12] Goldfeld M A, Starov A V, Vinogradov V V. Experimental study of scramjet module [J]. Journal of Propulsion and Power, 2001, 17(6): 1222-1226.

[13] Guoskov OV, Kopchenov VI, et al. Numerical Researches of Gaseous Fuel Pre-Injection in Hypersonic 3-D Inlet. Journal of Propulsion and Power, 2001, 17(6): 1162-1169.

[14] Odam J. Scramjet experiments using radical farming [J]. 2004.

[15] Mudford N R, Mulreany P J, McGuire J R, et al. CFD calculations for intake-injection shock-induced combustion scramjet flight experiments [J]. AIAA Paper, 2003, 7034.

[16] Owens M, Mullargili S, Segal C, et al. Effect of kerosene pre-injection on combustion flameholding in a Mach 1.6 airflow [J]. Journal of Propulsion and Power, 2001, 17(3): 605-611.

[17] Vinogradov V A, Shikhman Y M, Albegov R M, et al. Experimental research of pre-injected methane combustion in high speed subsonic airflow [J]. 12th AIAA International Space Planes and Hypersonic systems and technologies, Norfolk, Virginia, USA, 2003.

[18] Reynolds W C, Perkins H C. Engineering thermodynamics [M]. McGraw-Hill, 1977.

[19] Bertin J J. Hypersonic aerothermodynamics [M]. AIAA, 1994.

[20] Weidao Shen, Jungeng Shen. Engineering thermodynamics [M]. Beijing: Higher Education Press 2011.