

Combustion efficiency test method in scramjet engine

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Abstract: A scramjet engine combustion efficiency measure system was designed. The combustion efficiency was measured by chromatography method, and the results of chromatography method were compared with those of temperature method. The results indicate that the combustion efficiency measured by chromatography method was 80.7%, lower than the combustion efficiency of 84.5% measured by temperature method; the combustion efficiency could be measured more precisely by chromatogram method than by temperature method. The combustion efficiency measure system based on chromatogram method can work well, and thus can be used to measure the combustion efficiency of scramjet engine.

Key words: supersonic; combustion test; combustion efficiency; sampling analysis; sampling probe

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The combustion efficiency is an important performance parameter of scramjet engine. The temperature and velocity of the scramjet engine combustor exit are very high, so it is difficult to measure the combustion efficiency of scramjet engine.

The combustion gas composition analysis method is a widely used method for combustion efficiency measuring^[1-9]. In this paper, a sample gas chromatographic method was used to measure the combustion efficiency of scramjet engine. The chromatography system was CP3800 gas chromatography system of America Varian Company. The combustion efficiency measured by chromatography method was compared with that of temperature method.

1 Introduction of sampling probe

1.1 Sampling probe design

According to the sampling probe design

experience in American and Japan, sampling probe inlet diameter was selected as 0.3—1.0 mm^[2,4-6,10-15]. In this paper, the sampling probe was designed as 3 parts in Fig. 1, and the sampling probe inlet diameter was selected as 0.6 mm.

In the first part, no water cooling, so the inlet and outlet diameters of the first part were selected as 0.6 mm, and the length was selected as 1.0 mm.

In the second part, sampling probe inlet diameter was selected as 0.6 mm. The sampling gas outlet static temperature T changing with different outlet diameters was given as Fig. 2. According to the simulation results of Fig. 2, the second part outlet diameter D was selected as 1.8 mm, and the length was selected as 2.5 mm.

In the third part, the sampling gas outlet static temperature changing with different outlet diameters was given as Fig. 3. From Fig. 3, it was found that, if the outlet diameter was more than 3.2 mm, the sampling gas outlet static tem-

perature began to decrease slowly. According to the results of Fig. 3, the inlet and outlet diameters of the third part were selected as 3.2 mm with 25 mm in length.

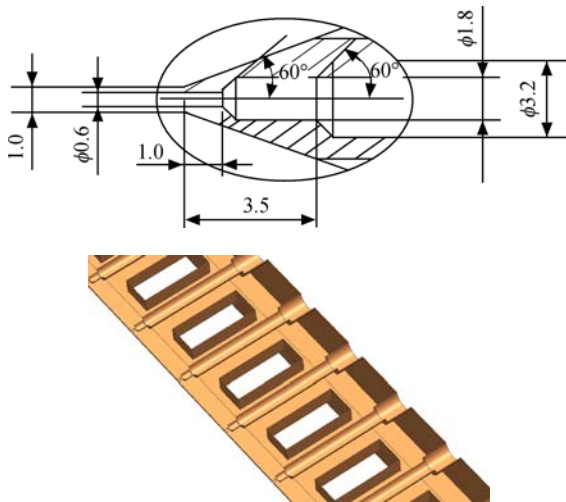


Fig. 1 Structure of sampling probe (unit:mm)

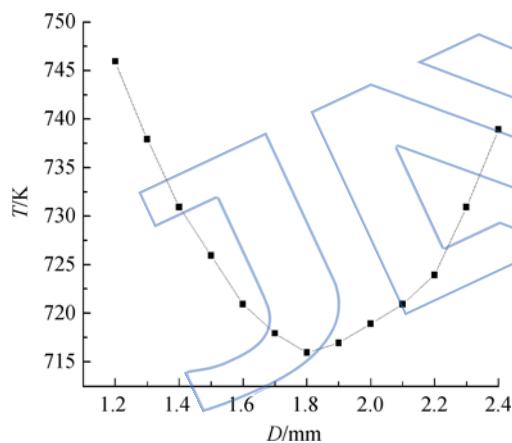


Fig. 2 Static temperature distribution of the second part

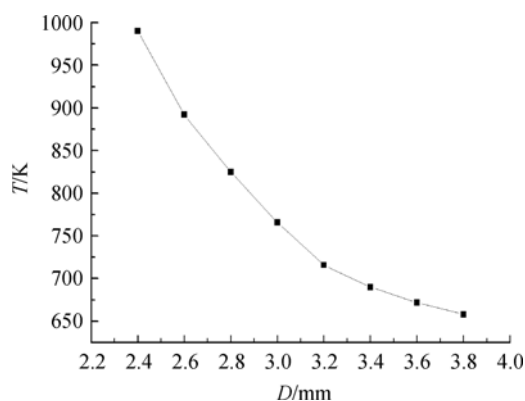


Fig. 3 Static temperature distribution of the third part

1.2 Sampling probe parameter distribution

In the ordinary case, if the sampling gas outlet static temperature decreases to 500 K, the sampling gas can be frozen. In order to keep the sampling gas without chemical reaction along the sampling probe, the sampling gas outlet static temperature need to be decreased to 500 K during the sampling gas pass through the sampling probe.

In order to get the sampling gas outlet static temperature changing along the sampling probe, numerical simulation of the sampling gas flow was made. Figure 4 showed the grid of sampling probe; Fig. 5 and Fig. 6 were the Ma and static temperature changing along the probe length X ; Fig. 7 and Fig. 8 were the Ma and static temperature distribution along the probe length.

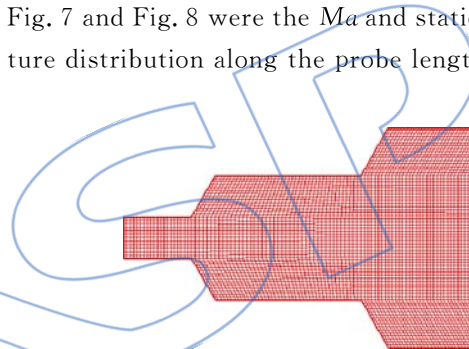


Fig. 4 Grid of sampling probe

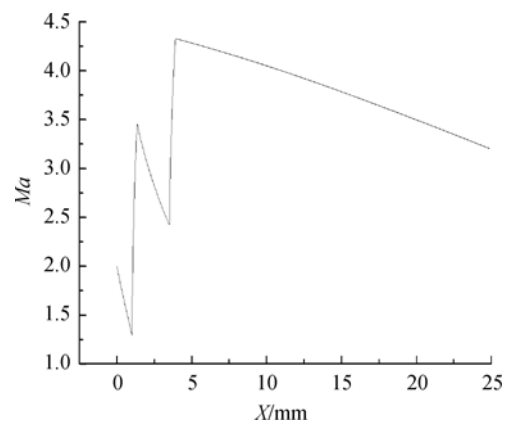


Fig. 5 Ma changing along probe length

The time of the sampling gas outlet static temperature decreased to 500 K can be calculated as follow:

$$\tau = \frac{L}{V} = \frac{0.005}{1101} = 4.5 \times 10^{-6} (\text{s}) \quad (1)$$

The time of the sampling gas chemical reaction rate decreased to 1/100 of starting value can be calculated as follow:

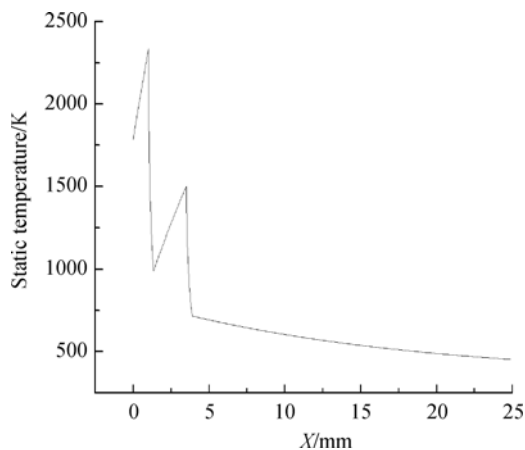


Fig. 6 Static temperature changing along probe length

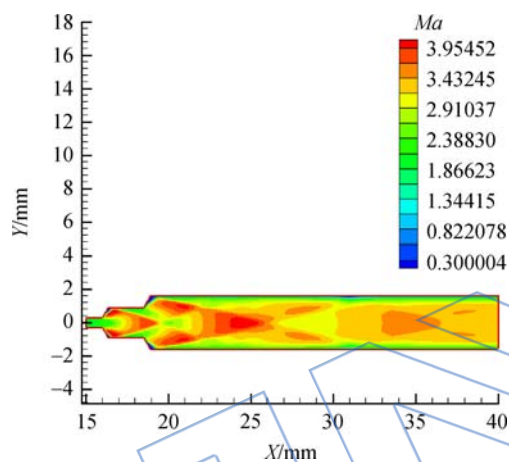


Fig. 7 Ma distribution along probe length

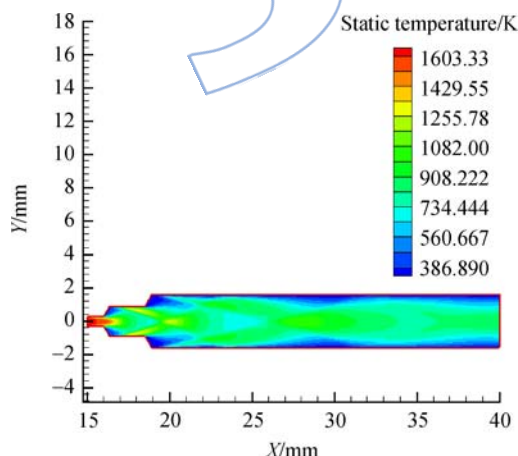


Fig. 8 Static temperature distribution along probe length

Where L is the frozen front moving distance of sampling gas; V is the sampling gas flow velocity; R is universal gas constant; E is activation energy of the reaction; T_i is the inlet temperature of sampling gas; T_c is the frozen temperature of chemical reaction.

From the results of Fig. 5 to Fig. 8, it was found that the sampling gas outlet static temperature was 450 K, lower than the frozen chemical reaction temperature of 500 K; the temperature decreasing time was 4.5×10^{-6} s, and the time of the sampling gas chemical reaction rate decreasing to 1/100 of starting value was 2.79×10^{-5} s, also lower than the frozen chemical reaction time of 4.5×10^{-6} s. It indicated that no chemical reaction appeared in the sampling gas during the sampling process.

1.3 Test system

Test plant schematic diagram of scramjet engine gas analysis was given as Fig. 9. The experiment plant included sampling system, sample transport system, chromatographic analysis system and control system. Figure 10 and Fig. 11 showed sample control system and sampling probe structure, and Fig. 12 was the gas chromatographic system flowchart.

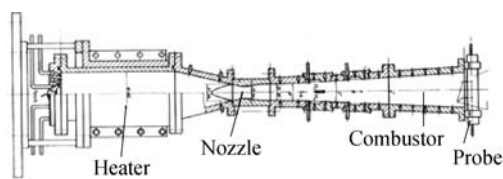


Fig. 9 Schematic diagram of test plant

As shown in Fig. 12, the sampling gas was gotten from the sampling probe, then was transported to the sampling gas chromatographic analysis system, and then the sampling gas components were analyzed by the chromatographic analysis system and the combustion efficiency of the scramjet engine was gotten.

1.4 Combustion efficiency calculation of chromatography method

The fuel combustion equation could be written as

$$2 \left(\frac{RT_i}{E} \times \frac{T_i}{T_i - T_c} \times \ln 10 \right) \times \tau_1 = 2.79 \times 10^{-6} \text{ (s)} \quad (2)$$

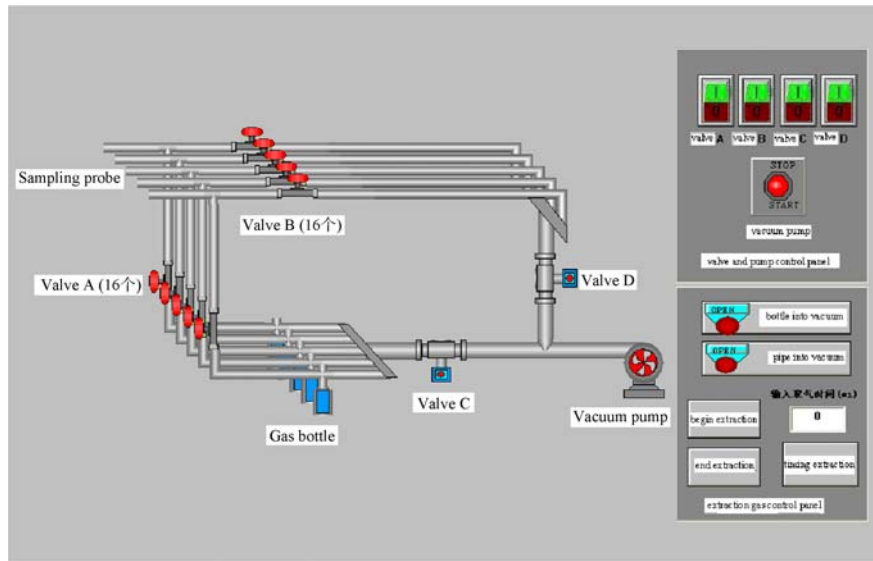


Fig. 10 Sample control system

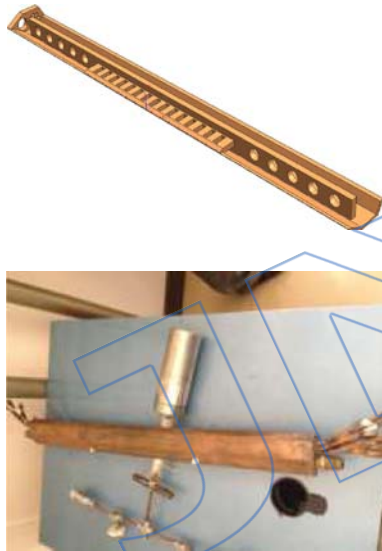


Fig. 11 Sampling probe structure

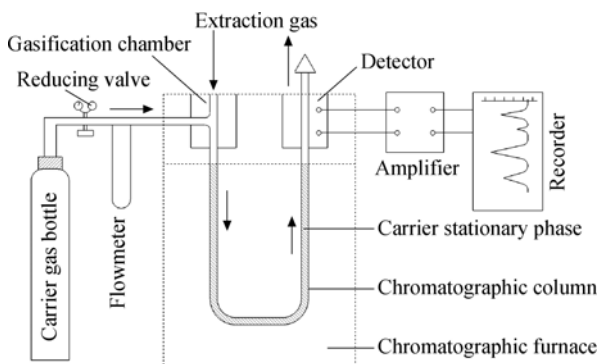
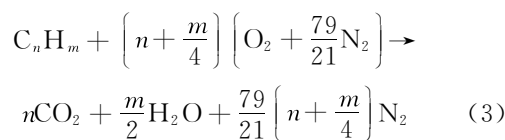


Fig. 12 Gas chromatographic system flowchart



The fuel equivalence ratio could be written as

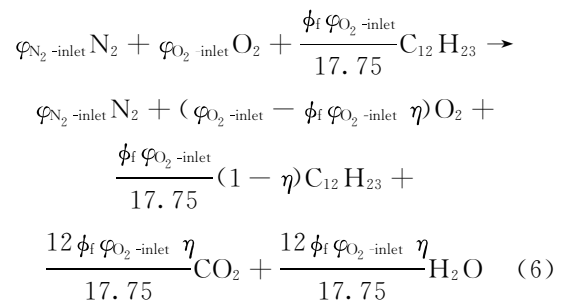
$$\phi_f = \frac{1}{\alpha} = \frac{f}{f_{st}} \quad (4)$$

Where f was gas/fuel ratio; f_{st} was stoichiometric gas/fuel ratio, which could be written as

$$f_{st} = \frac{36n + 3m}{103(4n + m)} \quad (5)$$

Supposing fuel molecular formula was $C_{12}H_{23}$, the stoichiometric gas/fuel ratio could be calculated as $f_{st} = 0.06796$.

The chemical reaction equation could be written as



Where $\varphi_{N_2 - \text{inlet}}$ was volume fraction of N_2 in combustor inlet; $\varphi_{O_2 - \text{inlet}}$ was volume fraction of O_2 in combustor inlet; η was the combustion efficiency. Obviously, the combustion efficiency could be gotten as follow:

$$\frac{\varphi_{CO_2}}{\varphi_{N_2}} = \frac{12 \phi_f \varphi_{O_2 - \text{inlet}} \eta}{17.75 \varphi_{N_2 - \text{inlet}}} \Rightarrow \eta = \frac{1.48 \cdot \varphi_{N_2 - \text{inlet}} \cdot \varphi_{CO_2}}{\phi_f \varphi_{O_2 - \text{inlet}} \cdot \varphi_{N_2}} \quad (7)$$

Where φ_{CO_2} was volume fraction of CO_2 in combustor exit; φ_{N_2} was volume fraction of N_2 in

combustor exit.

1.5 Combustion efficiency calculation of temperature method

The combustion efficiency could be written as

$$\eta = \frac{T_1 - T_0}{T_e - T_0} \quad (8)$$

Where T_0 was the initial reaction temperature; T_1 was the test temperature of the combustion products; T_e was the theoretical flame temperature of the combustion products.

2 Results comparison of chromatography method and temperature method

2.1 Combustion efficiency results measured by chromatography method

The combustor inlet condition was as follow: $T_0 = 298.15 \text{ K}$, $f = 0.027855$, $\varphi_{N_2} = 0.780840$, $\varphi_{O_2} = 0.209467$, $\varphi_{Ar} = 0.009365$, $\varphi_{CO_2} = 0.000319$.

The sample TCD (thermal conductivity detector) chromatogram was given as Fig. 13, the sample FID (flame ionization detector) chromatogram was given as Fig. 14.

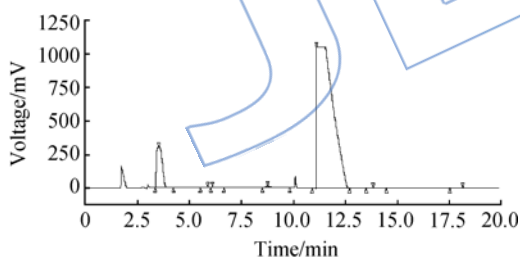


Fig. 13 Sample TCD chromatogram

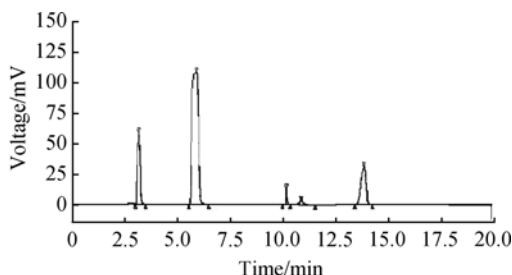


Fig. 14 Sample FID chromatogram

From Fig. 13 and Fig. 14, sample volume fraction in combustor exit could be gotten as fol-

low: $\varphi_{N_2} = 0.792000$, $\varphi_{CO_2} = 0.047100$, $\varphi_{CH_4} = 0.000458$, $\varphi_{C_2H_6} = 0.000353$, $\varphi_{NO} = 0.000497$.

Inserting the parameter in Eq. (7), the combustion efficiency could be calculated as 80.7%.

2.2 Combustion efficiency results measured by temperature method

The enthalpy of air and fuel at 298.15 K was $h_{air} = -125.530 \text{ kJ/mol}$, $h_{fuel} = -57740.001 \text{ kJ/mol}$.

From Eq. (3), the enthalpy of the combustion products could be calculated as $h_{gas} = 15.273 \text{ kJ/mol}$.

Supposing fuel molecular formula was $C_{12}H_{23}$, the combustor inlet condition was $T_0 = 298.15 \text{ K}$, $f = 0.027855$.

According to the thermodynamic calculation theory, the theoretical flame temperature of the combustion products could be calculated as $T_e = 1365.42 \text{ K}$. The sample volume fraction could be calculated as follow: $\varphi_{N_2} = 0.757900$, $\varphi_{CO_2} = 0.055660$, $\varphi_{H_2O} = 0.058110$, $\varphi_{O_2} = 0.118800$, $\varphi_{NO} = 0.000440$, $\varphi_{NO_2} = 0.000020$, $\varphi_{Ar} = 0.009090$, $\varphi_{H_2O} = 0.058110$, $\varphi_{OH} = 0.000010$.

The temperature in combustor exit could be tested as $T_1 = 1200 \text{ K}$.

From Eq. (8), the combustion efficiency could be calculated as 84.5%.

2.3 Results comparison

From the combustion efficiency results above, the combustion efficiency measured by chromatography method was 80.7%, lower than the combustion efficiency measured by temperature method of 84.5%.

3 Error analysis

From the combustion efficiency results above, it could be found that the combustion efficiency measured by chromatography method was lower than that of temperature method. The reason can be explained as follow.

The sample volume fraction in combustor exit measured by chromatograph method was $\varphi_{N_2} = 0.792000$, $\varphi_{CO_2} = 0.047100$.

The sample volume fraction in combustor

exit calculated by thermochemistry was $\varphi_{N_2} = 0.758000$, $\varphi_{CO_2} = 0.055700$.

From the sample volume fraction in combustor exit, it could be found that, CO_2 volume fraction measured by chromatography method was lower than the calculated.

From the sample volume fraction by thermochemistry calculation, it could be found that there were some other products in combustor exit, such as $\varphi_{NO} = 0.000440$, $\varphi_{NO_2} = 0.000020$, $\varphi_{OH} = 0.000010$, and so on. From the sample volume fraction measured by chromatography method, it could be found that there were some other products in combustor exit, such as $\varphi_{CH_4} = 0.000458$, $\varphi_{C_2H_6} = 0.000353$, and so on. So it could be concluded that the fuel could not be combusted completely, and combustion efficiency measured by chromatogram method was lower than that by temperature method.

The other reason of combustion efficient measured by chromatography method lower than that by temperature method is the sampling gas was the average of 16 sampling probes, but the temperature was the center temperature of combustor exit.

The other reason is that, in high temperature condition, the combustion products appear chemical dissociation phenomenon, so the test temperature and combustion efficiency by temperature method are higher than that by chromatography method.

Consequently, the chromatogram method could be used to measure the combustion efficiency more precisely than that by the temperature method.

4 Conclusion

By comparing the combustion efficiency results above, some conclusions can be gotten as follow:

1) The combustion efficiency measured by chromatography method was 80.7%, lower than

the combustion efficiency measured by temperature method of 84.5%.

2) The chromatogram method could be used to measure the combustion efficiency more precise than temperature method.

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