Gas sampling/analysis of the high enthalpy supersonic flow

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Abstract. Analysis of combustion efficiency is very important for evaluating the engine performance. The components of exhaust gas from the combustor may indicate the behavior of combustion. Therefore, a measurement system of the gas sampling/ chromatographic analysis has been developed under supersonic combustion condition. The components of H_2, O_2, N_2, CO, and CO_2 have been obtained under different pressure and temperature of kerosene injection. The results shown the combustion is not uniform, and the average combustion efficiency is around 70%. The further investigation should be carried out to get more details in order to improve the performance.

1 Introduction

Combustion efficiency is very important for evaluating engine performance. It could be inferred from the components of the exhaust. Therefore, some methods for analyzing the gas component have been developed, and gas sampling/chromatographic analysis is one of them. This method is widely used in subsonic combustion, but for scramjet engine it is particular difficult due to the high Mach number flow.

The key for the gas sampling is to sample the "real" gas, which means no further chemical reaction during the process for taking the sample. Since the reaction rate depends on the temperature strongly, the problem becomes how to cool the sample gas. Usually, there are three ways for cooling – through convection, expansion or dilution. Many researches about forced convection have been done to demonstrate that the cooling rate could be as high as 10^7K/s under certain conditions, which is fast enough to quench any reaction within 0.1-1ms. Expansion is usually used for the supersonic flow, since the static pressure and temperature would drop rapidly when the flow area suddenly expands. Colket[1] demonstrated that supersonic flow may be established inside the thin tubes with inner diameter of 0.075mm -2mm under certain configuration and pressure ratio. Dilution is the method to quench the reaction by mixing some inert gases into the sampling gas.

Mitani etc.[3,4] have obtained the samples for the supersonic combustion successfully by using the methods combined the forced convection and expansion. He also gave the critical Damkohler number to analyse the reaction quenching.

In the present study, a gas sampling/chromatographic analysis system has been established in the Institute of Mechanics, Chinese Academy of Sciences. The system is used for the direct connected supersonic combustion facility. The purpose is to analyze the combustion performance for the hydrocarbon fuel.

2 Experimental system

The sketch of the whole system is shown in Fig.1. The model supersonic combustor is connected directly with a vitiated heater through a nozzle. The facility was installed vertically. The lowest part is the vitiated heater, which can provide the main flow gas with high pressure and temperature. The nozzle is designed for Mach number of 2.5. Therefore, the flow condition for the

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entrance of the combustor is Mach 2.5, the total pressure about 1.1MPa, and the total temperature about 1800K. The sampling rake was installed at the exit of the combustor, and the design point is under the exit conditions of the supersonic combustor, i.e. Mach number about 2, static temperature above 2000K and static pressure around 0.1MPa.

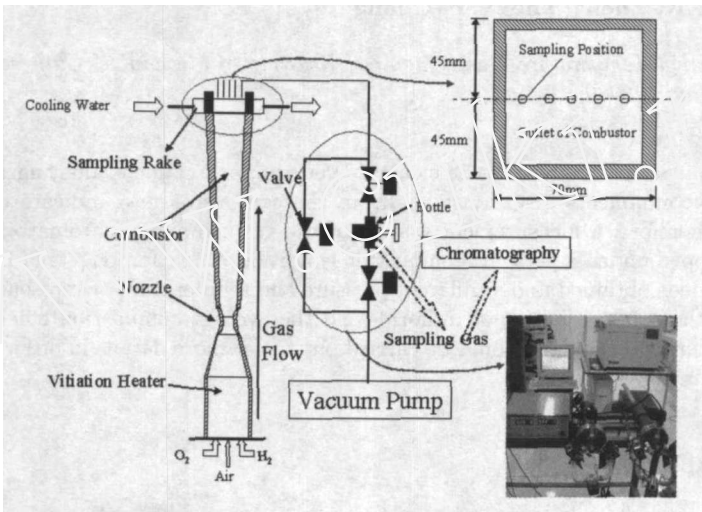

Fig. 1. Sampling/chromatographic analysis system

There are five measurement points for the sampling rake. The position is also shown in Fig.1. The sampling system includes the rake, control valves, the sample bottles, and the vacuum pump. The valves were controlled by the computer to ensure the time sequence with the main flow. Before the test starts, the vacuum pump evacuates the sample bottle. Then the valves turned the flow path to the bypass. Next, the vitiated heater ignited, the main supersonic flow established. After the flow became steady, the fuel was injected into the combustor. When the flow field with combustion became steady, the sampling began. Usually, the duration for sampling is 2-3 seconds. After the test, the sample gases were analyzed by using chromatography.

Fig.2 is the sketch of the probe. The angle for the outline is 60, which may generate attached shock wave under Mach 2. The inner diameter of the probe tip is varied from 0.3mm to 1mm to check the scale effect. Then the area expands suddenly to freeze the reaction. It follows a straight thin tube, which is surrounded by the forced cooling water to cool the sampling gas down.

Before the test, the back pressure for the thin tube, i.e. the pressure inside the sample bottle, is about 500Pa. After sampling, the pressure increased to 10-30 kPa. We may use a simple 1-D theory to analyze the flow inside the thin tube:

$$\frac{dM^2}{M^2} = -\frac{2(1+(\gamma-1)M^2/2)}{1-M^2}\frac{dA}{A} + \frac{(1+\gamma M^2)(1+(\gamma-1)M^2/2)}{1-M^2}\frac{dT_0}{T_0}$$

$$+\frac{\gamma M^2(1+(\gamma-1)M^2/2)}{1-M^2}4c_f\frac{dx}{d}$$

in which the Mach number would change with the variation of the area, the total temperature, and the friction. The variation of the total pressure will change as following:

$$\frac{dP_0}{P_0} = -\frac{\gamma M^2}{2}\frac{dT_0}{T_0} - \frac{\gamma M^2}{2}4c_f\frac{dx}{d}$$

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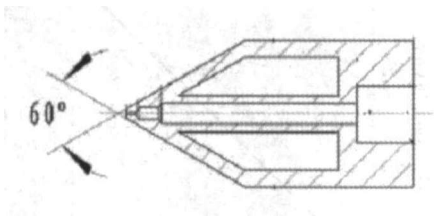

Fig. 2. Sketch of the sampling probe

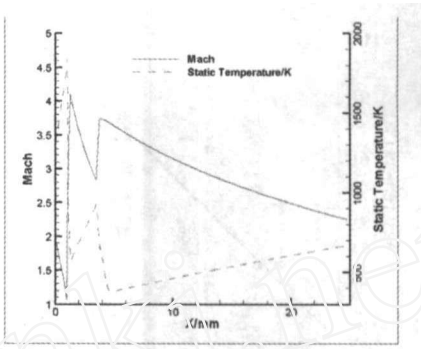

Fig. 3. Flow inside the probe

From this one-dimensional analysis, we can get the Mach number and static temperature distribution along the probe, as shown in Fig.3. The whole process may be divided in two parts. Firstly, the area suddenly expanded, so the static temperature dropped rapidly to freeze the reaction. Correspondingly, the Mach number increased since the local sound speed decreased. In the section of the straight tube, the velocity decreased gradually due to the friction, and the heat was brought away by the cooling water. In most part inside the probe, the static temperature is below 700K, which is low enough to quench the reaction.

The fuel for scramjet model test is hydrogen/kerosene. Therefore, the chromatographic analysis includes 5 components: H_2, N_2, O_2, CO and CO_2. Two columns were used to distinguish the gas components, one for CO2, another for others.

2.1 Calibration test results and discussions

Before test, the "cold" and "hot" calibrations have been carried out.

In "cold" calibration, there is a vessel connected with the sample tube directly but no rake. Firstly, the vessel was evacuated, then a certain value N_2/O_2 inserted. The mole fraction of each gas can be calculated through the pressure inside the vessel. After the mixing finished, open the sample valve to start sampling. Then analyze the components chromatographically. During the whole process, the flow is slow and uniform. Therefore, this calibration can be used to check the leakage of the system, as well as the accuracy of the chromatographic instrument. The results are shown in Fig.4. The X-coordinate is the given mole fraction of O_2, and Y-coordinate is the measured value. If there is no error, all points will be on the 45 line. As shown in Fig.4, the results are good, and the error is within 4%.

In the "hot" calibration, the sample rake was installed at the exit of the supersonic combustor, as shown in Fig.1. The principle of the vitiated heater is to get the mass flow with high pressure and temperature by burning hydrogen. There are three main incoming flows for the vitiated heater – hydrogen, oxygen, and air. In the supersonic combustion test, the oxygen must be complemented as the same amount as in air, which is 21%, to simulate the atmosphere. However, in the "hot" calibration, the amount of each gas entered the vitiated heater can be changed to get the different gas components. Since the facility was designed for the 21% O_2, the range for variation is limited. The mass flow for each was measured by the choked flowmeter. Therefore, the mole fraction of N_2 and O_2 at the exit can be calculated based on the assumption that all hydrogen has been burned out. No H_2 has been found from the measurements, which support the above assumption. Fig.5 is the results of the component N_2. The X-coordinate is the calculated value from the gas amount into the vitiated heater. The Y-coordinate is the measured value from the sample rake. The agreement is not good as in Fig. 4, but the error is less than 6%. There are two factors must be taken into account when analyzing the error. Firstly, the accuracy of the flow parameter and the pressure measurement is very important for the calculation for

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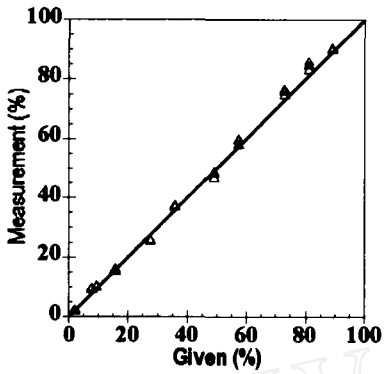

Fig. 4. "Cold" calibration of O_2 component

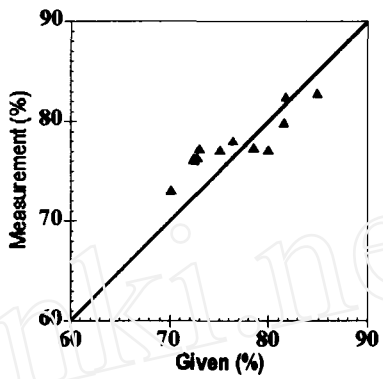

Fig. 5. "Hot" calibration of N_2 component

the choked flowmeter. Secondly, the value for X-coordinate is from the global amount, but the value for Y-coordinate is from the one point measurement. Fig.6 shown the distribution along the central line at the exit for the same test. There are some differences among the five points, which imply the flow field is not uniform.

In the "hot" calibration, the condition for taking sample is quite similar to the real supersonic combustion test. Therefore, from these two sets of calibration, the system has been validated.

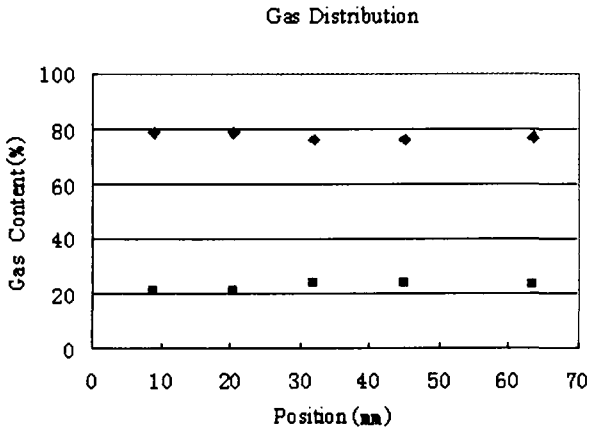

Fig. 6. Gas distributions along the exit central line

3 Results for supersonic combustion

After the calibrations, the probe rake was installed at the exit of the combustor to investigate the supersonic combustion performance of the hydrocarbon fuel, as shown in Fig.1. The tests were carried out in the direct-connected facility. The flow at the entrance of the combustor is Mach 2.5, total pressure 1.1Mpa, total temperature 1800K. The fuel is kerosene with different injection pressure and temperature.

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Fig. 7 is the typical chromatography results for the tests. For the first column, H_2, O_2, N_2, and CO peaks can be checked. For the second column, the first high peak is for other components, and the second peak is CO_2. Sometimes, there were small peaks appeared after CO peak, which imply small amount low-carbon compounds may be generated.

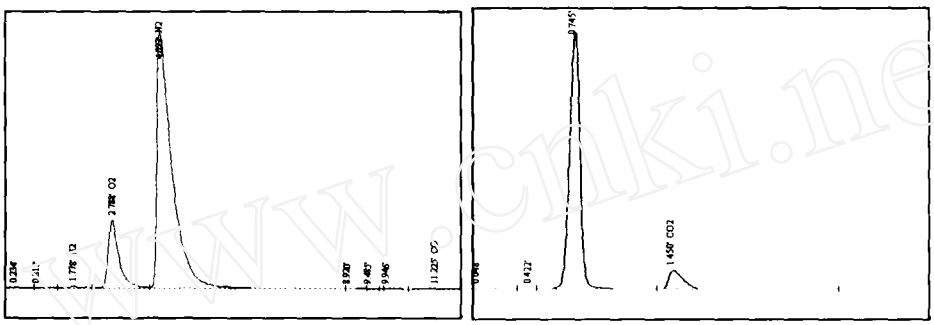

Fig. 7. A representative chromatography (H_2, O_2, N_2, CO, CO_2)

There are several cases may occur except for the fully combustion. For example, the ignition happened but the flame can not be stabilized. In this case, the measurements shown the large amount H2 remained, but only small amount of CO_2 and no CO. This means only few fuel reacted. The fully combustion case results is shown in Fig.7. Notice the very small amount hydrogen still can be caught, which proved indirectly the reaction has been frozen successfully during the sampling since hydrogen is so active.

Fig. 8 is the typical results of the nondimensional CO_2 distributions along the central line at the exit. If ignoring CO and other small amount of hydrocarbon compounds, this value can be considered as the combustion efficiency. The legend shown the temperature and pressure of the fuel injection. As the results shown, the distribution is not uniform, which indicated the combustion field. Notice the combustion behaviour random to some extent, some results can not fully repeat. However, generally for higher injection pressure and temperature, the combustion efficiency is higher because the higher injection pressure and temperature can increase atomization and mixing. For the core region, the efficiency is between 60%-80%. The results are also compared with 1-D analyse, and given the reasonable agreement.

4 Conclusions

The gas sampling/chromatographic analysis system has been successfully established under supersonic combustion condition. The results show the different distribution under different fuel injection parameters, which indicate the non-uniform combustion. Combined with the wall pressure measurements, the more details may be revealed, and the further improvements on combustion would be investigated.

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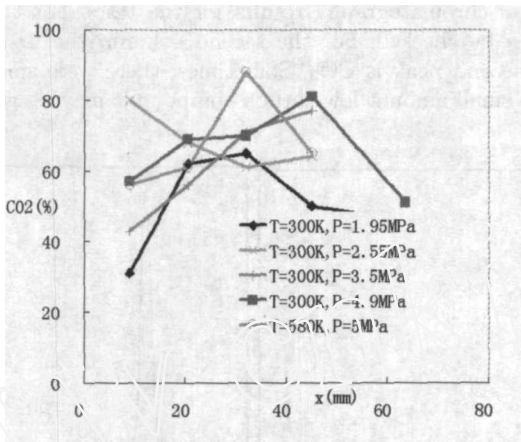

Fig. 8. CO_2 distribution along exit

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