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Analyses of Supersonic Combustion by Gas Sampling

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ABSTRACT

The probe sampling-gas chromatography system has been designed and tested in the direct-connected supersonic combustion facility and the free-jet hypersonic propulsion facility to detect the exhaust components of the scramjet model. The representative distributions were summarized under such conditions: almost completely burned, incompletely burned and without burning. The gas components including H_2, O_2, N_2, CO, CO_2, CH_4 and C_2H_4 can be identified To analyze the component distributions with the corresponding static pressure on the wall, the more detailed information can be achieved. The result can be used for the improvement of combustion.

KEY WORDS: scramjet, probe sampling, combustion efficiency, chromatography

INTRODUCTION

It's very important to analysis combustion for evaluating the engine performance. For scramjet model test, it is particular difficult to obtain the details inside since any intrusive measurement would induce shock waves then disturb the flow field. Therefore, a system of gas sampling/chromatographic has been developed to analyze the components of the exhaust.

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. Usually, there are three ways for suppressing reaction-- convection, expansion or dilution. Convection can bring the heat from the sample to coolant. Expansion can decrease temperature for supersonic flow. Dilution can quench the reaction.

Mitani etc.[1][2] have successfully developed sampling system for the supersonic combustion by using the methods combined the forced convection and expansion. Ciezki etc.[3] also used the similar method to analyze the combustion process in a scramjet model.

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

SAMPLING SYSTEM

The sampling probes have been designed under the exit conditions of the supersonic combustor, i.e. Mach number about 2, static temperature above 2000K and static pressure around 0.1MPa. The inner diameter of the probe tip is 0.8mm, then it 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. The angle for the outline is 60°, which may generate attached shock wave under Mach 2, as shown in Fig.1.

The fuel for scramjet model test is hydrogen/kerosene. Therefore, the chromatographic analysis includes 7 components: H_2, N_2, O_2, CO, CO_2, CH_4 and C_2H_4. Two columns were used to distinguish the gas components, one for CO_2, CH_4 and C_2H_4, another for others.

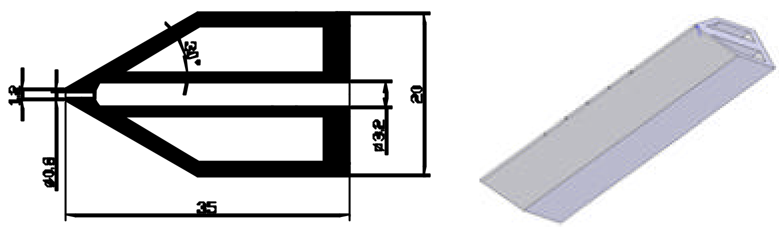


Fig. 1 Sketch of the sampling probe

RESULTS FOR SUPERSONIC COMBUSTOR TESTS

Firstly, the tests were carried in the direct-connected supersonic combustion facility. The sketch of the whole system is shown in Fig.2. The facility was installed vertically. The lowest part is the vitiated heater, which can provide the main flow with high pressure and temperature. Then the flow accelerated through the nozzle. There are two nozzles for the tests, with Mach 2.5 and Mach 3. The combustor is connected directly. The sampling rake was installed at the exit of the combustor. The sampling system includes the rake, control valves, the sample collectors, 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 collectors. 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 1s. After the test, the sample gases were analyzed by using chromatography. Before the test, the back pressure for the thin tube, i.e. the pressure inside the sample collector, is about 200Pa. After sampling, the pressure increased to 10-30 kPa.

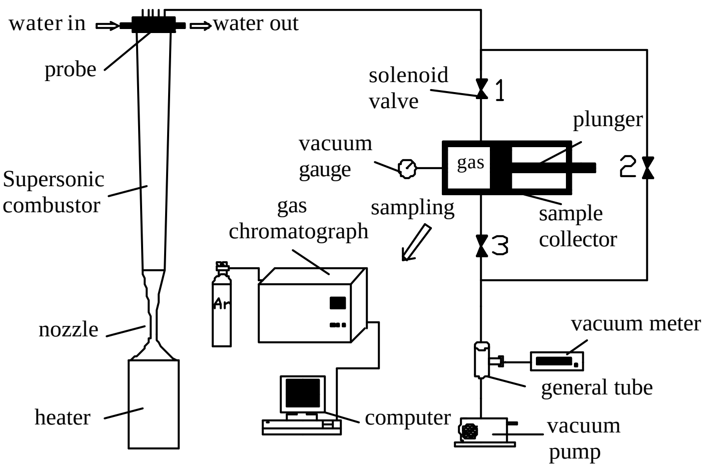
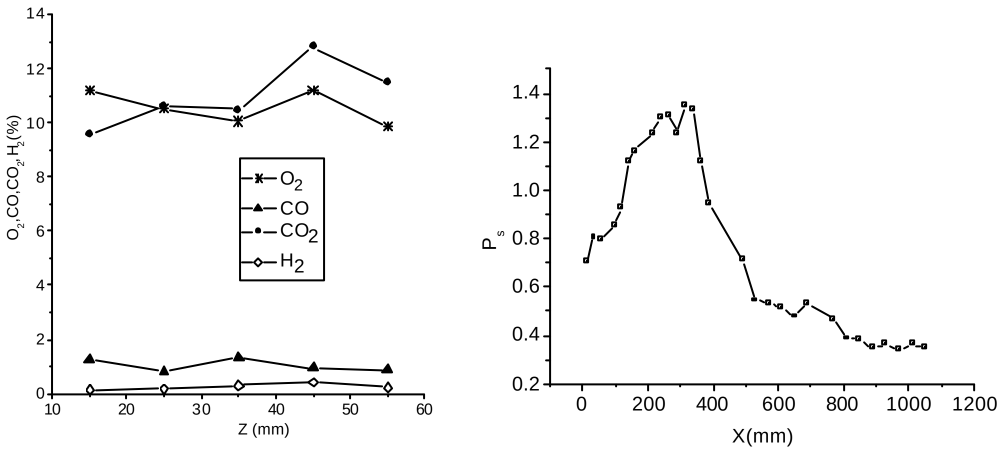


Fig. 2 Sampling/chromatographic analysis system

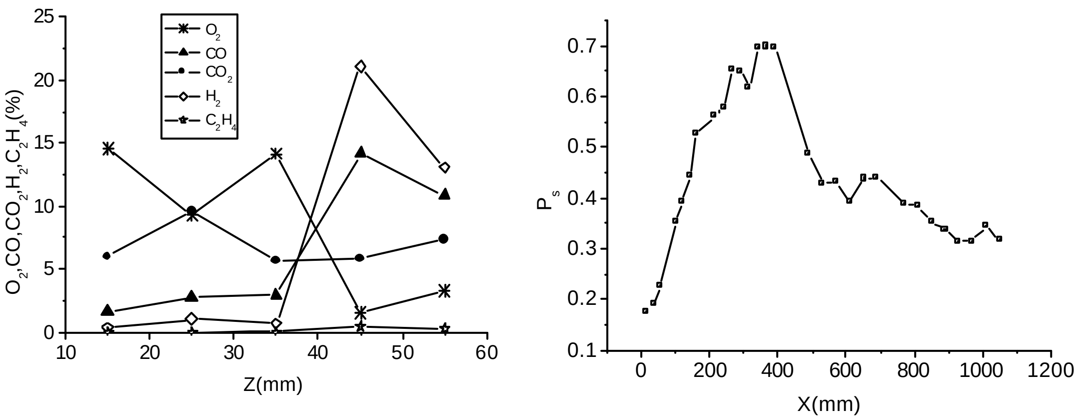
Fig.3 shown a representative distribution. The incoming flow is M2.5, the total pressure 1.06MPa, and the total temperature 1911K. Fig.3(a) is the gas components distributions, the X-coordinate is the position of the five measurement points, the Y-coordinate is the non-dimensional static pressure which is the wall pressure divided by the dynamic pressure at the entrance. The fuel is the kerosene, with injection pressure 4.08MPa and temperature 864K. The equivalent ratio is 0.71. The position for fuel ejection is x=290mm. The distributions are quite uniform, which indicates the



(a) Gas Components at Exit (b) Wall Pressure along the Combustor

Fig. 3 Distribution for the M2.5 Combustor with Single Cavity

combustion is uniform too. There is only a few hydrogen left, less than 0.5%, which means the pilot hydrogen was almost burned out. CO is also very low, around 1%. No CH_4 and C_2H_4 have been found. The component of CO_2 is above 10%, then the average combustion efficiency is about 78%, which is determined by the average CO_2 divided by the ideal content when fully burned. Fig.3(b) shown the corresponding wall pressure along the combustor.

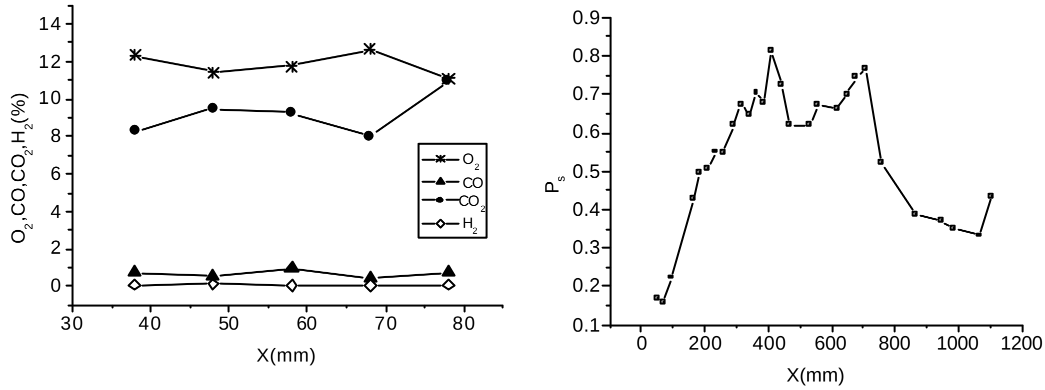


(a) Gas Components at Exit (b) Wall Pressure along the Combustor

Fig. 4 Distribution for the M3 Combustor with Single Cavity

Fig.4 shown a representative distribution in a M3 combustor. The total pressure is 1.75MPa, and the total temperature 1809K. The fuel injection pressure is 4.17MPa and temperature 874K. The equivalent ratio is 0.82. Compared with Fig.3, the position for fuel injection is more downstream x=411mm. Due to the main flow with higher Mach number and the fuel injection more downstream, the components distributions in Fig.4(a) indicates the combustion is highly uneven, which implied worse mixing and combustion. Especially for z=45mm, O_2 is almost consumed, and large amount of H_2 and CO generated. The reason for this is the kerosene was probably concentrated in this field, so that the local equivalent ratio was high. Since the temperature was high and no enough oxygen, kerosene may crack to generate large amount hydrogen and low-carbon compounds. The wall pressure distribution in Fig.4(b) also shown the pressure increment after combustion was smaller, which agreed with the sampling results.

For the similar condition, but change the combustor configuration from single recessed cavity to double cavities, the combustion improved, as shown in Fig.5. The contents of CO_2 are quite uniform and around 9%, which give the combustion efficiency about 65%. And the wall pressure increased.



(a) Gas Components at Exit (b) Wall Pressure along the Combustor

Fig. 5 Distribution for the M3 Combustor with Double Cavities

There are several cases may occur except for the fully combustion. For example, the ignition happened but the flame cannot be stabilized. In this case, the measurements shown only small amount of CO_2 and CO, and O_2 almost remained, as shown in Fig.6. This means only few fuel reacted. The evaluation of the combustion efficiency of the kerosene is only 21% in this case.

A series of tests have been studied under different conditions, such as different main flow, different fuel ejection, different combustor configurations, etc.. The results are additional information except the traditional static pressure measurements on the wall.

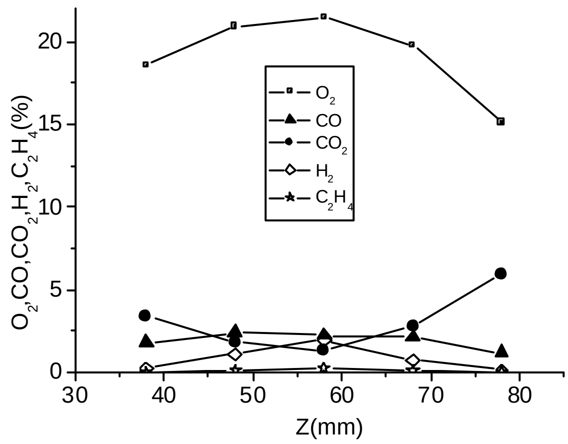


Fig. 6 Distribution for No Burning

RESULTS FOR SCRAMJET MODEL FREE-JET TESTS

The measurement of gas sampling/chromatographic analysis system has not only been used in the direct-connected facility, but also used in the free-jet facility to measure the exhaust of the scramjet model.

Fig. 7 is the sketch of the

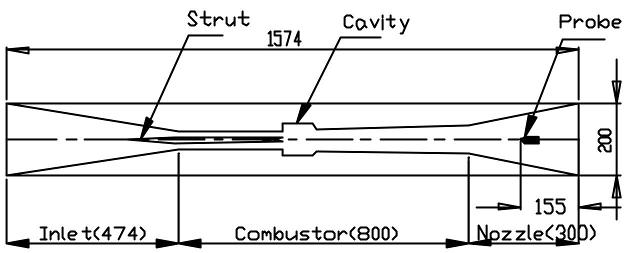


Fig. 7 Position of the Probe inside the Scramjet Model

engine model. The inlet is the sidewall compression. The strut- cavity is used as the flame holder. The sampling probe was installed on the central line, in the nozzle. Fig. 8 is the photo of the sampling system, including 5 sample collectors and relative solenoid valves and tubes. The system was installed inside the test cabin. After test run, the sample gases were analysed by using chromatography.

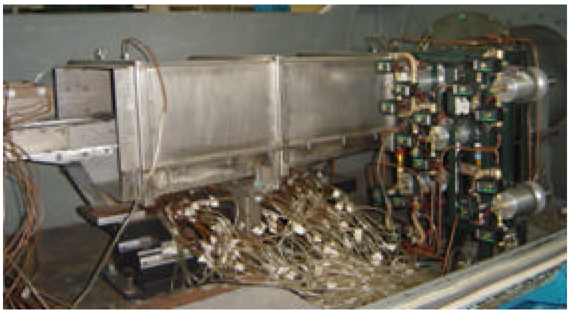
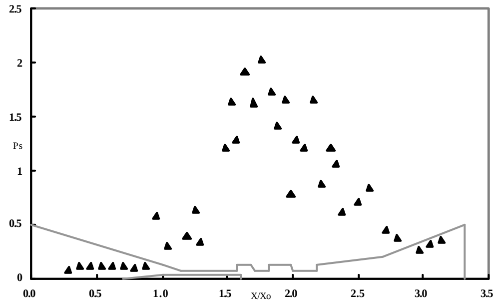


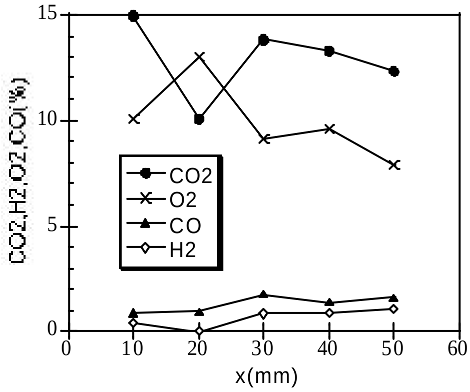
Fig. 8 Sampling system

Fig. 9 is a representative result for the model test. The incoming flow is Mach 5.8, total pressure 5.03MPa, total temperature 1730K. The kerosene injected from the central strut with equivalent ratio of 1.01. The pilot hydrogen ejected from the sidewall, upstream of the recessed cavity, with equivalent ratio of 0.13. As shown in Fig.9, a few H_2 left, and small amount CO generated. The content of CO_2 is quite high with the average of 12.9%, which gives the combustion efficiency about 79%.

Similar to the tests in the direct-connected facility, some other distributions have also been detected under the cases with uncompleted burning or without burned.



(a) Pressure distribution along the sidewall



(b) Gas Component of the five ports

Fig. 9 Representative result for model test

CONCLUSIONS

The gas sampling/chromatographic analysis system has been successfully established under supersonic combustion condition. The results demonstrate that it is a very useful tool to analyze the mixing and combustion under different conditions. Usually, better combustion would give more uniform distributions. In the case of nearly fully combustion, only a few H_2 and CO would be detected, but large amount CO_2 would be found. However, the worse combustion may give non-uniform distributions, which indicates worse mixing and/or combustion. Combined with the wall pressure measurements, the more details may be revealed, and the corresponding improvements on combustion would be done.

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