

PULSE COMBUSTION FACILITY AND ITS PRELIMINARY APPLICATION IN SCRAMJET RESEARCH

Le Jialing, Liu Weixiong, He Wei, and Tan Yu

China Aerodynamics Research and Development Center,
Sichuan Mianyang, 621000

1. Introduction

The ramjet/scramjet engine is a unique propulsion system in that it can not be operated statically. It can only function with a supersonic flow entering the inlet to accomplish the necessary ram compression. Consequently, it can only be tested in a supersonic/hypersonic wind tunnel capable of closely replicating the true flight environment. Actually, the progress of wind tunnel testing for ramjet/scramjet has actually profound influence on the successful development of this kind of propulsion, perhaps more than any others. For this reason, to develop a wind tunnel to test ramjet/scramjet with affordable cost and reasonable size is urgently needed, especially for fundamental combustion research and performance (such as specific impulse and thrust) testing. Compared with utilizing arc heater, at present, the most popular and economical way to provide desired test gas enthalpy is utilizing H₂-Air-O₂ combustion heater for scramjet test, like facilities in NASA Langley, Russia CIAM, Japan NAL [1 - 3]. However, for long duration combustion test, it still needs much investment in the huge vacuum volume or in the ejector system, and maybe in the large and costly exhaust pumping system. In addition, there are technological difficulties need to be solved, such as ignition, combustion and cooling systems for its most parts. As for the aspect of short duration facilities, such as shock tunnel and expansion tube, they can produce the required combination of temperature and pressure for simulating the flight with Mach number higher than 8, but the test time is very limited (less than 10ms) and there are few published papers about experiments in hydrocarbon fuel combustion. For above mentioned reasons, a new, more efficient and economical facility (which is capable of simulating flight Mach number less than 7) of pulse combustion and short duration (more than 30ms) was conceived and built two years ago in CARDC, based on our original experience in short duration techniques for simulating exhaust plumes at high altitude [4]. Preliminary experimental results from hundreds of tests of combustor and model engine with fuel of hydrogen and hydrocarbon demonstrate that this kind of facility is suitable for scramjet research.

2. Test Facility and Principle

The principle of the test facility is as following (Fig. 1): before test, cool gaseous fuel (mixture of hydrogen and nitrogen) and oxidizer (mixture of oxygen and nitrogen) are stored in a pair of charge tubes, respectively. They are contained by a pair of quick-acting valves at the end of each tube. As the test begins, the valves open, and the gases discharge into an un-cooled combustion heater where combusting takes place so that the desired test gas enthalpy and pressure can be reached. Ignition is usually initiated by a electrical spark plug. The total temperature, pressure, and mass flow rate in the combustion heater can be controlled by changing the pressure and composition ratio of fuel (H₂+N₂) to oxidizer (O₂+N₂) in the charge tubes, while the mole-fraction of oxygen after combustion remains at 0.21 just the same as in the atmosphere. The duration of the test depends on the length of tube and the size of vacuum tank. The total pressure (2.7-2.8 MPa) of the heater with the time is presented in Fig. 2. From

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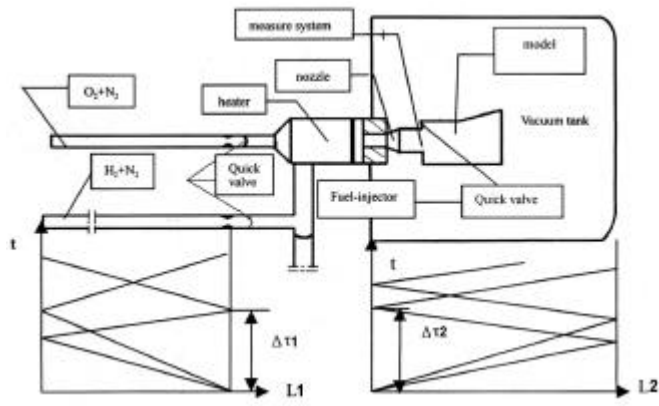


Fig. 1. Schematic of the facility operation principle.

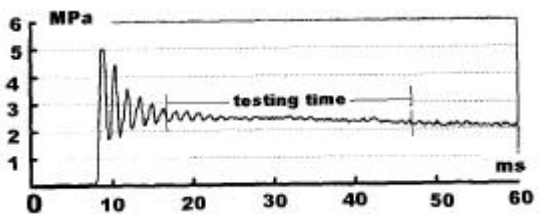


Fig. 2. Total pressure trace.

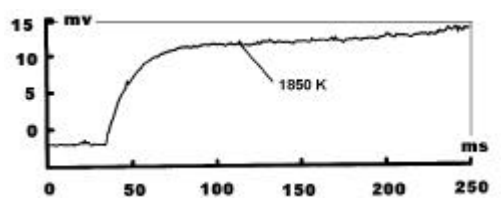


Fig. 3. Measured total temperature.

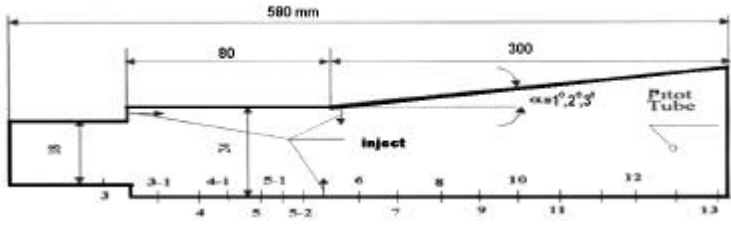


Fig. 4. Configuration of combustor model

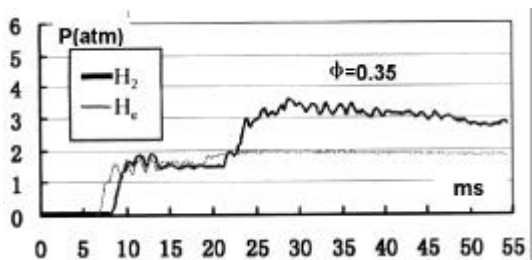


Fig. 5. Wall pressure for gases of H₂ and He.

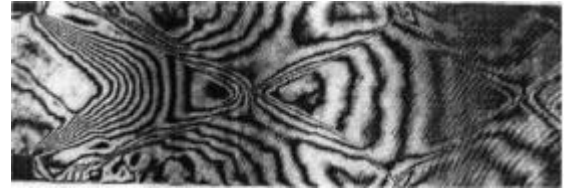


Fig. 6. Hologram interferogram of flow without combustion.

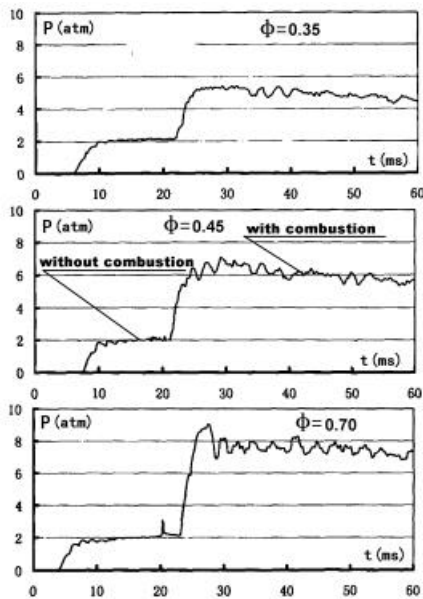


Fig. 7. Wall pressure traces of point 5-1 with different fuel air ratios (H_2).

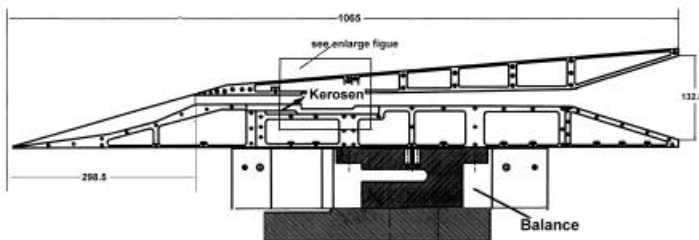


Fig. 8. Model engine for thrust measurement.

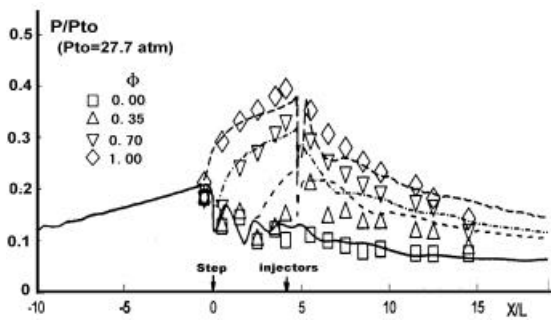


Fig. 9. Axial variation of lower wall pressure.

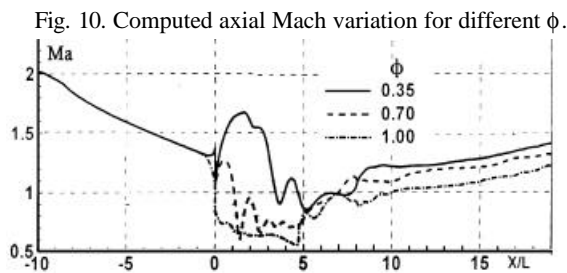


Fig. 10. Computed axial Mach variation for different ϕ .

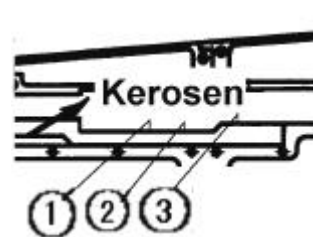


Fig. 11. Enlarged part of combustor.

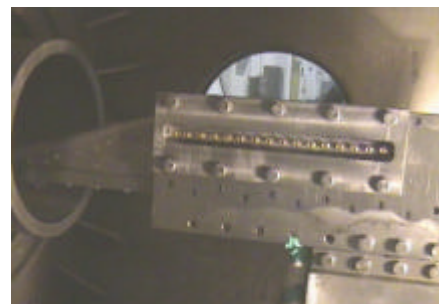


Fig. 12. Model engine installed in the test section for free jet testing.

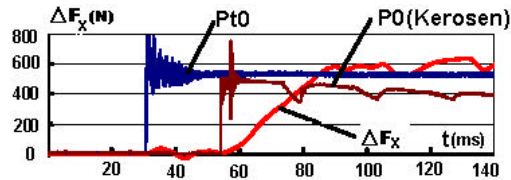
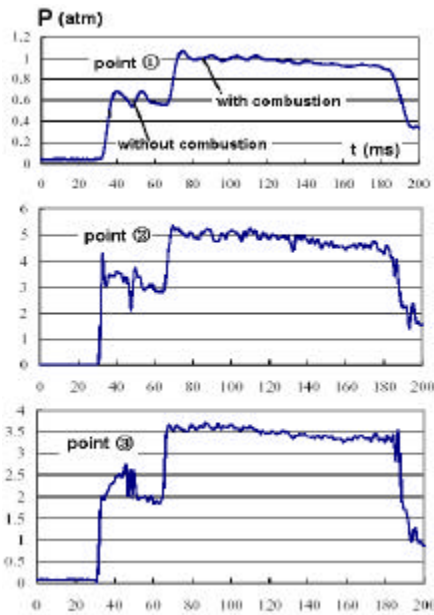


Fig. 14. Internal thrust response to fuel supply $M = 5$, $P_{t0} = 5 \text{ MPa}$, $T_0 = 1500 \text{ K}$

Fig. 13. Wall pressure traces of model engine for kerosene.

pressure trace, the test duration of more than 30ms has been obtained. The total temperature of the heater is measured by a fast thermocouple of Pt-Rh, and its output temperature (shown in Fig. 3), based on China GB2902-82 temperature calibration, is about 1850K. The computed total temperature (without any heat loss) equals to 2040K, and the combustion efficiency of about 0.91 of the heater can be deduced. The heater's mass flow rate can be calculated from total pressure and temperature as well as nozzle throat. Now CARDC has built two pulse combustion facilities, one for directly connect testing of combustor (mass flow rate is about 1kg/s), the other for model engine testing in free jet flow (mass flow rate is about 10kg/s).

3. Experiment Results of Direct Connect Testing of Combustor

The combustion model shown in Fig. 4, includes an isolator, a constant area section and an expanding section, and the size of the isolator entry is 40mm×18mm. The locations of hydrogen injectors with sonic jets are also shown in the figure. The mass flow of the fuel, which can be controlled by total pressure, number and size of injectors, is provided with a type of long Ludwig tube. The hydrogen fuel supply from wall is normal to income flow by 7 orifices of 1.2mm in diameter and the injection of kerosene is paralleled to the income flow by a strut located near the isolator exit. Table 1 summarizes the combustor entry flow conditions.

Table 1. Supersonic combustor entry flow conditions

M	2.05	$P_{\text{H}_2\text{O}}$	0.258
P	0.341MPa	P_{O_2}	0.21
T	1172K	P_{N_2}	0.532
U	1417m/s		

In order to further confirm whether the injected fuel of H_2 is in ignition and combustion within short time of the order of milliseconds, two kinds of gases, hydrogen and helium, are injected. Comparison between lower wall pressure measurements (shown in Fig. 5) of the two gases indicates that the injected hydrogen is actually auto-ignited, and the time of transition to combustion is less than 2ms. Fig.6 is typical wall pressure histories at point5-1 with different

fuel (H_2)/air ratios ϕ . Self-ignition and good combustion is also further confirmed from these pressure traces. As for fuel of liquid kerosene, typical wall pressure traces of model engine are shown in Fig. 13. It seems that, all the three processes, drop breaking, evaporation and the chemical delay of ignition, are completed within 4ms for pure liquid kerosene by our present strut scheme of combustor. Figure 7 is a picture of Laser holographic interferogram of the flow without fuel injection. It clearly shows that, on account of the steps in the combustor, shock waves are produced and interact with each other. The income flow traverses oblique shocks having its static temperature increased, and provides necessary ignition conditions. In addition, oblique shocks enhance the fuel-air mixing process. This may be the explanation for liquid kerosene to have better spontaneous self-ignition and supersonic flame stabilization in our short duration experiments. Fig. 9 is the measured wall pressure distribution along the combustor for $\phi = 0.35, 0.7$ and 1.0 . The axial variation of calculated pressure and average M number obtained using 2-D turbulent chemical reaction flow (7 species, 8 element reactions) are shown in Fig. 10. Different types of flow patterns are predicted from Fig. 10. For $\phi = 0.35$, the combustion flow is supersonic, while for $\phi = 0.7$ and 1.0 , most of the flow in combustor is subsonic (Mach number is less than 1), which means that the flow in the combustor is very complicated with mixed pattern of subsonic and supersonic flow, and at the same time, the main flow of the channel experiences a dual model transition from supersonic to subsonic with the change of the fuel/air ratio ϕ .

4. Testing Results of Model Engine in Free Jet Facility

For further examining the ability of studying the performance of model engine in pulse combustion facility, a typical model engine is shown in Fig. 8. It has a two-dimensional inlet of three-wave system with the size of 120mm (width) \times 80 mm (height) and the whole length of the model is about one meter. Fig. 12 shows the model installed in the test section of the facility, the nozzle exit is 30 cm in diameter. The engine model has been tested in the condition of total temperature 1500 K, total pressure 5 MPa. Both engine internal thrust and wall pressure are measured for the fuel of H_2 and hydrocarbon. Fig. 14 shows the whole time histories of the total pressure P_0 , kerosene supply pressure P_0 and internal thrust F_x . From Fig. 14, we can see F_x responds gradually. It begins when liquid kerosene is supplied to the injectors of the combustor and approaches maximum after 20 ms. Figure 11 is an enlarged picture of a part of the model engine, marked in Fig. 8. Three pressure gauges are placed on the lower wall. Their pressure traces are given in Fig. 13, from which excellent kerosene combustion are indicated. The combustions at the three points are completed within 60-80 ms. Combining pressure measurement (Fig. 13) (with thrust measurement (Fig. 14), we can deduce that the gradual responding of F_x is mainly due to balance instead of the combustion itself.

5. Conclusion

1. Under present experiment condition, the ignition and stabilization of combustion for fuel of hydrogen and kerosene are confirmed from wall static pressure history. For hydrogen, the time of transition to combustion is less than 2ms, while for kerosene, less than 4ms.

2. The pulse combustion facility with 30-100ms duration can be successfully used for scramjet research, including direct-connected combustor testing and model engine testing in free jet facility, which means that in the respect of time requirement, this facility is both perfect and economical for performance research of hydrocarbon scramjet used for hypersonic cruise vehicle. This conclusion is suggested by J. T. Best [5].

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