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Experimental Research on Hydrogen and Hydrocarbon Fuel Ignition for Scramjet at Ma=4

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Abstract

Ignition experiments of Hydrogen and Ethylene were performed on direct-connected pulse combustion facility. Air stagnation temperatures were 900 K and stagnation pressures were 0.8 MPa, the entrance Mach number was approximate 2.0 provided by a two-dimension nozzle. The experimental results indicate that: (1) Hydrogen self-ignition won't occur at stagnation 935 K when it is injected upstream the cavity in this combustor model. But with low input power igniter, hydrogen can be ignited reliably. (2) Ethylene cannot be ignited with igniter only even at high igniter power. Under the assistant of both igniter and pilot Hydrogen, Ethylene can be ignited reliably and maintain stable combustion after the igniter and pilot hydrogen completely turned off. (3) The lowest equivalence ratio of pilot hydrogen for successful ethylene ignition is 0.05 below that ignition will fail. (4) When pilot hydrogen and igniters were both employed for ignition, the function of igniter is to ignite the hydrogen and the input power of igniter has no influence on ignition performance.

Keywords: scramjet, ignition, hydrocarbon fuel, engine design

1. Introduction

In Turbine based combined cycle (TBCC) propulsion system, the turbojet engine provides its highest speed of Ma 3-4, then the Scramjet engine should startup near Mach 4 and maintain appropriate performance to accelerate to higher speed. The stagnation temperature of the flow captured at flight Mach number 4 is only 800-1000 K, the static temperature of the supersonic flow in the combustor is about 500-600 K, lower than the self-ignition temperature of most fuel. The research on assistant ignition methodology for Scramjet engine at low stagnation temperature is necessary.

There are four major factors for successful ignition at low stagnation temperature flow: high static temperature, low velocity, sufficient mixing of fuel and oxidizer and combustion radicals. Common assistant ignition technique includes: (1) Igniter. Igniters, producing a small high temperature region in the flow-field such as spark (Chadwick et al., 2005), flame torch, arc discharge (Aleksandrov et al., 2006) etc. and also releasing lots of radicals such as plasma torch (Watanabe, Abe, & Takita, 2009), could effectively assist for ignition and combustion. (2) Fuel technology. Fuel technology includes fuel additive and calefaction. Additives for fuel can effectively facilitate fuel ignition and combustion but most of them are poisonous to environment and staff. Some researcher heat the fuel to 500-600 K (Mathur et al., 2000) or even to the supercritical state to simulate the fuel as coolant in real flight situation, and this also will help for ignition and combustion. (3) Fuel mixing enhancement. Sufficient mixing of fuel and oxidizer can reduce the ignition delay and promote combustion. Mixing enhancement devices are employed in scramjet combustor such as physic ramp and aerodynamic ramp (Wang, Song, Li, & Cai, 2008) injectors, strut injectors and atomization technology for liquid fuel. The aerated-liquid jet (Lin, Kirkendall, Kendedy, & Jackson, 1999; Lin, Kendedy, & Jackson, 2000; 2002) being developed for years has proved its effect on reducing the liquid droplet diameter and improving for the local equivalence ratio if the gas is air or oxygen (Segal, 2009). (4) Air throttle technical. Air throttle mechanism (Yang, Li, Choi, & Lin, 2010) that usually be settled at downstream of the combustor can induce shock chains to slowdown the velocity of core flow and increase the static temperature in the combustor, which will facilitate the ignition. Once ignition succeeds, withdraw air throttle at right time and stable combustion could maintain (Lin et al., 2007; Mathur et al., 1999). All the experiments presented above were performed on continuous facility, continuous facility can provide longer igniting time and ignition processe started at hot wall temperature condition which has been proved to be efficient methods to facilitate ignition at low total temperature inflow. These ignition experiments were carried out on the pulse facility, pilot hydrogen and torch igniter were employed as assistant for ignition, by adjusting the injection schemes and ignition time, Hydrogen and gaseous ethylene ignition succeed and stable combustion maintained at stagnation temperature approximate 900 K.

2. Facility Introductions

2.1 Pulse Directly-Connected Combustion Facility

The facility consists of Ludwieg tube, Hydrogen supply system, heater, settling chamber, test section and vacuum tank (Figure 1). The hydrogen fueled heater was used to achieve the air stagnation temperature of 900~1900 K, which corresponds to a range of flight Mach numbers 4~7. Stable experimental time is about 250 ms. Total temperature and inflow Mach number of the inflow gas are verified by thermal couple, Pitot Pressure measurement and cavulation respectively. For this experiment, the ideal parameters and actual parameters are listed in Table 1.

Table 1. Experimental parameters of facility

	Flight Ma [-]	Inflow Ma [-]	Tt [K]	Pt [MPa]	Mass Flow rate [kg/s]
Ideal parameters	4	2	900	0.8	3.09
Actual parameters	4	2.1	935	0.8	3.09

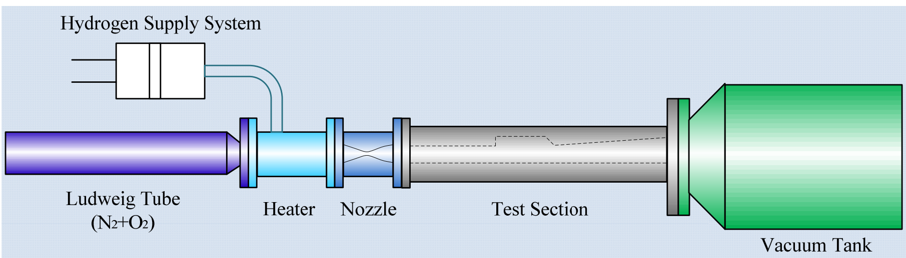

Figure 1. The directly-connected pulse combustion facility

2.2 Torch Igniter

The igniter employed in the experiments is Hydrogen-Air torch igniter, it consists of three subsystems: the hydrogen supply system, the air supply system and the spark (Figure 2). The spark igniter the mixture of Hydrogen and air, then the hot gas after combustion injects into the flow-field from the cavity floor. The rated thermal power of igniter is approximate 70 kW, and the input power can be adjusted by changing the upstream pressure of Hydrogen and air. Two igniters are settled on the cavity floor but each is controlled individually. The total input power of igniter can be adjusted among 20 kW - 180 kW.

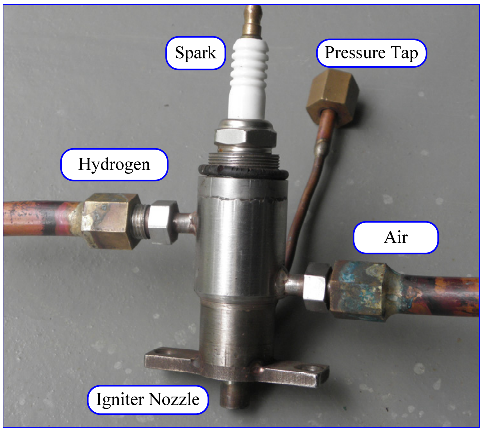

Figure 2. Torch igniter

2.3 Scramjet Combustor Test Model

The entrance cross section of isolator is 50 mm height by 100 mm width, total length is 1700 mm. The top wall consists of several diverges at different angles and the bottom wall is flat, a cavity used as flame-holder is settled on the top wall which is characterized by depth=18 mm, L/D=10.8 and a ramp angle of 22.5° (Figure 3). Pressure sensors are installed on sidewall of the combustor model (Figure 4).

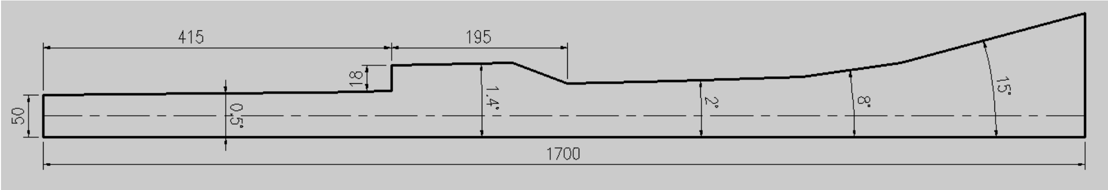

Figure 3. Side-view of the scramjet combustor configuration (units: mm)

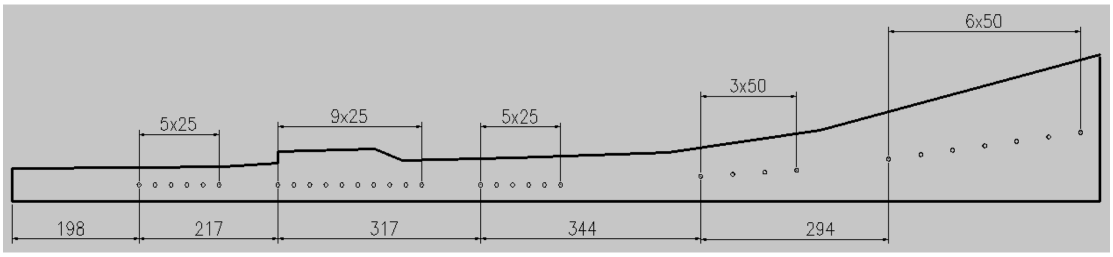

Figure 4. Locations of pressure sensors on side wall of combustor model (units: mm)

Eight fuel injection positions were designed around the cavity, four were used in these experiments (Figure 5): upstream of the cavity (A), on the cavity floor (B) and downstream the cavity (C, D). Each position located twelve 1-mm-diameter injectors that were 8mm apart. All the injection positions are controlled individually.

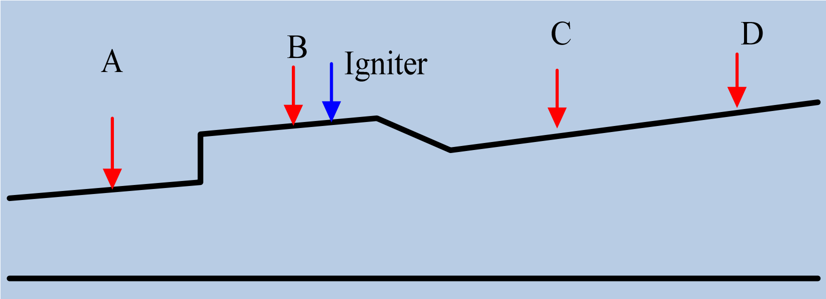

Figure 5. Positions of cavity, injectors and igniter

2.4 Experimental Schedule

The typical experimental schedule is: facility starts → igniter on → pilot hydrogen injecting on → ethylene injecting on → igniter off → pilot hydrogen off → ethylene off → facility end. Time from pilot hydrogen injecting on to igniter off was defined ignition time (Figure 6), and it could be measured according to the igniter pressure and pilot hydrogen injection pressure. Time from pilot hydrogen off to ethylene off is defined maintain combustion time. If ethylene could maintain stable combustion after igniter and pilot hydrogen completely shut off, it indicates ignition succeed.

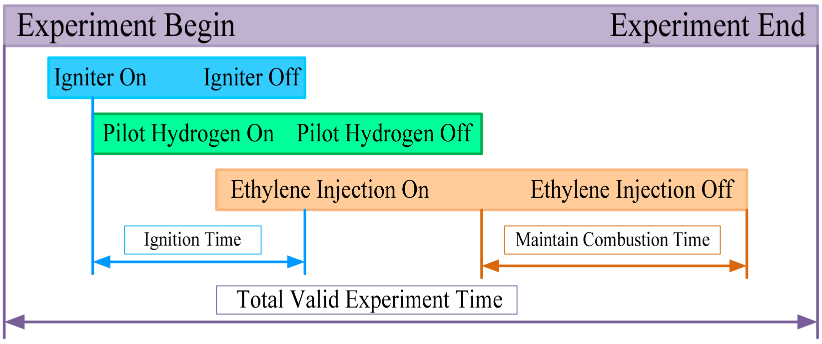

Figure 6. Schematic of ignition experiment system

2.5 Fuel/Air Ratio

Fuel/air ratio is an important parameter in scramjet combustor. The fuel/air ratio is defined as:

$$\frac{Fuel\,mass\ flow\,rate}{Entry\,air\,mass\ flow\,rate} = f = \frac{\dot{m}_f}{\dot{m}_A} \tag{1}$$

The ideal fuel/air ratio is named as stoichiometric fuel/air ratio which means the oxygen in the air can react with all the reactants available in the fuel. For hydrogen and hydrocarbon fuels the chemical equation is:

$$C_xH_y + (x+\frac{y}{4})(O_2 + \frac{79}{21}N_2) \rightarrow xCO_2 + \frac{y}{2}H_2O + \frac{79}{21}(x+\frac{y}{4})N_2 \tag{2}$$

Then the stoichiometric fuel/air ratio is defined as:

$$f_{st} = \frac{36x+3y}{103(4x+y)} \tag{3}$$

The equivalence ratio to describe the fuel/air ratio is defined as:

$$\varphi = \frac{f}{f_{st}} \tag{4}$$

3. Experiment Results and Analysis

Ethylene and hydrogen ignition experiments were carried out at stagnation temperature 935 K. Gaseous ethylene and hydrogen were successfully ignited by adjusting fuel equivalence ratio, igniter input power, ignition time and fuel schedule. Pressure distribution was measured and ignition parameters and experience were obtained.

3.1 Hydrogen Self-ignition Experiments

Experiments on hydrogen self-ignition had carried out at different conditions with hydrogen injected upstream the cavity, and hydrogen self-ignition never occurred. During the experiments cavity configurations, hydrogen equivalence ratio had been varied. It indicates that some orther assistant ignition mechanism is necessary for pilot hydrogen and ethylene ignition.

3.2 Ethylene Ignition Experiments with Torch Igniters

Ethylene ignition experiments at different injection schemes, equivalence ratios and cavity configurations had been performed with torch igniter for assistant, the torch igniter input power varied from 50 kW to 150 kW, ethylene ignition never achieved. These results indicate that the torch igniter is not competitive for ethylene ignition and some other assistant methods are required.

3.3 Hydrogen Ignition Experiments at Various Igniter Input Power

Two igniters was equipped on the test model, there are two ways to vary the igniter input power: (1) vary the supply pressure of hydrogen and air to change the individual input power; (2) using one or two igniters for each experiment to change the total input power. For hydrogen ignition experiments, the total input power was varied from 20 kW – 140 kW (Table 2), at different cavity configurations and fuel injection schemes, hydrogen were ignited successfully and maintained stable combustion.

Table 2. Hydrogen ignition experiments at different igniter input power

No.	Injection Position	Equivalence Ratio	Igniter Amount	Igniter Power kW	Ignition Time ms	Results
052202	A+C	0.1+0.2	2	50.0+50.0	30	succeeded
053101	B+C	0.13+0.37	2	55.7+55.7	50	succeeded
052104	A+C	0.11+0.11	2	65.5+65.5	30	succeeded
052103	A	0.25	2	71.1+71.1	30	succeeded
052501	B+C	0.30+0.16	1	46.0	30	succeeded
052302	A	0.32	1	47.4	30	succeeded
052401	A+B	0.19+0.22	1	55.7	30	succeeded
052304	B	0.28	1	57.8	30	succeeded
071602	A	0.05	1	20	30	succeeded

At a wide range of torch igniter input power, hydrogen could be ignited successfully and reliably at different injection schemes, equivalence ratio and ignition time. Results from Table 2 proved that there is no severe problem on hydrogen ignition at stagnation temperature 935 K, and hydrogen is suitable as a pilot fuel.

3.4 Pilot Hydrogen Limit for Ethylene Ignition Experiments

Pilot hydrogen is necessary for ethylene ignition as torch igniter is not competitive. A series of experiments were performed to find the equivalence ratio limit of pilot hydrogen below which ethylene ignition would be impossible.

Ethylene was injected from the cavity floor at equivalence ratio is approximate 0.2. The total input power of igniters is 80kW which was determined based on Table 2 to ensure successful pilot hydrogen ignition, pilot hydrogen was injected upstream of the cavity. The equivalence ratio of hydrogen reduced from 0.12 till ignition failed (Table 3).

Table 3. Ignition experiments on pilot hydrogen limit

No.	Ethylene		Pilot Hydrogen		Igniter Energy	Ignition results
	Injection Position	Equivalence Ratio	Injection Position	Equivalence Ratio		
071303	B	0.194	A	0.12	80kW	succeeded
071304	B	0.202	A	0.079	80kW	succeeded
071501	B	0.202	A	0.049	80kW	succeeded
071701	B	0.20	A	0.034	80kW	failed

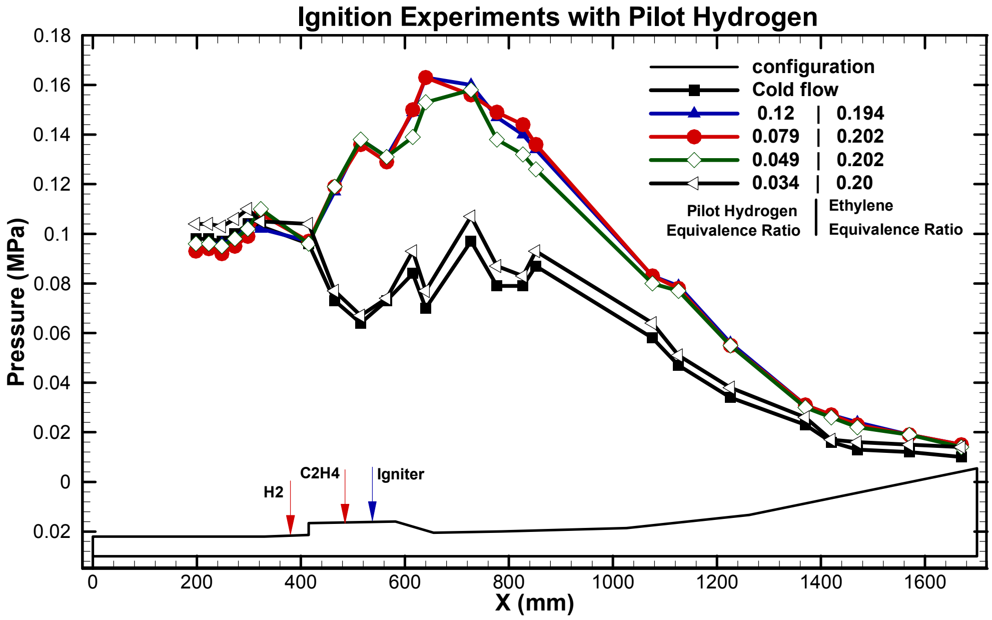

Figure 7. Wall pressure of ignition experiments on pilot hydrogen limits

The wall pressure in Figure 7 was measured 100 ms after pilot hydrogen and torch igniters were completely shut. These four experiments with almost the same experimental parameters except hydrogen equivalence ratio, when the hydrogen equivalence ratio reduced to 0.034, ethylene ignition failed, the wall pressure agreed with cold flow wall pressure well. Also as the Figure 7 shows, with similar ethylene equivalence ratio, after hydrogen and igniter turned off, the wall pressure of combustor agreed well which proved that the hydrogen equivalence ratio has little effect on combustor wall pressure.

3.5 Ethylene Ignition Experiments at Various Igniter Input Power Combined with Pilot Hydrogen

Experiments were performed to research on the igniter input power for ignition. The pilot hydrogen was injected upstream the cavity at equivalence ratio of 0.05, ethylene was injected from the cavity floor at equivalence ratio of 0.2. Combustor wall pressures were measured when igniter and hydrogen were shut 100 ms later.

The Figure 8 shows the experiments details. The curves are different from cold flow wall pressure curve which means ethylene ignition achieved for all experiments. The pressure curves at igniter input power 116 kW and 44 kW were much lower than the other four curves, after analyzing the differences is induced by the ethylene equivalence ratio. The pressure curve at igniter input power 20 kW agree with the other three curves well before 650 mm, after the wall pressure reduced, this may be caused by the igniter input power and ethylene equivalence ratio both. The results also indicate that the function of igniter is to ignite pilot hydrogen which serves as source of heat and combustion radicals, and then ignite the ethylene.

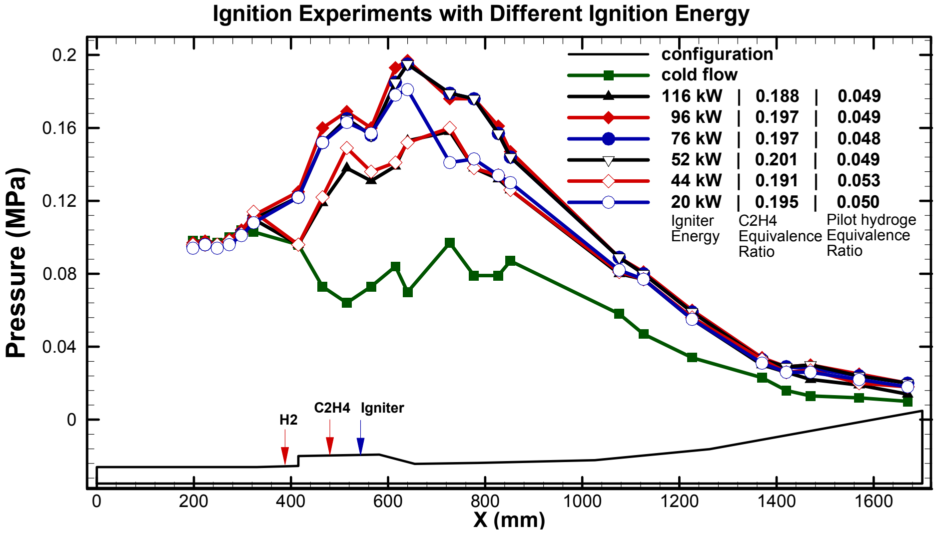

Figure 8. Wall pressure of ignition experiments on igniter input power

4. Conclusions

Ignition experiments at stagnation temperature of 935 K were carried out on pulse facility, experimental technical for pulse facility was mastered, the ignition performance of low stagnation flow-field was researched, and some conclusions were summarized:

(1) Hydrogen self-ignition won't occur at stagnation 935 K when it is injected upstream the cavity in this test model. But with low input power igniter, hydrogen can be ignited reliably.

(2) With the igniter for assistant only, ethylene could not be ignited even at high input power of 172 kW. Igniter combined pilot hydrogen, ethylene had been ignited reliably and maintained stable combustion even at very low input power of 20 kW for igniter.

(3) When pilot hydrogen is injected upstream of the cavity, the equivalence ratio of Hydrogen, should be higher than 0.05 that ethylene can be ignited reliably and maintain stable combustion.

(4) When igniter and pilot hydrogen at equivalence ratio of 0.05 were both employed, ethylene ignition achieved in a wide range of igniter power from 116 kW to 20 kW. The results indicate that the main function of igniter is to ignite pilot flame which serves as the source of heat and combustion radicals to facilitate ignition.

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