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Abstract

The investigations on characteristics of selfignition and sustaining of kerosene-hydrogen dual fuel were conducted in a direct-connect supersonic combustor with a fixed entrance Mach 2.5. The experiments were conducted with stagnation temperature varied from 1416K to 1700 K and stagnation pressure kept in 1.8 MPa. The average droplet diameters of kerosene spray were measured by using of a laser particle sizer. Four types of integrated modular structure of pilot flame and recessed cavity flameholder with different configurations were tested to seek the required minimum hydrogen equivalence ratio for kerosene ignition and combustion sustaining. Under combined promotion of pilot hydrogen flame and recessed cavity, the required minimum hydrogen equivalence ratio of 0.03 was found in an optimized condition. Performances of the combustor were preliminarily estimated by using of the home-developed code SSC-3. A combustion efficiency of 50% was obtained in a combustor with length of 425 mm. The effects of configuration of integrated modular structure on combustor performances were discussed.

Introduction

Liquid hydrocarbons, such as kerosene, are attractive candidates for fueling the scramjet in the flight regime of M<8 due to its simplicity of operation and management [1, 2]. However, except the difficulties of atomization, vaporization and mixing, the relatively slow chemical reaction kinetics of the pure kerosene, which is two or three orders of magnitude slower than that of hydrogen, becomes the major barrier in the realization of liquid hydrocarbon scramjet. In order to ignite hydrocarbons and stabilize the combustion, additional igniting and flame-holding elements should be installed in the channel. Pilot hydrogen flame with sufficiently high concentration of active radicals was usually used as an ignitor and the primary fuel (hydrocarbons) was injected after or before the pilot flame [3, 4, 5]. Many studies demonstrated the mixing and flame-holding benefits of using a rearward-facing step with fuel injection downstream or upstream of the step [4, 6, 7, 8].

In this study the pilot hydrogen was injected from the base of a rearward-facing step and was parallel to the airstream. Downstream of the pilot flame, kerosene was injected normally from the bottom of the recessed cavity. The chemical reactions of kerosene are expected being accelerated by the pilot hydrogen flame and promoted by the low speed recirculation flow, which provides longer residence time. The minimum equivalence ratios of the pilot-hydrogen, which were required for ignition of liquid kerosene, were investigated in different conditions as follows: 1) the distance between the liquid kerosene injectior and pilot hydrogen injector; 2) stagnation temperature of vitiated air flow; 3) recessed cavity. A modified code SSC-3 [9] was used to analyze the experimental data.

Experimental facility

The Schematic of experimental facility is shown in figure 1. Details of the facility have been described in Ref. 10. In the experimentation, high temperature vitiated test air was produced by burning hydrogen, oxygen, and air in a heater, with the resulting oxygen volume fraction equal to that of normal air. The heater can provide air up to its maximum capability with a temperature of 2200 K, a pressure of 4.5 MPa, and a flow rate of 1.5 kg/s. The nozzle with contour walls produces a two-dimensional supersonic airflow of Mach 2.5. The supersonic combustion chamber is a rectangular duct with an entrance cross section of 30×30 mm. The duct is composed of two sections, which have lengths of 125 mm and 300 mm respectively. Their side-walls are parallel to the two-dimensional nozzle with boundary-

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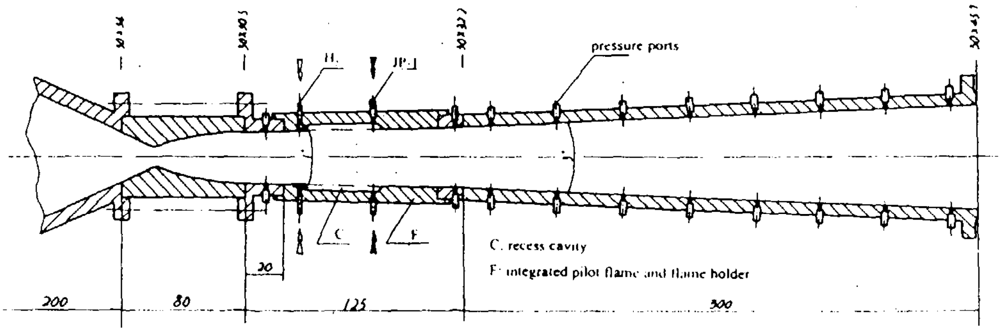

Figure 1, Schematic of experimental device

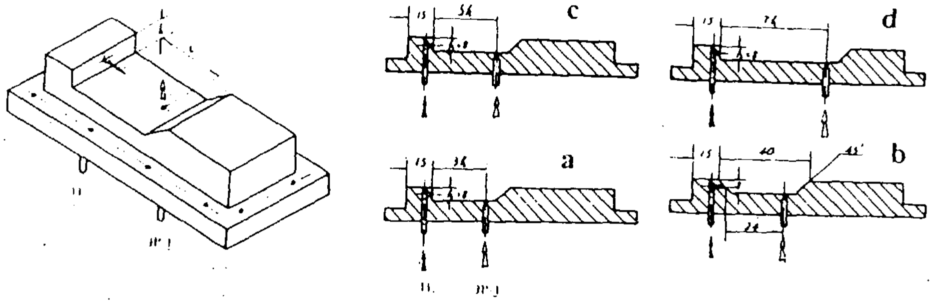

Figure 2, Schematic of integrated fuel injectors and flame-holder

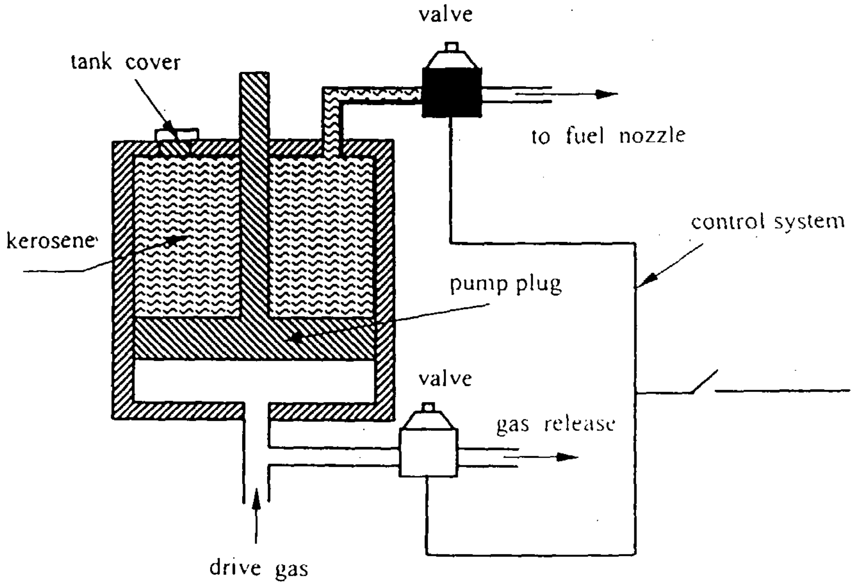

Figure 3, Schematic of kerosene supply system layer correction angles of 0.5 and 1.5 degree, respectively. To monitor the static pressure distribution within the combustor, 16 pressure ports along the center line of each side wall are arranged.

Figure 2 shows four types of integrated modular structure of pilot hydrogen injector and recessed flame-holder. Their common features are as follows: 1) the pilot hydrogen is injected from the step base and parallel to the air stream; 2) the kerosene is injected from the downstream recessed wall and perpendicular to the air stream; 3) The kerosene injections from a pair of opposite walls are expected to form a counter-jet spray; 4) the aft ramp of the cavity is 45°. Their major difference is the distance L between the kerosene injector and the hydrogen injector. In the figure 2-(a) L is 3H, where H is the step height and is 8mm. There are two types of recess length: 30 mm and 45 mm. For simplicity, we shall call the configuration of L=3H and recess length of 30mm as 3H, which will be the baseline. In the figure 2-(b) the step angle is 45° in comparison with the configuration 3H, in which the step angle is 90°. Figure 2-(c-d) show the L=5H and 7H, the recess length is 45mm and 60mm respectively.

The gas flow system is computer controlled to achieve the required accuracy and reliability. The computer also serves as the data acquisition and processing unit.

The schematic of kerosene supply system is shown in figure 3. The kerosene is pressurized to form a spray by cylinder nitrogen. The kerosene flow rate was calculated according to the real amount of kerosene entering the combustor divided by running time.

Data reduction

A modified code SSC-3 [9] was used to analyze experimental data. The flow parameters and combustion efficiency of the combustor can be calculated out by the code SCC-3 according to the experimental static pressure data.

Because kerosene is a complex mixture of many components and its reaction mechanism is more complicated than that of hydrogen, some simplified assumes were adopted. The one-formula surrogate fuel model, in which the molecular formula of kerosene is $C_{12}H_{24}$, and the three thermodynamic functions of heat capacity, enthalpy, and entropy as functions of temperature in a usable form are used: [11]

$$C_p/R = a_1 + a_2T + a_3T^2 + a_4T^3 + a_5T^4$$

$$H_T/R = a_1 + a_2T/2 + a_3T^2/3 + a_4T^3/4 + a_5T^4/5 + a_6 / T$$

$$S_T/R = a_1 \ln T + a_2T + a_3T^2/2 + a_4T^3/3 + a_5T^4/4 + a_7$$

Equivalence ratios of pilot hydrogen and kerosene in the mixture were calculated according to definitions in the reference [12]. Because the mole fraction of the pilot hydrogen is small, there is enough oxygen in the air to react with it.

The equivalence ratio of pilot hydrogen is expressed by

$$\Phi_H = \chi_H / \chi_A / (\chi_H / \chi_A)_{st} = \chi_H / \chi_A / 0.418$$

The effective equivalence ratio of kerosene is expressed by

$$\Phi_F = \chi_F / [\chi_A - \chi_H / (\chi_H / \chi_A)_{st}] / (\chi_F / \chi_A)_{st}$$

$$= \chi_F / [\chi_A - \chi_H / (\chi_H / \chi_A)_{st}] / 0.0116$$

where χ_H, χ_F, and χ_A, are mole fractions of pilot hydrogen, kerosene and air respectively. The subscript st is the abbreviation of stoichiometry.

Measurement of the kerosene droplet size

Atomization of kerosene is an important factor affecting ignition and combustion sustaining. The average droplet diameters of pressurizing kerosene with different injector geometry were measured by using of the MALVERN 2600/3600 PARTICLE SIZER. Results show that the droplet size is dependent mainly on the pressure. For injector with diameter of 0.4mm, when the kerosene pressure increases from 2.1Mpa to 5.5MPa, the average droplet diameter decreases from 25.2 micron to 20.2 micron. The droplet sizes for injector diameter of 0.5mm are almost same as that for injector diameter of 0.4mm.

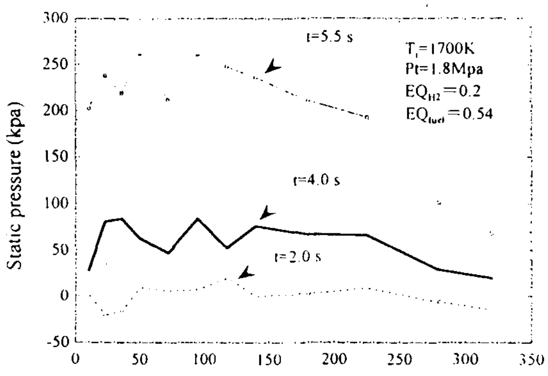

Figure 4, Typical static pressure history and distribution

Results and discussion

1. Experiment procedure

The typical test time is 6.5 seconds. The

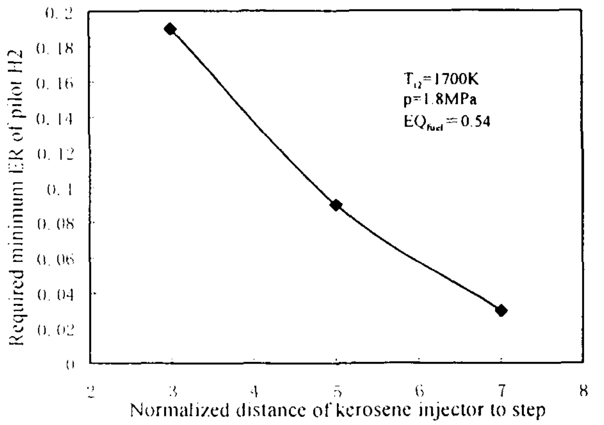

Figure 5, Influence of kerosene injector location on ignition

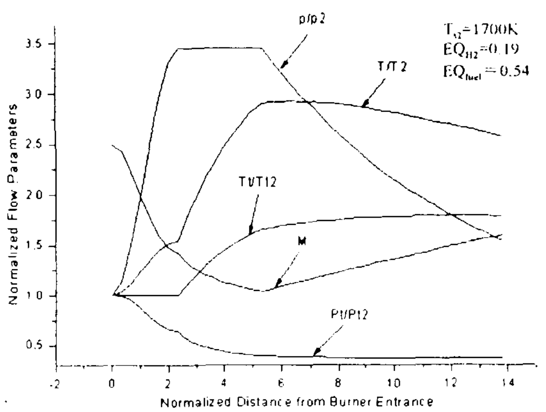

Figure 6, Typical parameter distributions in the combustor calculated by using of code SSC-3

operation sequence was programmed and controlled by a computer. Usually kerosene was injected two seconds later than the pilot hydrogen and injection lasted two seconds, because it only needed 1.5 seconds to achieve stable pressure distribution. Figure 4 shows a typical static pressure history and distribution. In the figure three curves represent the static pressure distributions along the combustor at the time before pilot hydrogen injection, pilot hydrogen injection and during kerosene injection respectively. If kerosene was ignited, the static pressure increased obviously as the figure shows. Otherwise the pressure would not increase but decrease a little. From the figure we can find that, after the pressure pick, the static pressure with kerosene combustion decreases more steeply than that of hydrogen. At the downstream of the combustor exit a bright supersonic flame jet was observed. This implies the chemical reaction of kerosene is slow and the combustor is not long enough for completion of kerosene combustion.

2. Influence of pilot hydrogen on the kerosene ignition

We conducted a series of experiments, in which the air total temperature, total pressure and the kerosene equivalence ratio were kept in about same values as 1460K, 1.8Mpa and 0.54 respectively. The only variable factor was the flame holder configuration (the distance between the pilot hydrogen injector and the kerosene injector).

Figure 5 shows the influence of kerosene injector location on ignition. The kerosene injector station is normalized by the step height H (here H = 8mm). The figure shows that, when the distance increases from 3H to 5H and then to 7H, the required minimum equivalence ratio of pilot hydrogen decreases from 0.19 to 0.09 and then to 0.03.

A preliminary explanation of these experimental results is as follows: when the kerosene injector is too close to the pilot hydrogen injector, the pilot hydrogen flame has not fully developed to produce enough heat and radicals for ignition of kerosene. The pilot flame would be quenched by cold kerosene spray due to absorption of evaporation heat. In this case increasing the amount of pilot hydrogen is required.

Figure 6 shows the flow parameters distribution in the combustor, which were calculated by using of the code SSC-3 according to the experimental data of static pressure. All the parameters are normalized by their values at the combustor entrance. The code SSC-3 can also compute the combustion efficiency of the combustor. In our combustor geometry and experimental conditions the combustion efficiency was found not more than 50%.

Figure 7 shows a comparison of the static pressure distribution of the 3H and 5H configurations. Both experiments were in the same conditions (total pressure is 1.8Mpa, total temperature is 1470K, the kerosene drive pressure is 2.1Mpa and the pilot hydrogen equivalence ratio is 0.19), except the positions of kerosene injectors. From the figure we can find that the pressure pick in configuration 5H is higher than that of configuration 3H. So we can expect that the configuration 5H will have higher

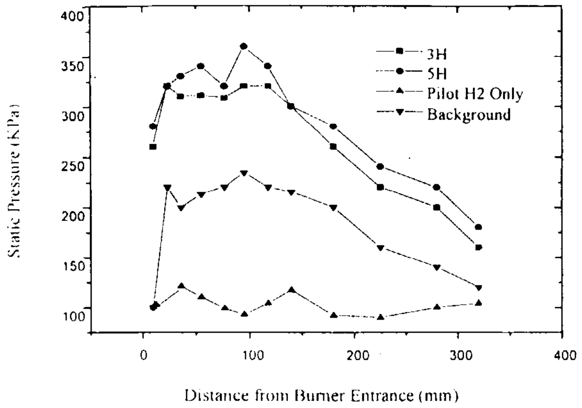

Figure 7, A comparison of static pressure distributions of 3H and 5H configurations.

combustion efficiency.

3. The influence of total temperature of vitiated air on the kerosene ignition

Increasing the total temperature will facilitate evaporation of kerosene spray and then may benefit the kerosene ignition. Our experimental results show that when the total temperature increases from 1470K to 1700K the required minimum equivalence ratio of pilot hydrogen kept almost constant of 0.19 for configuration 3H within the test errors. These results imply that the characteristic evaporation time of the kerosene is smaller than the mixing time and the characteristic reaction time of kerosene, and the evaporation of kerosene is not the control factor. This result also means that for the kerosene ignition the effect of radicals increased by temperature increasing may be neglected compared with the radicals produced by the pilot hydrogen flame.

4. The influence of the recessed configuration on kerosene ignition

Further studies were conducted by changing the rearward-facing step from 90 degree to 45 degree. While other conditions were kept constant, the required minimum equivalence ratio of pilot hydrogen increased from 0.19 to 0.23 for the configuration 3H. Compare with the 90° step, in the recirculation zone of 45° step the recovery temperature of the air was lower and the mixing of the pilot hydrogen and air was poor. It needed more hydrogen to produce enough radicals to ignite the kerosene spray.

Another set of experiments was conducted with recessed cavities in different lengths (30mm and 45mm) for the configuration 3H. The results show that the required minimum equivalence ratio of pilot hydrogen was almost same within the test errors.

Summary

Preliminary studies on the characteristic of ignition and combustion sustaining of kerosene were conducted in a direct-connect supersonic combustor with a fixed entrance Mach 2.5. The total pressure and temperature of the vitiated air was 1.8Mpa and 1416-1700K respectively.

The radicals produced by the pilot hydrogen flame play an important role in the kerosene ignition. Without additional ignitor, a proper combination of pilot hydrogen and recessed flame-holder may ignite kerosene and maintain sustain combustion. The distance from pilot hydrogen injector to the kerosene injector has significant influence on the kerosene ignition. In our test facility, if keeping the same test conditions, in order to ignite kerosene, the required minimum equivalence ratio of pilot hydrogen could be down from 0.19, 0.09 to 0.03 for combustors 3H, 5H and 7H respectively.

When the total temperature increased from 1470K to 1700K the required minimum equivalence ratio of pilot hydrogen kept in 0.19 for configuration 3H within test errors. These results imply that the characteristic evaporation time of kerosene is smaller than the mixing time and the characteristic reaction time of kerosene, the evaporation of kerosene is not the control factor. This result also means that for the kerosene ignition the effect of radicals increased by temperature increasing may be neglected compared with the radicals produced by the pilot hydrogen flame.

Compare with the 90° rearward-facing step, in the recirculation zone of 45° step the recovery temperature of the air was lower and the mixing of the pilot hydrogen and air was poor. It would need more hydrogen to produce enough radicals to ignite the kerosene spray.

The flow parameter distributions in the combustor, which were calculated by using of the code SSC-3, show that the combustion efficiency of kerosene would not be high. In our combustor geometry and experimental conditions the combustion efficiency was found not more than 50%.

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