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Experiments on Liquid Kerosene Ignition in a Supersonic Combustor with Various Ignition Assistance Methods

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Abstract

In this research, the ignition characteristics of the liquid kerosene in a model supersonic combustor was explored with the assist of atomization, pilot gaseous hydrogen, and fuel heating. The supersonic combustor model contains two fuel injector sets, each of the sets consists of one main liquid hydrocarbon injector and one pilot gaseous hydrogen injector. A simple orifice-type injector or a gas-blast-type injector was used as the main injector. For the gas-blast-type injector, the gaseous hydrogen is supplied and mixed with the main liquid fuel in a small chamber in the injector, acting as the atomization assist. The hydrogen also becomes the ignition source in this case. For the orifice-type injector, there is no atomization assist besides the main transverse supersonic airflow. A simple orifice-type is used for the pilot injector. A regenerative heat exchanger was installed on the combustor model optionally. The purpose of the heat exchanger was to heat up the main kerosene fuel before it was provided through the injectors. The tests were performed in a continuous-type, direct-connected combustor test facility. The air flow speed at the inlet of the model was Mach 2.0, the air total temperature was 1,100 K, and the air total pressure was 500 kPa(abs). Test variables were the different atomization/piloting scheme as described above, as well as the flow rate of the main and the pilot fuel and the main fuel temperature. The orifice-type injector couldn't provide enough level of atomization for the ignition and flame holding of the main liquid fuel under the supersonic flow condition. The gas-assist-type, in contrast, was able to maintain supersonic combustion when assisted by hydrogen. In either case of using the hydrogen as the atomizing gas or pilot fuel, the ignition and flame holding was possible, provided that the hydrogen flow rate was equal to or more than 0.8 g/s. For the main fuel injectors of larger injection holes, the ignition was marginal even with the hydrogen flow rate over 0.8 g/s. In this case, main fuel heating was helpful for the ignition, even though the temperature was still below the boiling temperature.

Keywords: *Supersonic combustion, hydrocarbon, fuel injector, atomization, direct-connected*

Nomenclature

N/A

1. Introduction

Scramjet engines are thought to be useful for various aerospace vehicles, including space launches, cruising vehicles, and so on. There have been researches on the scramjet engines for more than 50 years in all around the world, but their practical applications are not accomplished yet. But it is now widely accepted among researchers that, for their practical uses, the fuel for the scramjet engines should be liquid hydrocarbon. There have been researches using other types of fuel, e.g. hydrogen, ethylene, and so on. But they may not be used in the vehicle because of their bad storability and low volumetric energy density. Liquid hydrocarbon may be the only solution in this regards. But it has drawbacks regarding its ignition and flame holding. Liquid hydrocarbons have higher ignition energy and low flame speed compared to other gaseous fuels. Therefore, ignition and flame holding of the

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liquid hydrocarbon fuels in supersonic combustors are crucial for the development of a real, practical scramjet engine system.

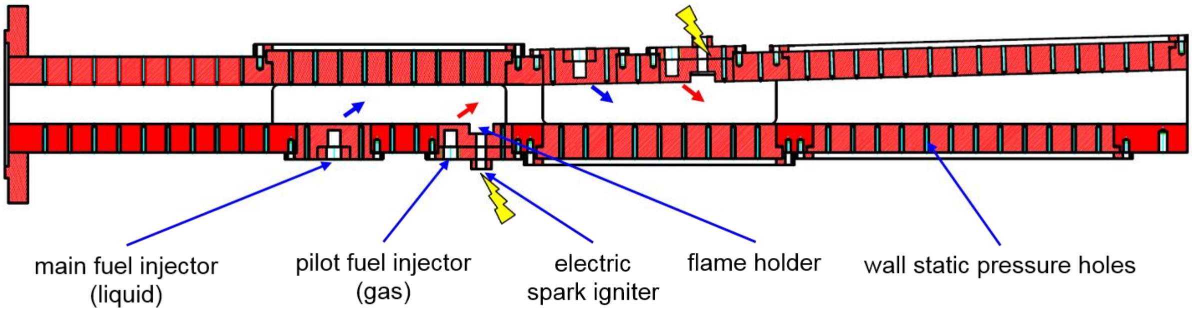
Many types of ignition methods have been proposed for this purpose. The first approach was to provide high ignition energy or better reaction environment. Electric spark igniter may not be enough for this purpose. Pilot flame igniter, plasma igniter, and or laser igniters were proposed [1-3]. The second was to mix the liquid hydrocarbon fuel with other gases to enhance the atomization of the liquid [4]. The third was heating up the fuel, over its boiling temperature, up to the critical temperature, or even thermal cracking temperature [5-6]. There are examples of ignition/flame holding success using one or combination of these methods.

In this research, the authors tried several methods of ignition and flame holding for a given supersonic combustor configuration at a given test condition. They wanted to see if the ignition and flame holding of the liquid hydrocarbon fuel is possible, and find out which is the best and most efficient method for this purpose.

2. Test Model and Test Facility

2.1. Supersonic Combustor Model

The supersonic combustor model, shown in figure 1, was designed with the intention of being tested in a direct-connected test facility.



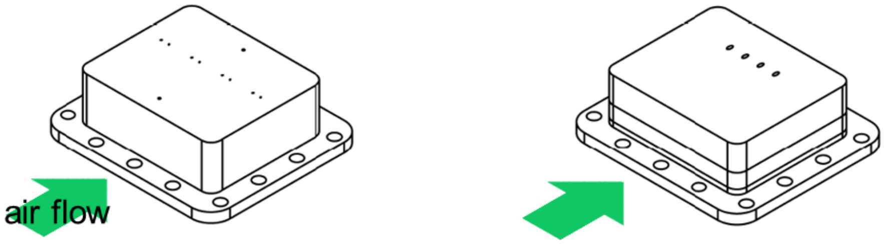
(a) Internal layout of the model

(b) Photograph of the model installed in the facility

Fig 1. Supersonic combustor test model

Therefore, it consists of the isolator and the combustor, not the intake or the thrust nozzle. The design condition for the model is as shown in Table 1. Main fuel of the model was assumed to be kerosene at room temperature. The cross-sectional area of the model is 70 mm of width by 32 mm of height at the model inlet. The isolator section has constant-area cross section, which is followed by a constant-area combustor. The combustor slightly diverges at certain point after the constant-area section.

There are installed two sets of fuel injector/cavity, one on the upper wall, the other on the bottom wall. One set of the fuel injector/cavity consists of one main fuel injector, one pilot fuel injector, one cavity flame holder. The main fuel injector was installed 105 mm upstream of the cavity flame holder. Two types of main fuel injectors were used in this study. The external shapes of the injectors are shown in figure 2. The first is a simple orifice type injector [7]. The injector has eight holes arranged in the direction of model width. Each hole has the diameter of 0.3 mm. The second type is called as a barbotage type, a sort of a gas-assisted atomizer [8]. When the barbotage type injector was used, gaseous hydrogen was used as the atomizing gas. But in some tests with the barbotage type injector, no atomizing gas used and only the liquid fuel was injected through the injector. Gaseous hydrogen was also used as the pilot fuel. The pilot fuel injector was installed 10 mm upstream of the cavity. There are four holed in the pilot injector, arranged also in the direction of model width. The diameter of the holes is 0.8 mm. Both of the main and the pilot injectors use inclined injection with the inclination angle of 30°. The cavity has the depth of 8 mm and the length of 20 mm. An electric spark igniter is installed on the bottom of the each of the cavity. According to the purpose of the test, only the bottom-side main fuel injector was used for some tests. Even in those cases, both of the pilot fuel injectors and the electric spark igniters were operating.



(a) orifice type injector (b) barbotage type injector

Fig 2. External shapes of the main fuel injectors

The combustor model was made to accommodate a heat exchanger. This heat exchanger is aiming the heat exchange between the hot combustion gas and the cold liquid main fuel. The heat exchanger is installed on the downstream portion of the upper wall. The length of the heat exchanger is 320 mm, and the width is the same with that of the model. Inside the heat exchanger, there are 15 fuel passages arranged in parallel in the direction of the model width, each of which is a rectangular channel with 2 mm width, 2 mm height, and 300 mm length. The distance between these fuel passages is 2 mm, and the distance between these fuel passages and the main combustion gas passage is also 2 mm. On each of the inlet and outlet of the fuel side passages, a plenum chamber is installed to distribute and collect the fuel. The fuel outlet is connected to the inlet of the main fuel injector, so that the heated hot fuel can be injected through the injector into the combustion chamber. In this study, this heat exchanger was used optionally when the effect of the fuel temperature on the ignition was to be studied.

2.2. Direct-Connected Supersonic Combustor Test Facility

A direct-connected type supersonic combustor test facility, shown in figure 3, was used for this research. The test condition generated by the facility is described in table 1. The total pressure and total temperature were slight lower than the design point, while the flow Mach number was maintained as the same with that.

The facility consists of a turbo-type air compressor, electric air heater, vitiated air heater, oxygen mixer, facility nozzle, exhaust diffuser, and other auxiliary equipment such as fuel controller, data acquisition system, cooling water system, and so on. The turbo-type air compressor can supply the air at the pressure given in the table 1 continuously. The electric air heater can heat up the air up to 400 °C. The vitiated air heater takes the remaining portion of the temperature rise. Natural gas is used as the fuel of the vitiated air heater. The oxygen mixer is used to compensated the air vitiation by adding gaseous oxygen into the main flow.

The test procedure is as follows: first, the air supply and the electric air heater operation is established. Second, the vitiation air heater is operated with the make-up oxygen supply. By doing this the combustor test condition is established. Then, the electric spark igniters start followed by the pilot hydrogen supply. After the pilot flame is stabilized, main liquid fuel is supplied. After the main flame is stabilized, the pilot fuel is stopped, and the main fuel, spark igniter, and the vitiation air heater is stopped sequentially.

During all of this procedure, wall static pressures are measured along the center line of the combustor model at 100 Hz. Flame visualization was done for some test cases, not all of them. Typical video camera operating at 30 fps was used for the visualization. Quartz windows were installed on the side wall of the combustor model. Photos of the model with visualization windows can be found in later sections of this paper.

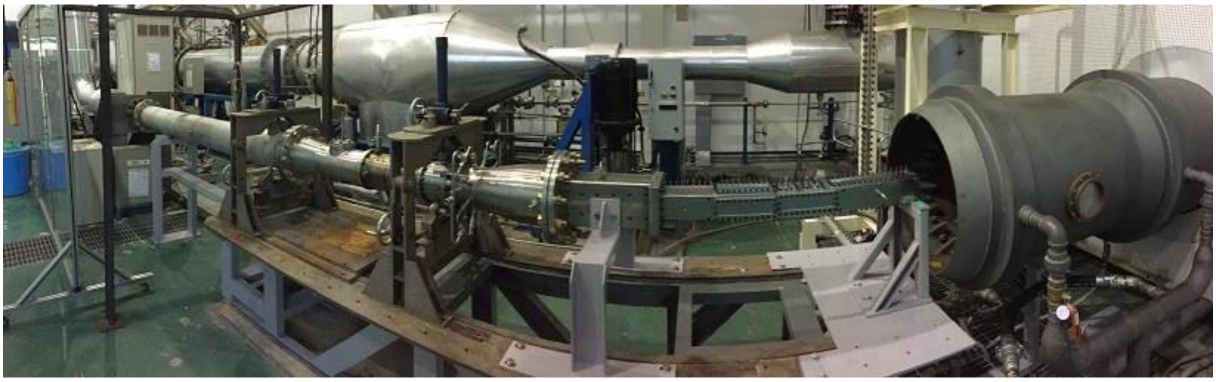


Fig 3. Direct-connected supersonic combustor test facility

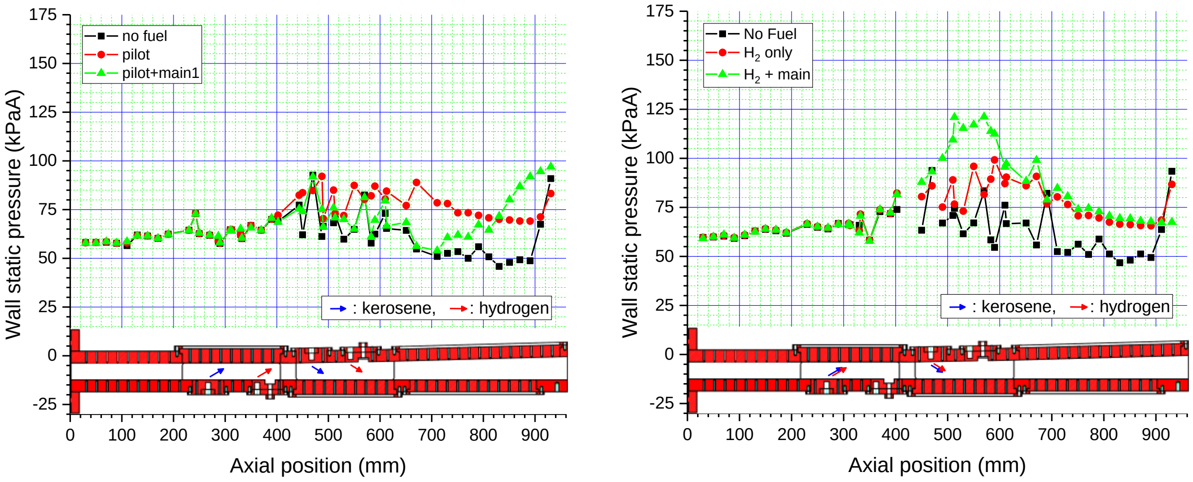
Table 1. The combustor design condition and the facility operation condition

	Speed	Total pressure	Total temp.	Static pressure	Static temp.	Air flow rate
Design condition	Mach 2.0	543 kPa	1,320 K	69 kPa	733 K	0.78 kg/s
Test condition	Mach 2.0	500 kPa	1,100 K	64 kPa	611 K	0.72 kg/s

3. Test Results

3.1. Effects of Atomization Methods

Figure 4 is the wall static pressure distribution during the test. Figure 4(a) is the result with the simple orifice-type main injector[1], while figure 4(b) is that with barbotage-type injector[2]. Hydrogen was used as the pilot fuel for figure 4(a), while as the atomizing gas for figure 4(b).



(a) Using aeroramp-type main fuel injector

(b) Using barbotage-type main fuel injector

Fig 4. Wall static pressure distribution for supersonic combustion

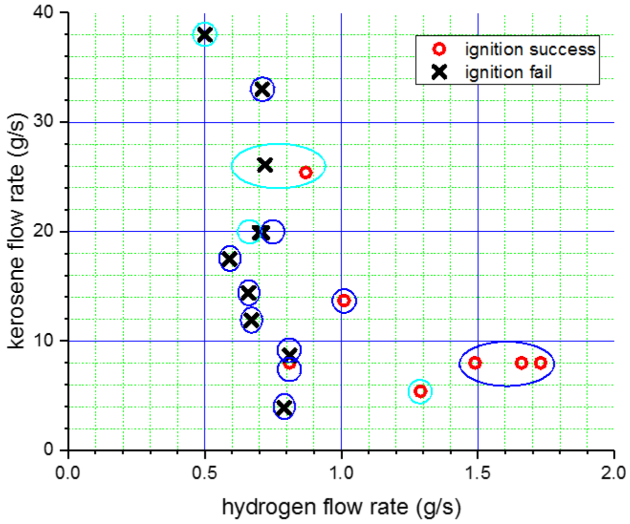
As one can see in the figure 4(a), for the case of pilot fuel injection, there is some pressure increase after x=600 mm indicating combustion is taking place. But for the case of main fuel injection, the pressure is not different from that for no fuel case down to x=700 mm, which means the main fuel is not ignited until this point, even the pilot flame is distinguished by the main fuel. The main flame becomes strong after x=800 mm, but this is thought to be because there is adverse back pressure by the atmospheric pressure, resulting in terminal shock at this location.

On the other hand, in the case of figure 4(b), main fuel combustion was successfully sustained in x=470-600 mm. Therefore, it can be concluded that the simple orifice type fuel injector cannot not provide enough level of atomization for combustion, while the barbotage type injector can.

3.2. Effects of Hydrogen Flow Rate

The flow rate conditions and the result of ignition were summarized in Fig. 5. In the tests, the pilot fuel, atomizing gas or main fuel were sometimes injected at only one set of the two fuel injector sets, or some other times injected at both of the two injectors. But the flow rates were expressed only as the sum of the two injector sets for brevity.

In the figure, it can be found that the success or fail of the ignition is dependent only on the total hydrogen flow rate, regardless of the location or injection scheme, pilot or atomizing, of the hydrogen. In other words, the ignition was successful whenever the total hydrogen flow rate was greater than 0.8 g/s, regardless of it was injected from the pilot injector or from the barbotage injector. Also, the ignition failed for all cases with the total hydrogen flow rate of less than 0.8 g/s. Therefore, it can be concluded that a minimum energy is required to ignite the liquid main fuel, and this can be provided by the hydrogen with the flow rate of more than 0.8 g/s.



O : barbotage only / O : pilot only

Fig 5. Results of ignition tests at various fuel flow rates

3.3. Effect of fuel temperature

High temperature kerosene fuel was provided for some tests to see the effect of the fuel temperature on the ignition and flame holding. The kerosene was heated by using the regenerative heat exchanger as described earlier. For the tests to see the fuel temperature effects, the geometry of the main fuel injectors and the cavities were changed. The diameter of the main fuel injector holes was increased from 0.5 mm to 0.7 mm. The length of the cavity was increased from 20 mm to 30 mm.

The tests were performed in the main fuel flow rate range from 3.2 g/s to 19.0 g/s, corresponding to the fuel equivalence ratio range from 0.06 to 0.4. In all of the tests, the pilot hydrogen flow rate was fixed as 0.92 g/s. The test result is summarized in table 2. In the figure, the "high temperature fuel" means that the fuel temperature is in the range of 170-220 °C. It should be noted that this temperature is below the boiling temperature of the kerosene.

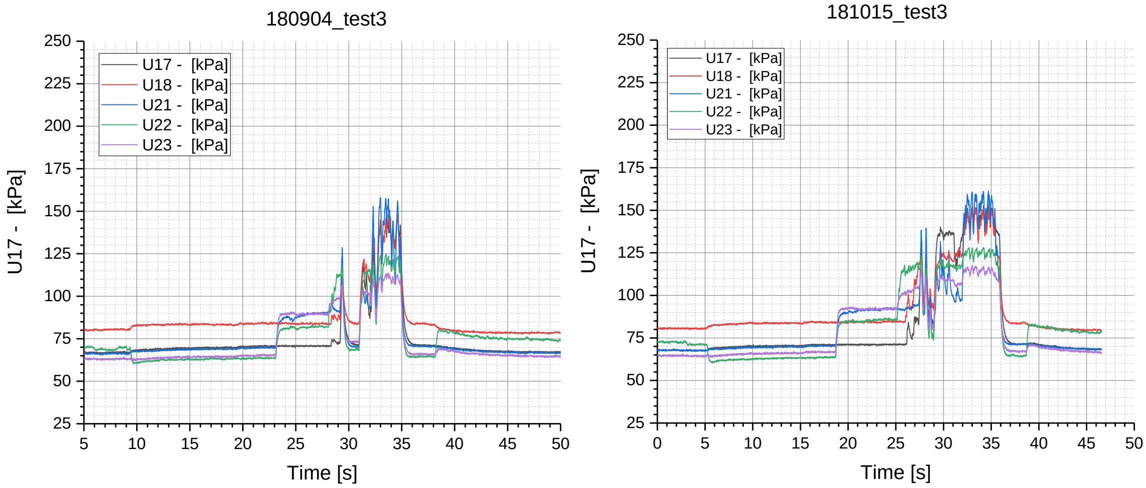
As can be seen in the table, for the room temperature fuel, there are only a few conditions for which the ignition was successful. On the other hand, for the high temperature fuel, the ignition was always successful in the range of the tested fuel flow rate. And also for the high temperature fuel, although there are not many test points, the ignition was more stable than for the mid temperature case.

Therefore, it can be concluded that higher fuel temperature results in more stable ignition and flame holding.

Table 2. Test result with different fuel temperature and the flow rate

Kerosene Flow rate	Room temperature fuel result	high temperature fuel result
3.2 g/s	not tested	success but unstable
3.5 g/s	〃	success but unstable
3.8 g/s	marginal	success
4.5 g/s	marginal	success
5.3 g/s	success	success
6.5 g/s	not tested	success
8.0 g/s	success	success
9.8 g/s	success	success
11.0 g/s	close to fail	success
12.2 g/s	fail	success
16.1 g/s	marginal	success
16.1 g/s	fail	not tested
17.6 g/s	fail	〃
18.3 g/s	fail	〃
19.0 g/s	success	〃

Some examples of the wall static pressure history is shown in figures 6-8. In the figures, the pressures of U17 and U18 are measured around the upstream cavity, and those of U21 to U23 are measured around the downstream cavity. In figure 6 first, the main fuel is supplied during t=28-33 s for figure 6(a), and t=25-38 s for figure 6(b). The pressure history experiences several steps of evolution, and finally stabilized during t=32-35 s for both cases. By comparing the pressures in this duration, one can find that the high temperature fuel case is more stable than the other.

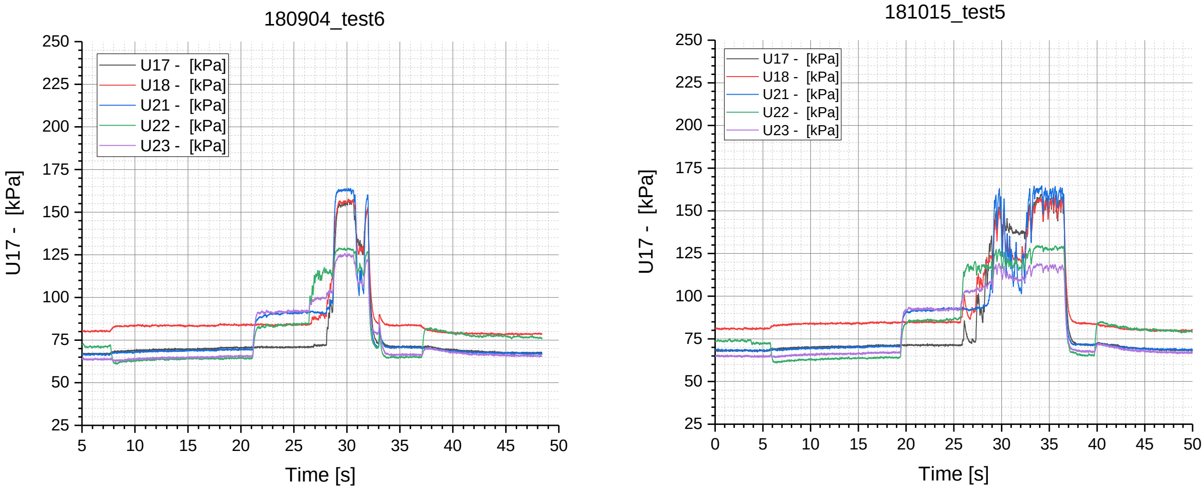


(a) Room temperature fuel (3.8 g/s)

(b) high temperature fuel (3.8 g/s)

Fig 6. Results of ignition tests at the same fuel flow rate and different temperatures

Figure 7 shows the results at a different fuel flow rate. Although it seems that the room temperature case of figure 7(a) has smaller fluctuation, it should be noted that there is a large pressure drop for this case during t=31-32 s. And also the flame is distinguished at t=32 s, which is a few seconds before the main fuel cut off. On the other hand, for the high temperature test of figure 7(b), the flame is stabilized during the entire main fuel supply of t=26-36 s, although there exists a small pressure drop during t=30-32.5 s.



(b) Room temperature fuel (5.3 g/s)

(b) high temperature fuel (5.3 g/s)

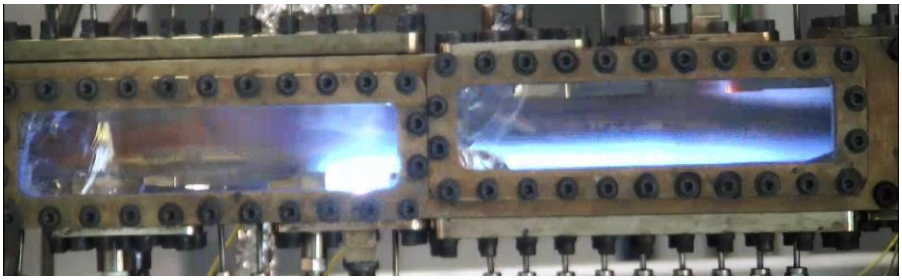
Fig 7. Results of ignition tests at the same fuel flow rate, but different temperatures

3.4. Flame holding of the liquid main fuel

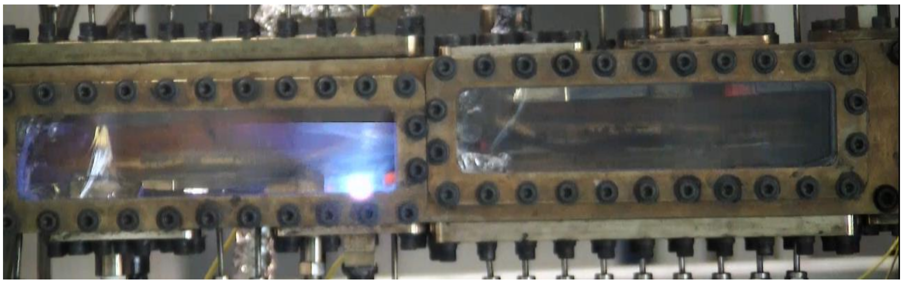
In all of the above tests, it can be found that, after cutting off the pilot hydrogen, the pressures drop to the level of no fuel case. In other words, after cutting off the pilot hydrogen, the main kerosene flame could not survive in any case of the above tests. The flame is totally distinguished.

But, for some cases of high temperature fuel case, the main flame was partly survived inside the cavity even after cutting of the pilot. This was found by the visual observation of the flame. The visual images are shown in figure 8. Figure 8(a) is a typical flame when both the pilot and main fuels are supplied. Figure 8(b) is a typical situation when only the pilot fuel is stopped. The main fuel cannot survive without the pilot fuel, even with the electric spark igniter. The bright, circular light inside the cavity is the electric spark igniter. Figure 8(c) shows the situation when the main flame is survived inside the cavity after the pilot fuel cut off. The instance of flame survival coincides with the instance of igniter operation, but it survived even for a while between the igniter operation. This flame survival was observed for the main fuel flow rate in the range of 3.8-8.0 g/s, and it was strongest for the cases of 4.5 g/s and 5.3 g/s.

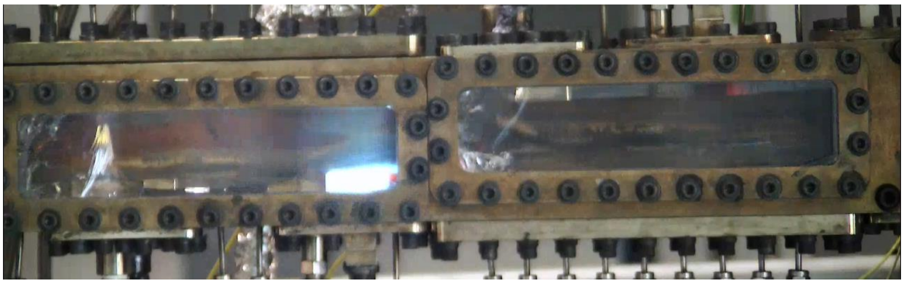
But the survived main flame was only confined inside the cavity, survived only for very short time, and too weak to have any effect on the wall static pressure. But anyway the room temperature fuel cases did not show even this weak combustion. Therefore, tests with higher fuel temperature may enhance the flame holding more.



(a) With pilot fuel and main fuel supplied



(b) With only main fuel supplied (flame off)



(c) With only main fuel supplied (flame on)

Fig 8. Flame visualization images with various fuel supply conditions

4. Summary and Conclusion

In this study, a series of ignition tests for the liquid-fueled supersonic combustor was performed with various ignition assistance methods. The methods include the gas-assisted fuel atomization, using pilot flame, and heating up the fuel temperature. The followings were found by this study.

(1) The simple orifice type fuel injector could not provide enough level of atomization for the ignition of the liquid main fuel. The barbotage type injector, which is a kind of gas-assisted fuel atomizer, had to be used for the ignition of main fuel.

(2) The hydrogen supply was necessary for the ignition and flame holding of the liquid main fuel. More than 0.8 g/s of hydrogen flow rate was required for the ignition. Otherwise the main fuel ignition failed. The location of the hydrogen supply, i.e., where the hydrogen was supplied through the pilot fuel injector or the barbotage injector, did not affect to the main fuel ignition.

(3) High temperature fuel provided more preferable environment for ignition. Even with the fuel temperature of 170-220 °C, which is below the boiling temperature of the fuel, the ignition was enhanced.

(4) Flame holding without the pilot hydrogen supply did not occur for the room temperature main fuel tests. It occurred only when the high temperature fuel was used. But the flame survived only for a very short time, and was very weak so that had no effect on the combustion pressure. Visualization tests with even higher fuel temperature, say over 300 °C.

Acknowledgement

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