A Research on Supersonic Combustion of Atomized/Vaporized Kerosene Fuel

Yoshitaka Uriuda, Jun Osaka, Shinji Nakaya
Hideyasu Tanaka, Shuhei Takahashi*, Kazunori Wakai**
Mistuhiro Tsue, Michikata Kono

Dept, Aeronautics and Astronautics, University of Tokyo
7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
**Dept. Mechanical and systems Engineering, Gifu University*
1-1 Yanagido, Gifu-shi, Gifu 501-1193, Japan

tt36290@mail.ecc.u-tokyo.ac.jp

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Abstract

An experimental research on supersonic combustion of kerosene in a model scramjet combustor has been conducted. Kerosene was injected normally into a Mach 2 vitiated airstream either at an atomized liquid state or at a gaseous state. The atomization of kerosene was achieved by the "effervescent atomization" method, and the gaseous kerosene was supplied by passing kerosene inside a heated pipe. The results are discussed and are also compared to those in our previous experiment, in which no atomization nor vaporization methods has been conducted to the kerosene.

Introduction

Recently, hydrocarbon fuels are gathering increasing attention as a candidate for scramjet engine fuel. Although reactivity and burning velocities of hydrocarbon fuels are much smaller compared to hydrogen fuels, they are attractive for it's high volumetric energy density, which allows the fuel tank to be relatively smaller, and the fact that they are more easier to handle than hydrogen.

However, it is also well known that hydrocarbon fuels have a long ignition delay time as its defect, sometimes exceeding the fuel's residence time within the combustor. In order to overcome this problem, many researches has been previously conducted[1-2]. Those experiments revealed that a deeper fuel penetration, and a development of a smaller fuel droplet is essential to shorten the ignition delay time, each representing quick mixing and fast evaporation. The same results has been obtained in our previous research[3], where we have conducted a series of experiments injecting kerosene, which are commonly used for jet engines, normally into the supersonic airstream, downstream of a backward facing step. In the experiment, we also used several types of combustors (e.g. combustor with flow expansion, combustor with a cavity) to see the effect of geometric changes upon the combustion limits. In this research, we again used kerosene as a fuel, and attempted to enhance its combustion by changing the injection methods. One method was to enhance the atomization of kerosene by using the "effervescent atomization" method, and the other was injecting kerosene at a gaseous state by preheating the kerosene before injection.

Effervescent atomization is an atomization method in which gas bubbles are introduced directly into the liquid fuel before injection to create a two phase flow[4-8]. The gases "explode" after injection, generating a small fuel droplet. According to Gruenig and Mayinger[4], the effervescent atomization method was first applied to supersonic kerosene combustion by Avrashkov et al[5]. Also, in 1998, Sabelnikov et.al[6] tested hydrogen, nitrogen and air as the barbotage gas, and showed that hydrogen works well rather than air or nitrogen. However, since we first wanted to explore the effect of the kerosene atomization independently, we used nitrogen as the barbotage gas so that it does not react with the airstream. Later in the experiment, air was also employed as the barbotage gas.

By the way, these problems accompanied with liquid fuels, such as the long ignition delay times or the problem in creating a smaller droplet diameter for fast fuel evaporation could be solved if kerosene could be injected at a gaseous state. Since gaseous kerosene reacts more faster than liquid kerosene[9], it is expected that supersonic combustion would occur at relatively low total temperatures compared to liquid kerosene. Therefore, an experiment of gaseous injection of kerosene has also been conducted to confirm this concept.

Experimental Apparatus

Wind Tunnel Facility

The experiments were conducted at the University of Tokyo's Mach 2 blow down wind tunnel. To raise the enthalpy of the airstream to a desired level, a vitiation heater is used in which hydrogen and air are preburned. Also, additional oxygen is added so that the mole fractions of the vitiated gas becomes the same with the standard atomsphere. The hot gas is then accelerated by a 2-dimensional Laval nozzle and is introduced into the rectangular duct combustor,

mach number	total temperature [K]	total pressure [MPa]	static pressure [MPa]
2	1800~2400	0.38	0.05

Table 1 Airstream conditions at the entrance of the combustor

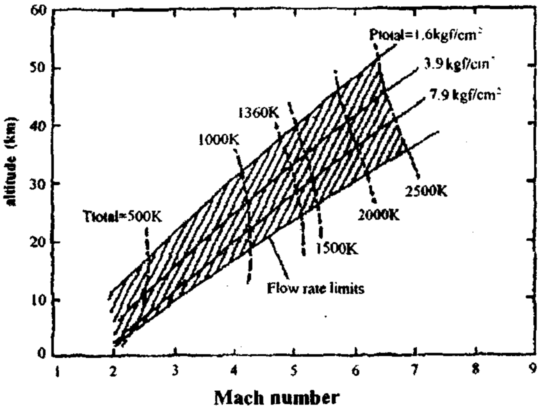
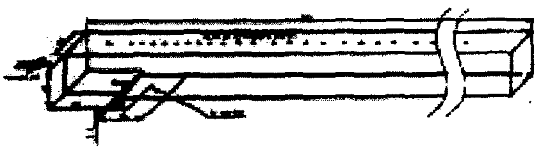
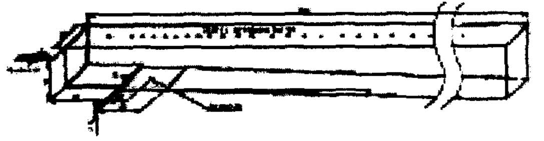


Fig. 1 Wind tunnel simulation map



Combustor A (with no flow expansion)



Combustor B (with 2 degrees flow expansion)

Fig. 2 Schematic of Combustor

which is directly connected to the nozzle. The condition of the airstream at the entrance of the combustor is shown in Table 1, and the range of flight conditions it can simulate in Fig. 1.

Combustor

Two types of zinc bronze combustors, as shown in Fig. 2, were used in the experiments. The cross section at the entrance of the two combustors is rectangular with a height of 36mm and 30mm wide. The overall length of the combustor is 400mm and has a backward facing step with a height of 3.6mm, located 50mm downstream of the combustor entrance to create a recirculation zone (for the purpose of enhancing mixing and ignition). The fuel injector hole is located 18mm downstream of the step. Starting at 40mm downstream of the combustor entrance, the flow path diverges in Combustor B where it does not change in Combustor A. Both combustors could be equipped with a quartz window for optical access to the flow when the total temperature is below 1800K.

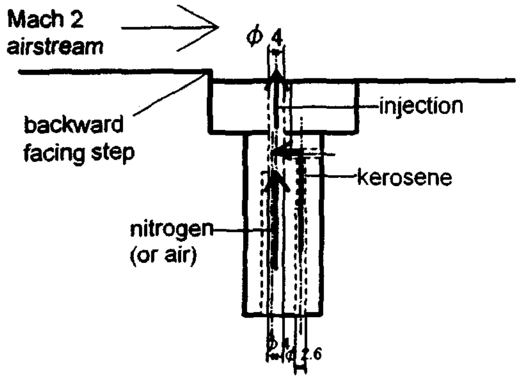
Fuel supply system/injector

Atomization experiment

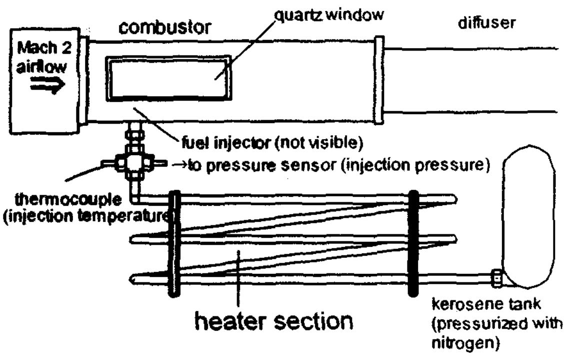
For the kerosene atomization experiment, injector A as shown in Fig. 3(a) was used. Within this injector, kerosene is mixed with the barbotage gas and is then injected into the combustor (effervescent atomization method). In most of the experiment, nitrogen was used as the carrier gas, but in some cases it was changed to air to explore the effect of the carrier gas on the combustion characteristics. The diameter of the injector hole is 4mm and the fuel mass flow rate is measured by a flow meter.

Gaseous injection experiment

The injection system for the gaseous kerosene injection experiment is shown in Fig. 3(b). The heater is made of a 5m long copper tube with its inner diameter of 10mm in which the kerosene flows through. The copper tube is wounded around and heated by a electrically heated wire. A heat insulating material is also wound around to prevent the heat from dissipating. The surface temperature of the copper tube and the heated kerosene reaches more than 700K and is injected at a gaseous state. The injection pressure and temperature are monitored by static pressure transducers and a thermocouple.



(a) effervescent atomization injector



(b) heater and injection system

Fig. 3 Injection systems

Measurement

The condition within the combustor is measured by means of 23 static pressure taps along the top wall of the combustor. In all the cases, combustion was judged by monitoring the static pressure rise. Also, when the total temperature of the flow is below 1800K, optical measuring were conducted by a digital video camera through the quartz window on the side wall of the combustor.

Results

It is known that when combustion takes place in a supersonic airstream, there sometimes appears a shock wave which we call the Precombustion Shock Wave (PSW), upstream of the reaction zone. By the location of the PSW, the modes of combustion could be classified as below.

1) Weak Combustion Mode
   A reaction rated combustion takes place near the bottom wall, downstream of the injection hole with no PSW generated.
2) Transition Combustion Mode
   Combustion takes place near the bottom wall, downstream of the injection hole accompanied with a PSW.
3) Intensive Combustion Mode
   A mixing-rated combustion is established with a PSW generated right behind the backward facing step.
4) Thermal Choking Combustion Mode
   Combustion in which the PSW is generated upstream of the step. In this mode, the combustor is thermally choked.

The occurrence of the mode depends on the amount of heat released by the combustion. The higher the heat release, the more upstream the PSW is generated. Fig. 4 shows the characteristic pressure distributions along the top wall of the combustor of the four combustion modes.

Since the airstream must be avoided from thermally choking, the amount of heat release should be controlled so that the most desired Intensive Combustion mode would takes place. For example, the results of the experiment in which kerosene was injected normally into the airstream from a 0.5mm injector hole is presented in Fig. 5. In this experiment, no special atomization methods nor heating has been conducted (this would be called the reference case). As could be seen here, at total temperature 2400K, the intensive combustion mode takes place at lower equivalence ratio than the choke combustion modes.

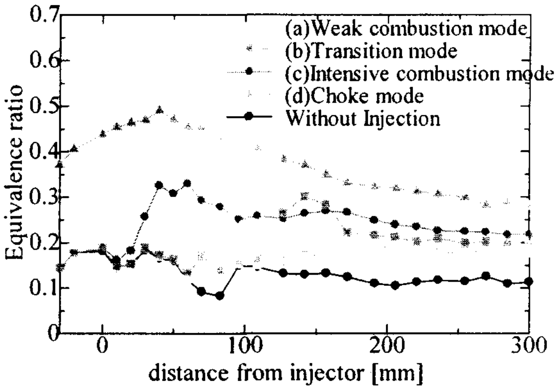


Fig. 4 Characteristic static pressure distributions of combustion modes (fuel: hydrogen)

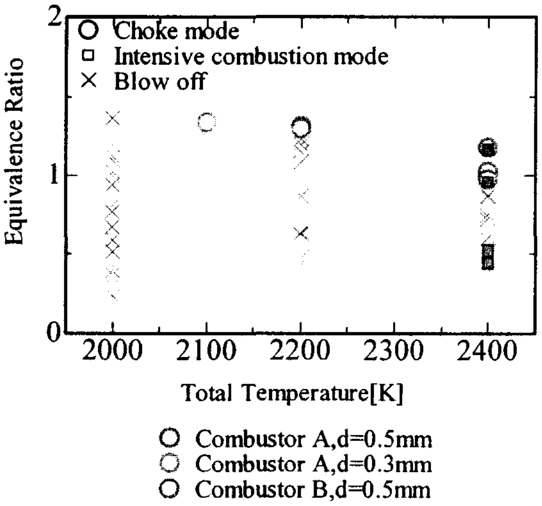


Fig. 5 Ignition limits of kerosene (reference case)

Atomization Experiment

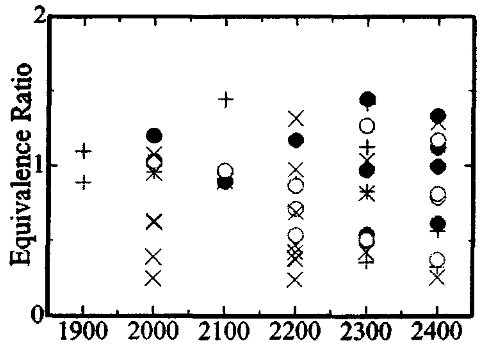
The image of fuel injection of this experiment, taken with a Xenon back lamp is shown in Fig. 6 (a), (b) and the image from our previous experiment in (c). Since we do not have a method to measure the droplet diameter, we estimate it by measuring the length of the scattered light. In our previous study, it is known that the smaller the injector hole, the shorter distance it takes until the scattered light becomes invisible (complete evaporation of the fuel), meaning that a more smaller droplet is made. Now, when we compare image (a) to image (c), it could be seen that the length until the scattered light disappears is almost the same, and therefore it could be said that a same level of atomization is achieved even by a relatively large, 1mm diameter injection hole. The image when the nitrogen barbotage injection pressure is increased to 1MPa is shown in (b). In comparison to (a), it could be seen that the fuel's penetration height into the airstream is increased, but no significant differences in the distance it takes to evaporate was observed.

(a) T_0=1600K injection diameter 4.0mm ϕ =0.32
Nitrogen pressure 0.5MPa

(b) T_0=1600K injection diameter 4.0mm ϕ =0.28
Nitrogen pressure 1MPa

(c) T_0=1600K injector diameter 0.3mm ϕ =0.41
Fuel back pressure 40atm (reference case)

Fig. 6 Images of injected kerosene with an Xenon back lamp



red figures indicates: nitrogen pressure 10kgf/cm^2
blue figures indicates : nitrogen pressure 5kgf/cm^2
● : combustion
× or +: blow off

Fig. 7 Combustion Limits (atomization experiment)

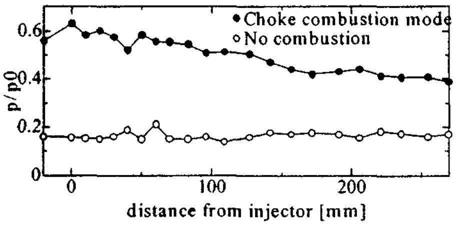


Fig. 8 Static pressure distributions of combustion of atomized kerosene

The results of all the experiments conducted in this atomization experiment are shown in Fig. 7. It could be seen that more amount of fuel is required for combustion at lower total temperatures. Also, there are some cases where combustion did not occur even though the same amount of fuel (equivalence ratio) was injected to the case in which combustion occurred. This may be due to some variable factors in the experimental facility, such as the total temperature of the flow. Nevertheless, it could be said that kerosene's ignition limit in this combustor lies in the range of 2000 to 2200K. Despite our expectations, no significant difference was observed in changing the pressure of the barbotage gas. All the combustion that occurred in this experiment was a thermal choke mode. The pressure distribution is shown in Fig. 8. Although we attempt to achieve an intensive combustion mode by reducing the amount of fuel, we were not able to find the appropriate amount of fuel. Therefore, it is likely that a severe control of fuel mass flow rate is required to establish intensive combustion.

We would like to compare this result with the reference experiment. In the reference case, combustion took place only at high equivalence ratio conditions, whereas in this atomization experiment, combustion took place in a wide range of equivalence ratio, especially in the fuel lean conditions. This is because, by adopting the effervescent atomization method, it became possible to control the penetration height and the mass flow rate independently by changing the carrier gas pressure and the fuel back pressure, whereas the penetration height was in proportion to the fuel mass flow rate in the reference case. This indicates that the effervescent atomization method is not only useful in atomizing the fuel, but serves as a good injection method for controlling the fuel penetration height.

The same experiment has been conducted in Combustor B, in which the flow expands. Although we expected it to have an effect on suppressing the flow from thermally choking, the results had the same trend with the results conducted in Combustor A. Also, in the experiments where we used air as the barbotage gas, no significant difference was observed to the nitrogen barbotage case in both combustors.

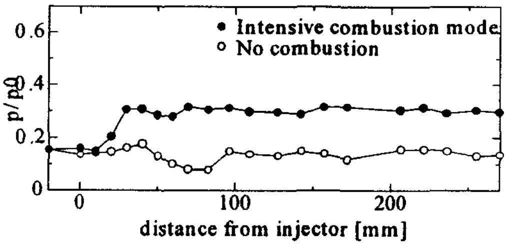
Vaporization Experiment

In this experiment, kerosene vaporization was confirmed by optically observing the injected kerosene with a Xenon back lamp. No light was scattered, indicating that vaporization has been achieved.

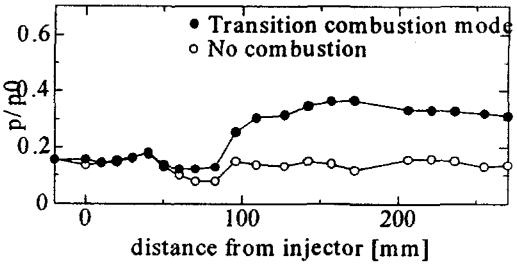
In this case, intensive combustion was observed at total temperature of 2400K, fuel injection pressure 7atm, equivalence ratio $\phi=0.7$. The static pressure distributions are shown in Fig. 9(a). For the reference case, intensive combustion occurred at equivalent ratio 0.5. The reason why combustion did not occur until the equivalence ratio of 0.7 could be explained that the injection pressure of the gaseous kerosene was not high enough for the it to mix with the airstream well compared to the higher penetrating liquid injection case. Also, when hydrogen was used as a fuel in the same combustor at the same condition, it achieved intensive combustion at a much lower total temperature of the airflow as 1400K. This could be explained by the fact that hydrogen has a much higher reactivity than kerosene.

Also, during this combustion process, a transition combustion mode was seen for a while as shown in Fig. 9(b). Since this mode has not been observed during combustion in any of our previous experiments using liquid kerosene as a fuel, this may be due to the effect of kerosene being gasified.

Unfortunately, although we expected to observe combustion at lower airsteram total temperatures than in the reference case, combustion did not occur at flow total temperature 2200K. However, it was extremely difficult to set up the desired experiment conditions (fuel mass flow rate, fuel injection temperature, fuel injection pressure) and therefore only a few experiments were conducted, in contrast with the atomization experiment. Because of the lack of adequate data, the detailed combustion characteristics for the vaporization experiment is still unclear, and further research should be needed.



(a) intensive combustion mode



(b) transition combustion mode

Fig. 9 Static pressure distributions of gaseous kerosene combustion

Conclusion

The following conclusions were derived from the experiments.

1. By using the effervescent atomization method, it became possible to control the fuel mass flow rate and the penetration height independently, and therefore combustion was established in a wide range of equivalent ratios

2. Severe fuel control should be required for the establishment of intensive combustion for effervescent atomization method using kerosene fuel.

3. A transition combustion mode was observed in the combustion of gaseous kerosene.

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