Observation of Flame Stabilized at a Hydrogen-Turbojet-Engine Injector Installed into a Lab-Scale Combustion Wind Tunnel

By Kazutaka MICHISHITA1), Hiroshi NOMURA1), Yasushiige UJIIE1) and Keiichi OKAI2)

1) College of Industrial Technology, Nihon University, Narashino, Japan
2) Japan Aerospace Exploration Agency, Chofu, Japan

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A lab-scale combustion wind tunnel was developed for investigation of low-pressure ignition and flame holding in a sub-scale pre-cooled turbojet engine with hydrogen fuel in order to make engine start at high altitudes sure. The combustion wind tunnel is a blow-down type. A fuel injector of the sub-scale pre-cooled turbojet engine was installed into the combustion wind tunnel. Conditions in which a flame can be stabilized at the fuel injector were examined. The combuster pressure and equivalence ratio were varied from 10 to 40 kPa and from 0.4 to 0.8, respectively. The mean inlet air velocity was varied from 2 to 48 m/s. Flames stabilized at 20 kPa in pressure and 0.6 in equivalence ratio were observed. It was found that the decrease in the combuster pressure narrows the mean inlet air velocity range for successful flame holdings. Flame holding at lower combuster pressures is realized at the equivalence ratio of 0.4 in the mean low mean inlet air velocity range, and at the equivalence ratio of 0.6 in the high mean inlet air velocity range. Flame luminosity is the largest near the fuel injector. The flame luminosity distribution becomes flatter as the increase in the mean inlet air velocity.

Key Words: Combustion Wind Tunnel, Low-Pressure, Hydrogen, Pre-Cooled Turbojet Engine, Ignition, Flame Holding

1. Introduction

In JAXA, research and development of pre-cooled turbojet engine have been conducted since 1986. This engine development is a key technology for realizing propulsion system of a hydrogen hypersonic airplane and first-stage propulsion system of a space-plane. In pre-cooled turbojet engine, a heat exchanger was installed behind an air intake to cool hot air at high flight Mach numbers. Liquid hydrogen passes the heat exchanger and then vaporizes. Vaporized hydrogen is injected into a combustor as fuel.

The Balloon-based Operation Vehicle (BOV), originally developed for micro-gravity experiments, was modified as a supersonic flight demonstration vehicle with a sub-scale pre-cooled turbojet engine. In the supersonic demonstration, the vehicle was lifted by a high-altitude balloon up to an altitude of 40 km and dropped in order to accelerate the vehicle to a supersonic velocity. Therefore, a sub-scale pre-cooled turbojet engine needed to start surely under high-altitude condition.

Reliable engine-restart at high altitudes must be ensured for safety in operations of a space-plane and a hypersonic airplane. Space-plane needs to restart engines after atmospheric re-entry at every flight. The hydrogen engine is also one of possible candidates which will be employed for future airplanes. Fundamental studies on ignition and combustion of hydrogen/air heterogeneous mixture flows at low pressures are important for safety flight.

A lab-scale low-pressure combustion wind tunnel was developed to obtain fundamental data useful for making engine-restart at high altitudes sure. A fuel injector of a sub-scale pre-cooled turbojet engine was installed into the combustion wind tunnel. The purposes of the present study are to investigate successful operation condition of the sub-scale pre-cooled turbojet engine combustor for low-pressure ignitions and subsequent flame holdings, and to observe flames stabilized at the injector.

2. Experimental Apparatus and Procedures

Figure 1 shows the experimental apparatus. The combustion wind tunnel is a blow-down type, which sucks air from the atmosphere into a vacuum tank. The experimental apparatus consists of the combustion wind tunnel, an air supply system, a hydrogen supply system, control devices, a data recorder, and an optical observation system. Air flow rate was controlled by a mass flow meter and speed controller (YAMATAKE CMS1500, max flow rate: 1500L/min). Hydrogen gas fuel was supplied by a mass flow controller (YAMATAKE MQV500, max flow rate: 500L/min). Figure 2 shows a schematic of a combustor, which is an upstream part of the combustion wind tunnel. The cross-section of the combustor is a rectangle (36mm X 18mm). The combustion section is 477 mm in length. Six quartz observation windows (diameter: 15 mm) were equipped with the combustor, which allows us to observe flame-holding process and flame shape. Flame was observed with a UV-CCD camera (Sony XC-EU50, picture size: 768 X 494 pix) and recorded with a digital video recorder. The UV-CCD camera has high sensitivity in the wave length range from 300 to 420 nm. Although the actual combustor of the sub-scale pre-cooled turbojet engine has 20 injectors, a single actual fuel injector was installed into the combustor of the lab-sale combustion wind tunnel.

A detail of fuel injector is shown in Fig. 3. A fuel nozzle is surrounded by a coaxial swirler covered by a cylindrical duct (swirler duct). Hydrogen fuel is injected in the radial direction as a cross-flow against the swirled air flow through 8
holes on the side wall of the fuel tube so that momentum mixing and further mixing due to the fuel flux impingement on the swirler duct wall are attained. The discharge energy was supplied by an ignition power supply (YOKOGAWA 5102-11, electrical energy: 2 J, discharge energy frequency: 3Hz), which is the same as that of the sub-scale pre-cooled turbojet engine. Needle-tip electrodes were used as spark electrodes because of convenience of adjusting the position of spark gap. The electrodes are made of tungsten wire of 1.2 mm in diameter and their tip-angle is 60°. Spark was discharged between two tungsten wire tips. The spark gap was located at 10 mm downstream of the fuel injector, and 6 mm above the combustor axis. The relative position of spark discharge gap to the fuel injector is approximately the same with that of the sub-scale pre-cooled turbojet, and provided us the best ignition and flame holding performance in the past research. Pressure and temperature in the combustor was measured with an absolute pressure gage (Kilite XTE-190, pressure range: 0-170 kPa) and a thermocouple (type K), respectively. The thermocouple was fixed at 431 mm downstream of the fuel injector. When temperature in the combustor exceeds 1200 K, hydrogen flow is stopped for safety. This emergency stop is controlled by a sequencer (KEYENCE KV-700). A gate valve installed between the combustor and the vacuum tank keeps the pressure in the combustor constant, which is controlled by the sequencer and driven by a stepping motor. Air flow rate, hydrogen flow
rate, combustor temperature, combustor pressure, and vacuum tank pressure were recorded with an oscilloscope (KEYENCE NR-2000, frequency: 400 kHz).

The experimental procedures are described as follows. Vacuum tank pressure $P_t$ is decreased below 2 kPa at all tests. After a decompression of the vacuum tank, experiment sequence is started. Discharge energy is supplied to the spark electrodes for a maximum of 5 seconds after combustor pressure, hydrogen flow rate and air flow rate become constant. Success or failure of ignition and flame holding is confirmed from the temperature data and UV-CCD camera images. When flame is stabilized at the fuel injector, the ignition power supply is turned off immediately.

The result is categorized into 3 patterns. Pattern 1 stands for successful flame holding, which means that flame holding continues over 5 s, or combustor temperature exceeds 1200 K. Pattern 2 stands for success of ignition only, which means that the increase in combustor temperature is more than 10 K during spark discharges. Pattern 3 stands for ignition failure, which means that the increase in combustor temperature is less than 10 K during spark discharges. The combustion wind tunnel was operated at various combustor pressures $P_c$, mean inlet air velocities $U_a$ and equivalence ratios $\phi$. The maximum air flow rate of the combustion wind tunnel is 550 NL/min. The combustor pressure was varied from 10 to 40 kPa in absolute pressure. The mean inlet air velocity was varied from 2 to 48 m/s. The equivalence ratio was set at 0.4, 0.6 and 0.8. The mean inlet air velocity was calculated from volumetric flow rate of air at the standard pressure, air density at the combustor inlet, and the cross-section area of the combustor.

3. Results and Discussion

3.1. Flame holding test

Figure 4 shows histories of the flame-holding test data, namely combustor pressure and temperature, mean inlet air velocity, equivalence ratio, air flow rate, and hydrogen flow rate. The combustor pressure and mean inlet air velocity were kept at 20 kPa and 10 m/s, respectively. The equivalence ratio was 0.6. Flow was ignited at about 4 s. The combustor pressure increased sharply due to the disturbance of the ignition, and rapidly converged to the setting value by the gate valve. The combustor temperature increased 0.6 s after the ignition. At about 14 s, hydrogen flow stopped.

Figure 5 shows the map of successful flame-holding conditions as functions of the mean inlet air velocity and the combustor pressure at each equivalence ratio. Pattern 3 was not observed in all tests. The border lines between Pattern 1 and 2 show the similar shape for all equivalence ratios. The mean inlet air velocity range where Pattern 1 appears becomes narrow with the decrease in combustor pressure. At the equivalence ratios of 0.4 and 0.6, the minimum combustor pressure of the Pattern 1 area appears at about 10 and 30 m/s in the mean inlet air velocity, respectively. This fact suggests that the mixing of fuel and air is too poor at lower mean inlet air velocities and chemical reactions are too slow at higher mean inlet air velocities to sustain flame at the fuel injector. It was found that flame holding at lower combustor pressures is realized at the equivalence ratio of 0.4 in the low mean inlet air velocity range, and at the equivalence ratio of 0.6 in the high mean inlet air velocity range.

Laminar burning velocity of hydrogen/air mixture takes the maximum at the equivalence ratio of 1.8 in the pressure range from 20 to 100 kPa. As shown in Fig. 3, the fuel injector is composed of coaxial air flow duct and swirler duct. Those cross-section areas are in the proportion of 17 to 32. Based on this area ratio, local equivalence ratio was calculated for the mixture throughout the swirler duct. When the total equivalence ratios are 0.4, 0.6 and 0.8, the local equivalence ratios of the mixture throughout the swirler duct are about 1.2, 1.7 and 2.3, respectively. It was considered that, since the burning velocity of the mixture throughout the swirler duct is the highest among the three conditions, the Pattern 1 area is the widest at high mean inlet air velocities in the condition that the total equivalence ratio is 0.6.

3.2. Observations of flame

In order to understand the effect of the mean inlet air velocity on flame length, a flame was observed through observation windows. The mean inlet air velocity was varied from 10 to 40 m/s. The combustor pressure and the equivalence ratio were constant at 20 kPa and 0.6, respectively. The flame length was defined as the extinction position of OH band. The emission spectrum of hydrogen/air flame is observed only in the OH band due to chemical reaction, and the largest peak wavelength is 306.36 nm.
The UV-CCD camera has high sensitivity in the wavelength range from 300 to 420 nm. Therefore it was considered that the UV-CCD camera image corresponded to the chemical reaction area. Flame images were converted to digital images and analyzed using a self-made software coded by MATLAB. Figure 6 shows the analyzed area at each observation window. The analyzed area was 5 x 27 pix in the observation windows (height: 31 pix, width: 33 pix). Figure 7 shows time histories of averaged luminosities in the analyzed area of each observation window. The luminosity corresponds to the gray-scale level (0-256) of the UV-CCD camera. When ignition occurred at 1 s, the averaged luminosity of all the observation windows increased simultaneously. It implies that flame propagated through the premixture which was formed in the combustor before ignition. After 2 s from the ignition, the disturbance caused by the ignition was damped and the averaged luminosities increased gradually with the increase in the combustor temperature.

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Fig. 8. Flame images at 20 kPa in combustor pressure and 0.6 in total equivalence ratio.

Fig. 9. Luminosity distributions (combustor pressure: 20 kPa, equivalence ratio: 0.6).
The luminosity distribution analysis was conducted for 1 s from the time when the combustor temperature reached 1000 K. Figure 8 shows UV-camera images of a hydrogen/air flame. Stream flowed in the direction from left to right of the image. The location of the observation windows are depicted in Fig. 2. One can observe that the luminosity in downstream observation windows increases with the increase in the mean inlet air velocity. The strongest luminosity of the flame was observed at the most left observation window in the case of the mean inlet air velocity of 10 m/s.

Figure 9 shows time-averaged luminosity distributions. In all cases, the luminosity was the largest near the fuel injector. The luminosity distribution becomes flatter as the increase in the mean inlet air velocity. Luminosity profiles along the central axis of the combustor are shown in Fig. 10. The slope of the luminosity decreases with the increase in the mean inlet air velocity. In order to estimate the flame length, each curve in Fig. 10 was extrapolated by linear approximation of three plots over 200 mm from the fuel injector. We assumed that flame length is equal to the distance where the luminosity is estimated to be zero.

The results were shown in Fig. 11. The flame length increases with the increase in the mean inlet air velocity. Increasing rate of the flame length becomes large with the increase in the mean inlet air velocity. At the mean inlet air velocity of 40 m/s, flame length was estimated to be about 810 mm. The length of the sub-scale pre-cooled turbojet engine combustor is about 145 mm. It is supposed that the flame reaches the turbine blades at low-pressure conditions.

4. Conclusion

A lab-scale combustion wind tunnel was developed to obtain fundamental data useful for making engine-start at high altitudes sure. A fuel injector of the sub-scale pre-cooled turbojet engine was installed into the combustion wind tunnel. Ranges of combustor pressure and mean inlet air velocity successful for low-pressure ignitions and subsequent flame holdings at the fuel injector were investigated, and flames stabilized at the injector were observed. Summaries of the results are as follows:

1. The decrease in the combustor pressure narrows the mean inlet air velocity range for successful flame holdings.
2. Flame holding at lower combustor pressures is realized at the equivalence ratio of 0.4 in the low mean inlet air velocity range, and at the equivalence ratio of 0.6 in the high mean inlet air velocity range.
3. In all cases, the flame luminosity is the largest near the fuel injector. The flame luminosity distribution becomes flatter as the increase in the mean inlet air velocity.

References