Combustion Characteristics of a Cavity Flameholder with a Burned-Gas Injector at the Cavity Bottom Wall in a Scramjet Model Combustor*

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The combustion characteristics of the cavity flameholder with a burned-gas injector at the cavity bottom wall in the scramjet model combustor was investigated experimentally. The flame structure in the cavity was investigated by direct imaging and OH-PLIF measurement. As the result, four combustion modes were identified: jet-plume mode, jet-wake mode, one-sided cavity mode, and two-sided cavity mode. In response to the experimental results, the effects of the airstream boundary layer thickness were additionally investigated numerically. Numerical results showed that an increase in the airstream boundary layer thickness adversely affected supported flameholding under conditions of a supersonic airstream with low total temperature. When the airstream boundary layer becomes thicker, interaction between airstream and burned-gas jet creates a wider boundary layer separation upstream of the cavity leading edge. If the width of the separation region is greater than the width of the jet-plume, additional air entrainment path from separation region decreases static temperature inside the cavity flameholder, which makes supported flameholding difficult. It was concluded that the scramjet combustor needs suppression of the interaction between the supersonic airstream and burned-gas jet or avoidance of the boundary layer separation to avoid supported flameholding failure in a supersonic airstream with a thick boundary layer.

Key Words: Scramjet Engines, Cavity Flameholder, Burned-Gas Injection, Combustion

1. Introduction

Cost reduction is one of the most important challenges for space and hypersonic transportation systems. Scramjet engines are expected to operate at a wide range of flight Mach numbers, from supersonic to hypersonic. The present study focuses on combustion phenomena in a scramjet combustor during supersonic flight ($M<5$), where forced ignition is required because the airstream total enthalpy is insufficient for self-ignition.

Candidates for forced-ignition devices include a spark plug, plasma jet torch,6,7) burned-gas torch,4,5) and detonation torch.6,7) From a practical perspective, the burned-gas torch, which injects mixture of fuel and high-temperature combustion product, was considered to be the most favorable method because it can easily increase the input energy for ignition by increasing the burned-gas flow rate. Moreover, the additional unburned fuel in the burned gas was expected not only to reduce the thermal load to the injection hole but also release additional heat into the scramjet combustor. It is necessary to increase the flow residence time or decrease the characteristic reaction (combustion) time to achieve flameholding in a supersonic airstream. Although burned-gas injection facilitates a shorter characteristic reaction time by increasing the mixture temperature, an effective increase in the flow residence time is also required for a scramjet combustor because the flow residence time, which is on the order of 1 millisecond, is much shorter than the characteristic reaction time. A cavity is a promising flameholding geometry because it can create a recirculation zone, which can efficiently extend the flow residence time without a large total pressure loss. Therefore, the combination of a cavity flameholder and burned-gas injection was considered in the author’s previous study.8) In the previous study, the combustion characteristics of a cavity flameholder with a burned-gas injector in a supersonic airstream was investigated in a semi-freejet supersonic combustion test facility, which was established by Niioka et al.9) to investigate fundamental phenomena in an external supersonic airstream. Hydrogen-rich burned gas, which was mixture of combustion product and unburned hydrogen, was injected from the single-hole injector at the cavity bottom wall. This injection scheme was expected to have a better forced-ignition performance than aft wall injection scheme. It is also expected to have a better flameholding performance without main fuel injection compared to the upstream injection scheme. As a result, two combustion modes were found: jet-plume mode and cavity mode. The existence of the cavity mode, which has a flame emission region not only in the cavity but also in the jet wake, suggested the effectiveness of the burned-gas injection from the cavity bottom wall. However, it was not clear whether this configuration would be effective in an actual scramjet combustor, where the boundary layer thickness of the incoming airstream is much thicker.

The objective of the present study was to investigate the combustion characteristics of the cavity flameholder with a burned-gas injector at the cavity bottom wall in a model scramjet combustor.
2. Experimental and Numerical Setup

Combustion experiments were conducted by the directly connected supersonic combustion test facility developed by authors.\textsuperscript{10)} The test facility consists of a high-pressure air tank, a heat-storage-type heat exchanger, a stilling chamber, a supersonic nozzle, a test section, a diffuser, and a silencer. The maximum test duration time is about 120 seconds. The maximum storage pressure for the air tank is 4.0 MPa. The maximum total temperature of the airstream is about 850 K. Although the total pressure of the airstream can be controlled by a hand-operated valve just downstream of the air tank, this is not an easy task because the total temperature of the airstream depends on the heat content and the temperature profile in the heat exchanger.

Figures 1(a) and 1(b) show cross-sectional views of the test section in the semi-freejet supersonic combustion test facility and in the directly connected supersonic combustion test facility, respectively. In the directly connected test facility, the supersonic nozzle is inserted into the stilling chamber. The length of the supersonic nozzle is 300 mm. The width and height of the supersonic nozzle exit are 90 and 30 mm, respectively. The test section consists of an isolator and an expansion duct. The height, width, and length of the isolator are 30, 90, and 200 mm, respectively. The expansion duct has an expansion wall, whose expansion angle is 2.5\degree, at its bottom. The average Mach number in the main stream at the isolator exit is 2.5. The test section has quartz glass windows at its side wall for optical measurement. The expansion duct contains a cavity flameholder 45 mm downstream from the leading edge of the expansion wall. A hydrogen/air burned-gas torch igniter is also connected to the bottom of the cavity flameholder.

Figure 2 shows the experimental setup of the cavity flameholder in the directly connected supersonic combustion test facility. Figure 2(a) shows a cross-sectional view of the test section with the cavity flameholder and the burned-gas torch igniter. Figure 2(b) shows an overview of the cavity flameholder with an H\textsubscript{2}/air burned-gas torch igniter. Figure 2(c) shows the geometry of the cavity flameholder. As shown in Fig. 1, the expansion surface and the cavity flameholder are on the lower side of the expansion duct wall. However, in the following discussion, the test section is considered to be upside down, as shown in Fig. 2(a). The depth, length, width, and aft ramp angle of the cavity flameholder are 10 mm, 22.07 mm, 90 mm, and 22.5\degree, respectively. The length of the cavity flameholder is based on the definition proposed by Gruber et al.\textsuperscript{11)} The length-to-depth ratio of the cavity flameholder is 3.207; the cavity is thus classified as “open.” The cavity flameholder has an injection hole at its bottom. The distance between the cavity leading wall and the injection hole is 2.5 mm. The burned-gas is supplied from the hydrogen/air burned-gas torch igniter\textsuperscript{12)} into the cavity flameholder. The torch igniter can control the injection gas temperature by generating burned gas with an jet equivalence ratio of 1 to 10. The diameter of the injection hole is 3 mm. Hydrogen gas and air are supplied to the burned-gas torch igniter. The mass flow rates for the hydrogen and air are measured by an orifice flow meter. The spark plug in-
313 nm, FWHM

section and parallel to the was about 55 mm. The planar laser was incident on the test sheet by the cylindrical lenses. The height of the laser sheet

The excitation laser beam was converted to a planar laser

Rhodamine 590 (Exciton) was used as the

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(convex lens, cylindrical lenses, optical filters, an ultraviolet (UV) lens, an image-intensifying CMOS camera (Andor

monics, HD-500B and HyperTRACK-1000), a dye laser with a frequency doubler (Lumonics, HD-500B and HyperTRACK-1000), flat mirrors, a convex lens, cylindrical lenses, optical filters, an ultraviolet (UV) lens, an image-intensifying CMOS camera (Andor Technology, iStar-sCMOS), and a programmable automatic stage (Sigmakoki, OSMS26-100X). The second harmonic of the Nd:YAG laser, wavelength of which is 532 nm, was used to operate the dye laser. A solution containing ethanol and Rhodamine 590 (Exciton) was used as the fluorescent dye. The excitation laser beam was converted to a planar laser sheet by the cylindrical lenses. The height of the laser sheet was about 55 mm. The planar laser was incident on the test section and parallel to the y–z plane. The position of laser incidence was controlled by the programmable automatic stage. OH fluorescence was detected by the image-intensifying CMOS camera through the UV lens (Nikon, UV-105 mm, F8.0). Optical filters UG11 (SCHOTT, central wavelength (CWL) = 320 nm, full width at half maximum (FWHM) = 150 nm) and LX0310 (Asahi Spectra, CWL = 313 nm, FWHM = 10 nm) were mounted in front of the UV lens to improve the signal-to-noise ratio. The frame rate in the OH-PLIF measurements was 10 Hz.

In the present study, both fixed-plane and moving-plane OH-PLIF measurement procedures were used. In the fixed-plane measurements, five measurement planes were selected and 30 images were taken for each plane. In the moving-plane measurements, single images were taken at 0.2-mm intervals in the x direction by moving the laser plane downstream at 2 mm/s. Figures 4(a) and 4(b) show schematics of the fixed-plane and moving-plane measurements, respectively. The origin of the x-axis was the leading-edge of the expansion duct. In addition to the two imaging techniques, the wall pressure distribution in the test section was measured by 30 pressure gauges placed along the center line of the top wall at intervals of 10 mm. The most upstream and downstream pressure gauges were placed at x = ±45 and 245 mm, respectively. Although the wall pressure measurements were conducted to investigate the effects of each combustion mode on the pressure field, there was no significant difference among combustion modes. This was considered to be caused by non-remarkable heat release due to small fuel flow rate.

Three-dimensional steady Reynolds-averaged Navier-Stokes (RANS) simulations were performed using Fluent v.14.5 CFD software (ANSYS Inc). The governing equations were the mass conservation equation, the RANS equation, the energy conservation equation, and the state equation for an ideal gas. These equations were implicitly solved using the finite volume method. The SST k-ω model proposed by Menter was used to model the turbulence. The detailed reaction mechanism for H2/O2 (9 species and 19 elementary reactions) proposed by Mueller et al. was used for chemical reaction modeling. Turbulence-reaction interactions were not taken into account. A stiff chemistry solver was not used in the present study. The turbulent Schmidt number and the turbulent Prandtl number were set to constant values of 0.7 and 0.85, respectively. The convection flux was evaluated...
using the AUSM method\textsuperscript{15}) and the gradient and derivative were evaluated using the least-squares cell-based method. The discretization methods applied to the convection term and the diffusion term were the second-order upwind difference method and the second-order central difference method, respectively. The minmod function was used as the slope limiter.

3. Results and Discussion

3.1. Representative combustion modes

Figure 5 shows direct photographs and OH-PLIF images of four representative combustion modes for the burned-gas injection. Each combustion mode was classified according to the presence or absence of a flame in four regions, namely the burned gas jet-plume region, the burned gas jet-wake region, and two recirculation zones, one at each side of the burned gas jet plume. The jet-plume mode, shown in Fig. 5(a), had a combustion region only around the jet plume. The jet-wake mode, shown in Fig. 5(b), had a combustion region around the jet plume and in the jet wake. The one-side cavity mode, shown in Fig. 5(c), had a combustion region around the jet plume, in the jet wake, and in the recirculation zone at one side of the burned gas jet plume. In Fig. 5(c), there was a combustion region in the far-side recirculation zone, although it was not clear from direct imaging. The cavity mode, shown in Fig. 5(d), had a combustion region in the jet-wake region and in the whole cavity volume. The non-luminescent mode, which had no apparent emission region either inside or outside the cavity flameholder despite successful combustion in the burned-gas torch igniter, was also observed. It is believed that the jet-plume mode and the non-luminescent mode were unfavorable for forced ignition since they had a small emission region. Here, the forced ignition indicates forced ignition of fuel in mainstream by the flameholding in the cavity flameholder. The cavity mode, one-side cavity mode, and jet-wake mode were believed to be favorable for forced ignition since they had a combustion region not only in the cavity flameholder but also outside it. Moreover, it was found that the jet-wake mode, one-side cavity mode, and cavity mode could maintain the flame even after the injection gas was switched from burned gas to pure hydrogen gas.

3.2. Maps of combustion modes

Figures 6(a) and 6(b) show maps of each combustion mode in the directly-connected supersonic combustion test facility and the semi-freejet supersonic combustion test facility, respectively. The jet equivalence ratio $\phi_3$ of the circular symbol was less than 3. That of triangle symbol was in the range of 3.0 to 6.0. And, that of the square symbol was greater than 6.0. Figure 6(b) was obtained from our previous study.\textsuperscript{8}) As described above, there were four combustion modes for the directly connected test facility. The jet-plume mode and non-luminescent mode were often observed, regardless of the airstream total temperature, when the enthalpy flow rate for the burned gas jet was less than 9 kW. Although the difference between these two modes was unclear, the jet-plume mode often occurred when the jet equivalence ratio was close to the stoichiometric value. As the enthalpy flow rate increased, the jet-wake mode, one-side...
cavity mode, and cavity mode occurred. The jet-wake mode was often observed when the enthalpy flow rate for the burned gas jet was greater than 8 kW. The one-side cavity mode and the cavity mode required higher enthalpy flow rates of 11 and 14 kW, respectively. The jet-wake mode, jet-plume mode, and non-luminescent mode were independent of the airstream total temperature, whereas the cavity mode and one-side cavity mode depended on it. In addition, the jet equivalence ratios for the cavity mode and the one-side cavity mode tended to be higher than that for the jet-wake mode, which means that the quantity of unburned hydrogen in the burned gas jet is more important than the temperature of the jet for achieving cavity mode or one-side cavity mode. In the enthalpy flow rate range of 11–14 kW, there was no clear difference between jet wake mode and one-sided cavity mode. In the combustion experiments, the one-side cavity mode often transitions from the jet-wake mode. Hence, it is considered that the one-side cavity mode tends to occur when the wall temperature is high enough. It can be seen in Fig. 5 that the flame structure in cavity mode was not symmetric, which suggests that the one-side cavity mode is caused by the asymmetry of the flow field. In Fig. 6, each combustion mode was arranged by the airstream total temperature, the enthalpy low rate of the burned-gas jet and the jet equivalence ratio. However, the boundary of each combustion mode was not sufficiently clear. This was considered to be due to the uncertainty of the wall temperature. Therefore, the wall temperature was also considered as an important factor which affects the combustion mode.

As can be seen in Fig. 6, the combustion characteristics of the cavity flameholder with a burned-gas injector at the cavity bottom were strongly affected by the type of supersonic combustion test facility. There were several differences between the directly connected test facility and the semi-freejet test facility. The enthalpy flow rate and the temperature of the burned gas jet required for cavity mode for the semi-freejet test facility are lower than those for the directly connected test facility. This indicated that it was more important to have high enthalpy when using a burned-gas jet to produce the cavity mode in the directly connected test facility. It was considered that the decreasing the entrainment of the low-temperature airstream or the burned gas into the recirculation zone of the cavity increases the required enthalpy flow rate for achieving cavity mode. There were several differences between the semi-freejet and directly-connected test facility, for example, airstream boundary layer thickness, existence of the combustor side wall and surrounding combustor wall, surface temperature of the cavity flameholder, and burned-gas torch configuration. After pondering these factors, the present study focused on the effect of the airstream boundary layer thickness since it was considered to be related to interaction between airstream and burned-gas jet. This effect was discussed in Section 3.4.

### 3.3. Effects of airstream boundary layer thickness on supported flameholding in the cavity flameholder

To clarify the reason why the combustion characteristics of the cavity flameholder with a burned-gas injector at the cavity bottom were strongly affected by the type of supersonic combustion test facility, the effects of the airstream boundary layer thickness on supported flameholding in the cavity flameholder were investigated numerically. Here, the supported flameholding indicates the flameholding maintained by the high-temperature burned-gas injection.

In this section, a cavity flameholder in a constant-area duct was considered in order to simplify the effect of the boundary layer thickness. Symmetry was assumed in the width direction to reduce the computational cost. Figure 7(a) shows the numerical grid for a cavity flameholder with a con-
stant-area duct. The flameholder consists of 587,424 hexahedral cells with a minimum cell size of 10 μm. The constant-area duct is 90 mm in width, 30 mm in height, and 94.14 mm in length. The cavity flameholder is installed 30 mm downstream of the duct inlet. The cavity flameholder has the geometry given in the previous section. The non-slip condition and the isothermal condition (300 K) were used as wall boundary conditions. To use the supersonic airstream condition with a thick boundary layer as the inlet boundary condition, a three-dimensional numerical simulation of the 500-mm-long constant-area duct was also performed using the grid shown in Fig. 7(b). The duct is 90 mm in width and 30 mm in height, and consists of 1,800,000 hexahedral cells with a minimum grid size of 10 μm. The flow condition which passed through the 500-mm-long constant area duct was adopted as the inlet boundary condition of the cavity flameholder with a constant-area duct.

Table 1 lists the simulation conditions. $\delta^*$, $T_{0a}$, $T_{0j}$, $P_{0a}$, $P_{0j}$, $\phi_j$, $\phi_{o,j}$, $Re_a$, $Re_j$, $M_a$, $q_a$, and $q_j$ are the displacement thickness of the airstream at the airstream inlet, the mean total temperature of the airstream, the mean total temperature of the burned gas jet, the mean total pressure of the airstream, the mean total pressure of the burned gas jet, the jet equivalence ratio, the overall equivalence ratio, the mean Reynolds number for the airstream, the mean Reynolds number for the burned gas jet, the mean Mach number for the airstream, the mean Mach number for the burned gas jet, the overall equivalence ratio, the mean Reynolds number for the burned gas jet, the jet equivalence ratio, and the mean Mach number for the jet, respectively. The characteristic lengths $Re_a$ and $Re_j$ are the height of the airstream inlet (= 30 mm) and the injection hole diameter (= 3 mm), respectively. Each mean value was calculated by the area-weight average. The effects of the airstream boundary layer thickness can be determined by comparing CASE 1A and CASE 1B, and CASE 2A and CASE 2B. For the thick airstream boundary layer (CASE 1B and CASE 2B), the total pressure of the airstream, the Reynolds number for the airstream, and the Mach number for the airstream are lower than those for the thin airstream boundary layer (CASE 1A and CASE 2A). CASE 2C was used to investigate the effects of the thermal field on supported flameholding for a thick airstream boundary layer. The total temperature of the airstream and the total temperature of the burned gas jet for CASE 2C are much higher than those for CASE 2B. To make the flow fields and concentration fields for CASE 2B and CASE 2C almost equal, the jet equivalence ratio, overall equivalence ratio, mean Reynolds number for the airstream, mean Reynolds number for the burned gas jet, mean Mach number for the airstream, mean Mach number for the jet, and mean dynamic pressure ratio were set to be almost equal for CASE 2B and CASE 2C. CASE 2D was used to investigate the effects of the concentration field on supported flameholding for a thick airstream boundary layer. The total equivalence ratio for the burned gas jet for CASE 2D was higher than that for CASE 2B. In addition, to make the flow fields for CASE 2B and CASE 2D almost equal, the Reynolds number for the airstream, Reynolds number for the jet, Mach number for the airstream, Mach number for the jet, and dynamic pressure ratio were set to be almost equal. CASE 2B and CASE 2D should be given in same airstream total temperature. However, it is difficult to investigate the effect of dilution while maintaining the similarity of the flow field and that of the temperature field. In this study, the total temperature of the airstream for CASE 2D was set to be higher than that for CASE 2B. This is based on the idea that the temperature difference CASE 2B and CASE 2D is not important because CASE 2D is considered thermally easier to stabilize flame than CASE 2B.
Figure 8 shows contours of the static temperature in the cavity flameholder for CASE 1A, CASE 1B, CASE 2A, and CASE 2B. Figure 9 shows contours of the OH mole fraction in the cavity flameholder for these cases. As can be seen, cavity combustion mode, for which the combustion regions are in the jet wake and the jet side recirculation zone, was achieved when the displacement thickness for the airstream is 0.038 mm (CASE 1A and CASE 2A). Jet-wake combustion mode was achieved in CASE 1B. No combustion is achieved for CASE 2B. The increase in the boundary layer thickness for the supersonic airstream was thought to adversely affect combustion in the cavity flameholder. Based on the static temperature contours inside the cavity flameholder for CASE 1B and CASE 2B, the static temperature did not reach 1,000 K except near the jet and in the jet-wake region, which suggested that the decrease in the static temperature inside the cavity flameholder makes supported flameholding difficult. There were two possible causes for the decrease in the static temperature of the recirculation zone inside the cavity flameholder: 1) an decrease in the enthalpy flow rate for the high-temperature burned gas jet entrained into the recirculation zone inside the cavity flameholder; 2) an increase in the mass flux for the low-temperature airstream entrained into the cavity flameholder. However, it was difficult to clearly distinguish these two factors and evaluate them quantitatively.

Figure 10(a) shows contours of mass flux in the y-axis direction in the cavity flameholder for CASE 1A, CASE 1B, CASE 2A, and CASE 2B. The red regions are where the mass flux in the y-axis direction is zero or more. Since the negative mass flux regions indicate the flow taken into the cavity, the flow not taken into the cavity, and recirculation in the cavity itself, it should be noted that not all regions of negative mass flux indicate air entrainment. However, it is believed that the airstream entrainment into the cavity flameholder appears as the flow in-
The formation of a new entrainment path indicated by the negative mass flux. The mass flux in the direction toward the bottom of the cavity flameholder increased when the boundary layer thickness for the supersonic airstream increased.

Figure 10(b) shows the position of each contour plane. As can be seen from the contour plane of $y/D = -0.1$ in Fig. 10(b), there are two airstream entrainment paths that may lead to the recirculation zone: 1) the jet side region, and 2) the region slightly away from the side wall. Furthermore, for CASE 1B and CASE 2B, where the boundary layer thickness for the supersonic airstream was relatively large, the formation of a new inflow path occurred in the region indicated by the black circle. Since this region was in the vicinity of the interaction region between the supersonic airstream and the burned gas jet, it was thought to be due to a change of the flow field in the interaction region as a result of a decrease in the dynamic pressure of the airstream near the wall.

Figure 11 shows surface streamlines on the wall upstream of the cavity flameholder and contours of the H$_2$ mole fraction for CASE 1A, CASE 1B, CASE 2A, and CASE 2B. The surface streamlines indicate the position and size of the separation region caused by the interaction between the supersonic airstream and the burned gas jet. The contours of the H$_2$ mole fraction indicate the structure of the burned gas jet. The positions of the contour planes are $x = 2.5$, 12.5, 22.5, and 32.5 mm, respectively. The red dotted circle indicates the separation region caused by interaction between the burned-gas jet and the supersonic airstream. As can be seen, the size of the separation region was clearly different between the thin boundary layer cases (CASE 1A and CASE 2A) and the thick boundary layer cases (CASE 1B and CASE 2B). Focusing on the shape of the jet in the $x = 2.5$ mm plane, CASE 1B and CASE 2B showed that the side edge of the burned gas jet was more bent toward the bottom of the cavity flameholder than in CASE 1A and CASE 2A. In addition, the width of the separation region was not greater than that in CASE 1A and CASE 2A, but was so for CASE 1B and CASE 2B. Since the position of the new entrainment path indicated by the black circle in Fig. 10(a) corresponds to just downstream of the side edge of the separation region for CASE 1B and CASE 2B, it was considered that this wide separation region forms the new entrainment path. There was another separation region for CASE 1B and CASE 2B near the side wall, which was considered to correspond to an increase in the mass flux in the region slightly away from the side wall in Fig. 10(a). Therefore, it was considered that an increase in the boundary layer thickness causes boundary layer separation in the jet interaction region and the neighborhood of the side wall, resulting in an increase in the airstream entrainment into the cavity flameholder.

Figure 12 shows entrained streamlines (color lines) and jet streamlines (black lines) for CASE 1A, CASE 1B, CASE 2A, and CASE 2B. The entrained streamlines show only the upstream side passing through sample points equally spaced on the sampling plane. The sampling plane was the $y/D = -0.5$ plane inside the cavity flameholder. The jet streamlines were those released from the inlet boundary of the burned gas jet. As can be seen, there was a mass inflow from the separation region formed by the interaction between the supersonic airstream and the burned gas jet regardless of the boundary layer thickness of the supersonic airstream. However, for CASE 1B and CASE 2B, where the boundary layer thickness for the supersonic airstream is large, more airflow streamlines and fewer jet streamlines are taken into the recirculation zone compared to CASE 1A and CASE 2A. Therefore, an increase in the boundary layer thickness of
the supersonic airstream facilitates the entrainment of the airstream into the recirculation zone and obstructs that for the jet flow into the jet side recirculation zone. Thus, an increase in the boundary layer thickness for the supersonic airstream leads to a decrease in the static temperature in the recirculation zone inside the cavity flameholder under low airstream total temperature, and a decrease in the local equivalence ratio in the recirculation zone inside the cavity flameholder.

To clarify whether the dominant cause that makes supported flameholding in cavity mode difficult was due to a temperature decrease or dilution, additional numerical simulations were performed (CASE 2C and CASE 2D). Figure 13 shows the numerical results obtained from non-reactive simulations for CASE 2B, CASE 2C, and CASE 2D.

Figure 13(a) shows surface streamlines in the upstream region of the cavity leading edge. Figure 13(b) shows contours of the static temperature, and Fig. 13(c) shows contours of the local equivalence ratio. It can be seen that CASE 2B and CASE 2C had almost the same flow fields and concentration fields. Since the main difference between CASE 2B and CASE 2C is the thermal field, the influence of a temperature decrease in the recirculation zone on supported flameholding can be investigated by comparing these cases in reactive simulations. CASE 2B and CASE 2D had similar flow fields and thermal fields; the main difference between them was the concentration field. Since CASE 2D has a hydrogen-rich mixture widely inside the recirculation zone, the influence of dilution in the recirculation zone on supported flameholding can be investigated by comparing CASE 2B and CASE 2D using reactive simulations.
Figure 14 shows the numerical results obtained from reactive simulations for CASE 2B, CASE 2C, and CASE 2D. Figures 14(a) and 14(b) show contours of OH mole fraction in the cavity flameholder and contours of static temperature in the cavity flameholder, respectively. Only for CASE 2C achieved the supported flameholding. In addition, the recirculation zone for CASE 2D was filled with an air-fuel mixture close to the stoichiometric ratio, and even though the airstream total temperature was slightly higher than that for CASE 2B, supported flameholding was not achieved for CASE 2D. Therefore, the dominant cause of supported flameholding becoming difficult by the increase in the boundary layer thickness of the supersonic airstream when the airstream total temperature was insufficiently high was the temperature decrease inside the cavity flameholder. Since airstream recovery temperature might be different due to the isothermal boundary condition, CFD results with adiabatic boundary condition are required in the future to reveal the dominant factor for supported flameholding mechanism firmly.

Based on the above discussion, the mechanism that makes supported flameholding difficult was considered to be as follows: 1) the airstream boundary layer becomes thick, which decreases the dynamic pressure of the airstream near the wall; 2) the interaction between the supersonic airstream and burned gas jet leads to a large boundary layer separation upstream of the burned gas jet; 3) the entrainment of air from the separation region into the recirculation zone in the cavity flameholder increases, and the entrainment of the combustion gas jet into the recirculation zone in the cavity flameholder decreases; 4) a temperature decrease in the recirculation zone inside the cavity flameholder makes supported flameholding difficult. Thus, the static temperature in the recirculation zone is the most important factor for achieving supported flameholding. It was considered that the difference between the jet-wake combustion mode and the cavity combustion mode was due to the difference in the static temperature in the jet-side recirculation zones. Cavity combustion mode occurs when the static temperature of the two recirculation zones is sufficiently high. The jet-wake combustion mode occurs only when the static temperature in the recirculation zone in the jet wake is sufficiently large, such as when the airstream total temperature is relatively low and the jet total temperature is relatively high. This is in good agreement with the experimental results obtained using the directly-connected supersonic wind tunnel. The increase in air entrainment by the large boundary layer separation does not adversely affect supported flameholding under conditions where self-ignition can occur, but makes it difficult to achieve supported flameholding under conditions that require forced ignition. Therefore, to avoid flame stabilization failure via the above mechanism, suppression of the interaction between the supersonic airstream and burned gas jet or prevention of boundary layer separation via boundary layer control is required in a scramjet combustor. It was considered that there are two important factors to suppress the airstream entrainment from the separation region. One is that the width of the separation region was less than that of the burned-gas jet. The other one was that there was an adverse pressure gradient from the separation region to cavity. Figure 15 shows the contours of the static pressure and H₂ mole fraction on the three representative plane in case with airstream entrainment from the separation region. The black lines in each contour plane indicate the surface streamlines. On the \( z = -7 \) mm plane, although static pressure in the separation region was greater than that in the recirculation zone, it was difficult to form the entrainment path due to the existence of the jet plume. On the \( z = -14 \) mm plane, it was possible to form the airstream entrainment path because there is not jet plume between the separation region and recirculation region. On the \( z = -21 \) mm plane, although there is not jet plume between the separation region and recirculation region, airstream entrainment path was not formed because the static pressure difference between the separation region and the recirculation zone was not so large. Therefore, the existence of the jet plume between the separation region and recirculation zone, or increase in the static pressure in the recirculation zone is important to suppress the airstream entrainment from the separation region. It should be noted that the air entrainment depends on the type of test fa-
3.4 Three-dimensional flame structure

Figure 16 shows three-dimensional flame structures obtained from moving-plane OH-PLIF measurements. Each image shows points with a signal intensity above the indicated threshold levels, which were chosen based on trial and error. Table 2 shows the experimental conditions for each OH-PLIF measurement.

From direct imaging, the structure in Fig. 16(a) was identified as jet-plume mode, those in Figs. 16(b) and 16(c) were identified as jet-wake mode, and that in Fig. 16(d) was identified as cavity mode. Since the OH-PLIF images were not obtained simultaneously, the continuity of the OH-PLIF signal was not guaranteed. However, the main features of the flame structure could be obtained using a simple moving average method. In jet-plume mode, shown in Fig. 16(a), an intense OH-PLIF signal existed around the jet-plume and jet-wake regions. However, the intense OH-PLIF signal region was divided into three zones. This was considered to be caused by the intermittency of combustion along the jet plume. In jet-wake mode, shown in Figs. 16(b) and 16(c), an intense OH-PLIF signal existed only in the jet-wake region. This was in good agreement with the results obtained from the fixed-plane measurements. Figures 16(b) and 16(c) were obtained with the same threshold value (60) and a similar laser power. A comparison of these two results indicated that a higher burned gas injection pressure made the flameholding region larger. In cavity mode, shown in Fig. 16(d), an intense OH-PLIF signal existed in the jet-wake region and at both sides of the burned gas jet. In addition, the intense OH-PLIF signal region in the jet wake was divided into two zones: the low-speed vortex pair region and the jet-wake zone. An intense OH-PLIF signal region inside the low-speed vortex pair region was also observed for jet-wake mode, but not for jet-plume mode. Therefore, it was considered that the difference between the jet-plume mode and the jet-wake mode was the existence or absence of a flameholding region even after the injection gas was switched from burned gas to pure hydrogen gas.

Figure 17 shows a schematic of the five distinct combustion regions observed in this study: jet-plume region, jet-wake region, recirculation zone on the near side, recirculation zone on the far side, and the low-speed vortex pair region.
4. Conclusions

In the present study, the combustion characteristics of a cavity flameholder with a burned-gas injector at the cavity bottom wall in a model scramjet combustor were investigated experimentally. Moreover, the effects of the airstream boundary layer thickness on the combustion characteristics of the cavity flameholder were investigated numerically. The following conclusions were obtained:

1) Four combustion modes, namely, jet-plume mode, jet-wake mode, one-side cavity mode, and cavity mode were observed in the combustion experiments. Jet-wake mode and one-side-cavity mode were newly observed for the directly-connected test facility. Jet-plume mode is considered to be less desirable than the other combustion modes because it does not have an intense OH-PLIF signal region in the recirculation zone. Moreover, it was found that jet-wake mode, one-side cavity mode, and cavity mode often maintained the flame even after the injection gas was switched from burned gas to pure hydrogen gas.

2) For the directly-connected supersonic combustion test facility, jet-plume mode and non-luminescent mode often occurred independent of the airstream total temperature when the enthalpy flow rate for the burned gas jet was less than 9 kW. Jet-wake mode often occurred when the enthalpy flow rate for the burned gas jet was greater than 9 kW. One-side cavity mode and cavity mode required enthalpy flow rates of more than 11 and 14 kW, respectively. The jet equivalence ratio for cavity mode and one-side cavity mode tended to be higher than that for jet-wake mode, which suggested that the quantity of unburned hydrogen in the burned gas jet was more important than the temperature of the jet for achieving either cavity mode or one-side cavity mode.

3) An increase in the boundary layer thickness for the supersonic airstream adversely affects supported flameholding under a low-total-temperature supersonic airstream. The mechanism was considered to be as follows: 1) the airstream boundary layer becomes thick, which decreases the dynamic pressure of the airstream near the wall; 2) the interaction between the supersonic airstream and burned gas jet creates a large boundary layer separation upstream of the burned gas jet; 3) the entrainment of air from the separation region into the recirculation zone increases, and entrainment of the combustion gas jet into the recirculation zone decreases; 4) a temperature decrease in the recirculation zone makes flameholding difficult.

4) To avoid flame stabilization failure in a supersonic airstream with a thick boundary layer, suppression of the interaction between the supersonic airstream and the jet, or prevention of the boundary layer separation via boundary layer control is required in a scramjet combustor.

5) Three-dimensional flame structure obtained from moving-plane OH-PLIF measurements showed that flameholding in the low-speed vortex pair region was important to maintain flameholding after the injection gas was switched from burned-gas to pure hydrogen gas.

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