	やまぐち　たつや
氏　　　　　　名	山　口　　達　也
研究科，専攻の名称	東北大学大学院工学研究科（博士課程）航空宇宙工学専攻
学 位 論 文 題 目	Development of a Torch Igniter for a Scramjet Combustor and Flame Structure in a Cavity Flameholder with a Bottom Single Hole Injector（スクラムジェット燃焼器用トーチイグナイタの開発および底面単孔噴射型キャビティー保炎器の火炎領域の構造に関する研究）
論 文 審 査 委 員	主査　東北大学教授　小林　秀昭　東北大学教授　浅井　圭介 東北大学客員教授　富岡　定毅　教授 東北大学准教授　中村　寿

論文内容要約

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 by changing the combustion mode in the combustor from subsonic combustion to supersonic combustion, which is called a dual-mode scramjet engine. However, even a dual-mode scramjet engine cannot operate from takeoff to subsonic speeds or outside the atmosphere. Therefore, the combined use of scramjet and rocket engines, which is called the rocket-based combined cycle, and the combined use of scramjet and turbojet engines, which is called the turbine-based combined cycle, are expected to become effective ways to realize an operational scramjet. 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, burned-gas torch, and detonation torch. From a practical perspective, the burned-gas torch, which injects mixture of fuel and high-temperature combustion product, is 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 is 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. Because bottom cavity wall injection shows better flameholding performance and jet penetration into the core flow, bottom wall injection was adopted as the burned-gas injection scheme. In the previous study, the combustion characteristics of a cavity flameholder with a single-hole injector in a supersonic airstream was investigated in a semi-freejet supersonic combustion test facility. Hydrogen-rich burned gas was injected from the single-hole injector. 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 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. Additionally, it was also shown that the cavity mode tends to be achieved when the burned-gas enthalpy flow rate is sufficiently large. However, quantitative information about the burned-gas enthalpy flow rate for the cavity mode was not clear, because the burned-gas total temperature could not be evaluated in the previous study. The objective of this dissertation is to investigate the combustion characteristics of the cavity flameholder with a bottom single hole injector in a scramjet model combustor.

To obtain quantitative information about the input energy of the burned-gas, a burned-gas total temperature estimation method is required. In chapter 2, a new estimation method was proposed and verified experimentally and numerically. Then, a hydrogen/air burned-gas torch igniter, which can control the total temperature of the burned-gas jet by changing the jet equivalence ratio, was newly developed. It was shown that the hydrogen/air burned-gas torch igniter developed in this study can successfully control the total temperature of the burned-gas jet by changing the jet equivalence ratio over a range of 1.0-10.0. Also, the chemical equilibrium assumption for determining compositions of the burned-gas jet was validated by measuring the oxygen mole fraction. The numerical results showed that the assumption applied for estimating the unmeasurable parameters, which are the mean molecular weight, specific heat ratio, critical flow coefficient, discharge coefficient, result in a maximum total error of 1.7% in the jet equivalence ratio of 1.0-10.0 in case that the actual burned-gas total temperature is larger than 80% of the adiabatic flame temperature. It was also shown that the discharge coefficient estimated in this study results in a underestimation of 7.02% at maximum due to heat lost to the side wall, which means that the maximum uncertainty of the burned-gas total temperature estimation is 14.7%. This indicates that the effect of heat loss on the discharge coefficient should be considered for more accurate estimation.

In chapter 3, a supersonic nozzle with a rectangular cross section was developed for a supersonic combustion experiments in the scramjet model combustor and verified experimentally and numerically. The newly proposed combined supersonic nozzle design method is easier to use than other design methods when the supersonic nozzle exit geometry is the constraints. This is because the method can estimate the displacement thickness prior to the supersonic nozzle contour determination. The airstream velocity profile obtained from a three-dimensional Reynolds-averaged Navier–Stokes (RANS) simulation was quantitatively in good agreement with results of laser Doppler velocimetry measurements, which meant that the three-dimensional RANS simulations could quantitatively evaluate the time-averaged flow field in the supersonic nozzle and the isolator developed in chapter 3. Although the displacement thickness estimation method applied in the present study underestimated the displacement thickness development, it was shown that the supersonic nozzle has good flow uniformity in the mainstream region at the supersonic nozzle exit. Also, the area-averaged Mach number in the mainstream region at the nozzle exit plane (=2.79) was in good agreement with the design Mach number (=2.80). In chapter 4, the combustion characteristics of the cavity flameholder with a bottom single hole injector in the scramjet model combustor was investigated experimentally. The flame structure of the burned-gas injection was investigated by direct imaging and measurement by OH planar laser-induced fluorescence (OH-PLIF). Four combustion modes were identified: jet-plume mode, jet-wake mode, one-side-cavity mode, and cavity mode. The jet-plume mode is considered to be less desirable than the other combustion modes because it has no intense flame emission region in the jet-wake and jet-side recirculation zones. Moreover, it was found that the jet-wake, one-side-cavity, and cavity modes often maintained the flame even after the injection gas was switched from burned gas to hydrogen. The jet-plume mode and non-luminescent mode, which has no flame emission region, often occurred regardless of the airstream total temperature when the burned-gas enthalpy flow rate is less than 9 kW. The jet-wake mode often occurs when the enthalpy flow rate of the burned-gas jet is greater than 9 kW. The one-side-cavity mode required a burned-gas enthalpy flow rate of more than 11 kW, and the cavity mode required a flow rate greater than 14 kW. The jet equivalence ratio for the cavity and one-side-cavity modes tended to be higher than that for the jet-wake mode, which suggests that the quantity of unburned hydrogen in the burned-gas jet is more important than the burned-gas temperature for achieving both the cavity and one-side-cavity modes. In addition, the effects of the airstream boundary layer thickness on the combustion characteristics of the cavity flameholder with a bottom single hole injector were investigated numerically. Numerical results showed that an increase in the airstream boundary layer thickness adversely affects flameholding in this cavity flameholder under conditions of a supersonic airstream with low total temperature. The mechanism of the effects of the boundary layer thickness is considered to be as follows: 1) when the airstream boundary layer becomes thicker, dynamic pressure of the airstream decreases near the wall; 2) interaction between the supersonic airstream and burned-gas jet creates a large boundary layer separation upstream of the cavity leading edge; 3) air entrainment from the separation region into the cavity flameholder is increased by formation of additional air entrainment paths in the jet side region; and 4) decreased temperature in the recirculation zone inside the cavity flameholder makes 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 flameholding failure in a supersonic airstream with a thick boundary layer.

In chapter 5, the effects of the cavity leading-edge geometry on the combustion characteristic of the cavity flameholder with a bottom single hole injector were investigated experimentally and numerically. The flame structure of the burned-gas injection and hydrogen injection were investigated by OH-PLIF measurement and three-dimensional RANS simulations. Additionally, the lean stability limits of the hydrogen injection were investigated experimentally. The burned-gas injection experiments showed that the cavity flameholder with a leading roof has two representative combustion modes, one-side-cavity mode and cavity mode, and that the leading roof successfully reduces the burned-gas enthalpy flow rate required for both of these modes. Numerical results for burned-gas injection showed that the burned-gas jet structure change caused by the leading roof mainly avoids entrainment of the airstream into the cavity from the separation region caused by the interaction between the supersonic airstream and burned-gas jet. It was also shown that the leading roof successfully formed a flameholding region in the jet-wake and jet-side recirculation zones in experiments, but the jet-wake flameholding region did not form in numerical simulations. This difference was considered to be caused by a decrease in the experimental injection hole diameter due to annealing for stress removal. The hydrogen injection experiments showed that a flameholding region exists in the recirculation zone near the cavity side wall for the case of moderate fueling and exists around the hydrogen jet-plume for the case near lean blow-out, which agrees with the numerical results for hydrogen injection. It was also shown that the leading roof increases jet entrainment into the cavity when the jet dynamic pressure is not large, and jet entrainment into the cavity becomes less sensitive to the cavity leading-edge geometry at large jet dynamic pressure. The lean blow-out limit for hydrogen injection showed that the cavity flameholder with a single hole injector has a much wider flame stability region compared to the cavity flame holder with multiple injectors regardless of the cavity leading-edge geometry. Apparently, the cavity flameholder with a single injector more easily forms a locally stoichiometric region than the flameholder with multiple injectors, which is why the cavity flameholder with a single injector produces a more stable flame compared to the flameholder with multiple injectors. Moreover, it was also shown that the cavity leading roof extends the stable flame region toward the fuel-lean side. This is thought to be due to the increase in the local equivalence ratio around the fuel jet region caused by the increase in jet entrainment into the cavity.