論 文 の 内 容 の 要 旨

論文題目　Numerical modeling on combustion behaviors in a hydrocarbon fueled scramjet combustor
（炭化水素を燃料とするスクラムジェット燃焼器における燃焼挙動に関する数値解析）

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Mixing and combustion in a hydrocarbon fuel injected scramjet combustor with cavity flame holder have been simulated computationally and its behavior by reaction model and injection parameters was investigated quantitatively. Scramjet engine, which is an air breathing, ram compression propulsion engine and maintains air flow in the combustor supersonic for lower loss and effective thrust generation, is expected to fulfill future demand for next-generation hypersonic flight missions in atmosphere due to its high specific impulse compared to conventional turbojet engines and rocket engines. Research on physical phenomena in scramjet engine combustor and development of operable engine design with higher efficiency and better controllability are essential for making fast and economical hypersonic vehicles. Hydrogen fueled scramjet engines have been studied primarily for its high reactivity and specific impulse. However, researches on hydrocarbon fuel for a scramjet engine are valuable in aspect of utilizing its higher energy density, versatility, safety and economic advantages. Especially numerical studies on the hydrocarbon fueled scramjet engine combustor are insufficient compared to hydrogen fueled engine due to complexity of participating reactions. However, numerical approaches are required as much as experimental investigations for proper development.

In this thesis, most of the results are obtained from numerical simulations, and are validated by comparing those with previous experimental results from a supersonic wind tunnel which is equipped with a cavity flame holder. Physical phenomena considered and modeled by numerical methods are energy/fluid flow and chemical kinetics of hydrocarbon. The fluid domain has been divided into 3 million grid mesh, and balance equations of mass, momentum and energy have been solved numerically by discretizing those equations with 3rd order local accuracy in space. To be capable of hyperbolic partial differential equation characteristics, AUSM^{+}-up and MUSCL which are high order TVD scheme have been used as limiter for numerical fluxes. Smagorinsky modeled LES has been applied for calculation of turbulence at a practical cost and reasonable resolution which is required for proper mixing and reaction modeling. The program used for running those simulations was parallelized using OpenMP and MPI technology in order to expedite heavy calculations.

In order to complement limited number of numerical researches on a hydrocarbon fueled scramjet engine combustor compared to that of experimental ones, effects on the flow phenomena and combustion behavior are compared between four different methane fuel combustion models. Methane has been chosen as the first hydrocarbon fuel because it is one of the simplest hydrocarbons which could be produced easily by fuel cracking and numerically simulated with lower computational cost due to simpler reaction chain. Frozen and fast chemistry exhibited two extrema cases of zero and infinite Damköhler number, respectively. 4-reactions and 7-species Jones-Lindstedt model and 9-reactions and 11-species Li-Williams model which have different purposes were compared as well using unsteady simulation results such as shock intensity, mixing and flow characteristics. Combustion behavior observed from numerical simulation agreed well with previous experiment on methane ignition stages. Pressure, density, temperature and species distributions with respect to reaction models were investigated and mixing/combustion efficiencies of each case were plotted. Numerical Schlieren images revealed differences of bow shock intensity and mixing shear layer on the cavity. Those differences could be also disclosed by pressure distribution on the wall and mid-plane section, which mentions vigorous combustion in case of fast chemistry and Jones-Lindstedt model cases. Temperature distribution also shows strong combustion in those two aforementioned cases, while indicates absence of established combustion when Li-Williams model is used. OH radical distribution has been compared to experimental visible light result to explain this absence. Also, distribution of carbon dioxide shows advantage of Jones-Lindstedt model over fast chemistry. The trend of mixing efficiencies of these combustion models requires further research on interaction between injection of the fuel and shear layer. From those results it has been confirmed that Li-Williams model is suitable for reproduction of initial ignition processed, while Jones-Lindstedt model is appropriate for combustion data acquisition without regarding complex ignition stage.

In addition, investigation on effect of heating of the fuel is important compared to other factors such as fuel composition, injection strategy and fuel air ratio because modified fuel temperature may influence controllability of a scramjet engine combustor and fuel heating is inevitable for cooling of a vehicle in flight operation. The investigation has been conducted by decoupling fuel injection dynamic pressure ratio with respect to main air flow from fuel total temperature. In order to achieve this, momentum of fuel injection has been modified by adding numerically inactive methane fuel in order to maintain identical dynamic pressure ratio or fuel total temperature between different parametric cases while equivalence ratio is constrained to be constant. By configuring in this way, all cases could be categorized into three lineup; pure active methane cases, identical fuel total temperature and identical dynamic pressure ratio. Visualized results of velocity, concentration distribution and velocity unveil flow field and combustion region. While the flow over the cavity represents their characteristics with respect to conditions, the flow inside the cavity is not fully stable. Large vortices which enhance mixing of the fuel could be also observed. Intensity of the bow shock induced by fuel injection is mainly dependent on dynamic pressure ratio, which is confirmed by pressure distribution. Investigation on penetration characteristics of the fuel injection revealed that influence of fuel temperature modification is restricted only to downstream region at limited degree and not visible in vicinity of the fuel injection hole, whilst penetration of dynamic pressure ratio is dominant near fuel injection hole as claimed in previous researches. However, due to diffusive mixing, the difference in penetration is moderated. Relation between each parameters and mixing/combustion efficiency is also analyzed. In case of dynamic pressure ratio change, two efficiencies followed similar trend, and optimum ratio of $J = 0.035$ and $J = 0.691$ could be found within given ratio range. From this result, it is confirmed that combustion efficiency is dependent on mixing efficiency when the temperature is constant. The existence of the optimum is thought to be originated from degree of interaction between the fuel streams and shear layer near wall and cavity flame holder. In case of fuel temperature change, mixing efficiency is inversely proportional to fuel temperature, while combustion efficiency is proportional. When fuel temperature is changed, determining factor of mixing efficiency is velocity difference between injected fuel and main flow. On the other hand, determining factors of combustion efficiency are mixing enhancement and reactivity of the fuel. Due to this effect, proportionality of combustion efficiency with respect to fuel temperature was observed in a diminished manner.