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論 文 内 容 要 旨

The innovative engine technology advanced to operate at high speeds such as ramjet or scramjet. The most typical engine is well-known as Scramjet. The technology challenge of the scramjet engine is to solve shock control, rapid fuel-injection, fuel-air mixing and self-ignition as to promote flame stabilization and combustion. Therefore, the development of the scramjet engine is essential for efficient hypersonic propulsion.

In this engine, Pseudo-Shock Wave (PSW), as well-known pre-combustion shock waves, generated by interacting with the boundary layer and shock wave. The pseudo-shock wave produces the pressure rise.　Pseudo-shock wave grows large through isolator to inlet due to induced heat release in combustor. The required isolator length in a scramjet is a critical part that allows the combustor to achieve the heat release in combustor and capture the induced pressure increase without an inlet surge or unstart. The purpose of setting an isolator in between the inlet and combustor is to hold and maintain the pseudo-shock wave. It is essential to have the ability of accurately predicting the possible length of the pseudo-shock wave at various inlet conditions. The pseudo-shock wave is well known for assistant mixing the injected fuel with oxidizer air flow and to increase combustion efficiency. However, some mixing state in pseudo-shock wave still is not understood not yet. To overcome these difficulties, detailed and correct understanding of physics occurring in the supersonic flow-field with pseudo-shock wave is essential.

Experiments are quite necessary to capture the structure of the pseudo-shock waves. However, it is sometimes difficult to collect detailed information about the flowfield of the pseudo-shock waves. The numerical studies have been rapidly moved to employ Large Eddy Simulation. Although LES require much expensive computational cost than that for RANS simulation, LES is supposed to give both qualitative and quantitative data about complicated supersonic flowfield. Many researchers have investigated the supersonic turbulent flow field using LES. However, the LES code applicable to Pseudo-shock wave in supersonic flowfield is still not so many. Moreover, it is the first time, the LES of mixing calculation with pseudo-shock wave.

The first objective of this dissertation is to develop and apply the LES code that can accurately simulate the pseudo-shock wave and its mixing phenomena. The forecast ability of the present LES is estimated with the comparison of available data with the Stereoscopic PIV experiments. Also, the understanding of the supersonic turbulent mixing state with pseudo-shock wave is conducted using the LES.

In Chapater 2, a supersonic turbulent flowfield involving the pseudo-shock waves in an isolator of a supersonic combustion ramjet is computed using two different LES codes which are a high order upwind finite volume scheme, and a sixth order compact differencing scheme utilizing the localized artificial diffusivity method for stabilizing shock waves and employing a wall model to enable the use of coarse mesh. In the validation study where a supersonic turbulent boundary layer flow over a flat plate is examined, both LES codes are well validated using velocity profile in the boundary layer given by the hot-wire anemometry and normal stress given by the laser Doppler anemometry. In particular, the sixth order compact differencing scheme gives closer agreements with these experimental data. Then, the validated LES codes are applied to solve the Mach number 2.5 supersonic turbulent flowfield involving the pseudo-shock waves. It is shown that typical features of unsteady flowfield of the pseudo-shock waves are well obtained by both schemes. Again, it is indicated that the sixth order compact differencing scheme gives closer agreements with the existing velocity data obtained by particle image velocimetry and pressure fluctuation data on the wall surface. Besides, the computational cost of the compact differencing scheme is found to be 1/7 of that for the upwind finite volume scheme, even though a wall model is solved at each grid point on the wall surface. Therefore, the obtained results in the present study allow to recommend the sixth order compact differencing scheme with a wall model for simulating supersonic turbulent flowfield in an isolator involving the pseudo-shock waves.

In Chpater 3, a supersonic turbulent flowfield in an isolator entailing the pseudo-shock waves with a sonic transverse jet is computed using a large-eddy simulation (LES). The validated LES code is applied to solve the Mach number 2.5 supersonic turbulent flow field concurrently existed the pseudo-shock waves with injectant. LES result well captured with particle image velocimetry experimental data both mean data and turbulent characteristics. The backward-leaning elliptic shape structure obtained in two-point spatial correlations rotated in a clockwise direction, and this structure repeatedly appeared in centerplane when vertical velocity of main stream changed from down to up caused by pseudo-shock wave. LES results showed that turbulent diffusion move toward the bottom wall and it rises along the both side walls. Probability Density Function and the combustible injectant mass flux showed that pseudo-shock wave plays an important role in the injectant mixing.

In Chapter 4, LES of Methane and Ethylene Jets into a Mach 2.5 supersonic flow with Pseudo-shock wave were conducted to investigate the differences in the behavior associated with injectant species between Methane and Ethylene gas. Also, two jet-to-crossflow conditions were carried out at the same mainstream state to examine how the value of J changes the flow filed with Pseudo-shock wave. The following results were obtained. The same J value had the similar size of large-scale structures which are elongated from the edge of barrel shock wave to mainstream core region. The difference between different J values exposed different sizes of barrel shock wave. And larger size of barrel shock wave seems to penetrate more highly into mainstream. The instantaneous distribution of injectant mass fraction in cross-section appeared to spread widely at large J value. The jet penetration defined by the average injectant mass fraction tracks were roughly the same regardless of the injectant species when the jet-to-crossflow momentum flux ratio is the equal. The bow shock wave was influenced to first shock wave which moved upstream a little. As TKE, the larger barrel shock wave fluctuated due to interacting with turbulent boundary layer. This fluctuation propagated to first shock wave. The total pressure loss increased moving up and down at $x/(J^{1.2}D)$ = 5~10, 17~22, 28~32 repeatedly. There distributions seem to govern by PSW. And J = 3.3 has larger total pressure loss than J = 1.65. Lower J value showed well mixed region in PDF. This feature indicate the J value is the important factor for mixing state regardless of the species. Methane had better mixing efficiency then Ethylene to spread easily for reason of light of weight. Above features result in better turbulent mixing property for CH4 jet.

論文審査結果の要旨

極超音速で飛翔する航空宇宙機の推進エンジンとして検討されているスクラムジェットエンジンでは，燃料が噴射された超音速気流が燃焼室に到達するまでの極めて短い時間内に燃料と酸化剤である空気を混合させなければならない。空気取り入れ口と燃焼室の間に設けられた分離部に生じる擬似衝撃波が燃料の混合を促進させることが知られているが，分離部に生じる擬似衝撃波の実験的研究は困難であることから混合促進メカニズムの詳細は未解明のまま残されている。本研究では，Large-Eddy Simulation (LES)を用いて分離部に生じる擬似衝撃波による混合促進メカニズムの解明に取り組んでいる。本論文はこれらの研究成果をまとめたものであり，全編 5 章からなる。

第 1 章は序論であり，本研究の背景，目的および構成を述べている。

第 2 章は，超音速乱流境界層の実験データを用いて高次精度風上型有限体積法に基づく既存の LES コード(スキーム A)と 6 次精度コンパクト差分に壁モデルを組み合わせて新たに構築された LES コード(スキーム B)の比較を行い，スキーム B がスキーム A より少ない格子点数かつ 1/7 の計算コストで実験データをより正確に再現できることを明らかにしている。また，分離部を模擬したダクト内の超音速気流に生じる擬似衝撃波の解析においても，スキーム B は実験データと良い一致を与えることが示されている。これらは分離部に生じる擬似衝撃波群を LES によって現実的な計算コストで解析可能であることを示す重要な成果である。

第 3 章は，擬似衝撃波が生じているダクト内の超音速気流中に燃料を模擬した空気を噴出させた流れ場の LES を行うことによって，擬似衝撃波による燃料の混合促進メカニズム解明を試みている。擬似衝撃波背後で交互に生じる圧縮領域と膨張領域をコア流が通過する様子や，噴射燃料濃度の確率密度関数から燃料混合領域がコア流内で拡大する様子を明らかにしている。これらは，擬似衝撃波が燃料混合促進に果たす役割に重要な知見を与えている。

第 4 章は，炭化水素系燃料ガスであるメタンおよびエタンを擬似衝撃波を含む超音速流に噴出させた流れ場の LES を行うことによって，化学種の違いや噴射流とコア流の運動量流束比の違いが混合に与える影響を詳細に検討している。大きな運動量流束比は燃料ガスの高い貫通高さを与えるが総圧損失も大きくなることを明らかにしている。また，擬似衝撃波を通過するたびに貫通高さや総圧損失に特徴的な変化が現れることを明らかにしている。さらに，運動量流束比に関わらず分子量の小さなメタンの混合効率が高くなることを具体的に示している。これらは擬似衝撃波を利用して燃料混合を促進させる分離部の設計手法確立に貢献する重要な成果である。

第 5 章は結論である。

以上要するに本論文は，擬似衝撃波を含む超音速乱流場の LES が現実的な計算コストで実現可能であることを明らかにするとともに，スクラムジェットエンジン分離部に生じる擬似衝撃波が燃料の混合促進に果たすメカニズムの解明に取り組んだものであり，航空宇宙工学および計算空気力学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。