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学位論文題目	Experimental Study of Scalar Structure in a Supersonic Turbulent Mixing Flowfield Using Acetone PLIF（アセトンPLIFによる超音速乱流混合流れ場におけるスカラー構造に関する研究）
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論文内容要旨

Detailed understanding of the fuel-air mixing mechanism in a supersonic flowfield is vital to the successful design of hypersonic propulsive devices such as scramjet engines. In the scramjet engine, fuel mixes with air which flows into the combustor at supersonic speed, and hence the whole combustion process needs to be completed in or less than a few milliseconds. However fuel is not likely to mix quickly because of the inhibition of development of two-dimensional vortex structure resulting from compressibility effect and low shear between fuel and air flow. Enhancement of fuel-air mixing is of great concern, and many study for mixing enhancement has been done. Recent study with highly resolved optical diagnostics revealed that there exists both two- and three-dimensional large-scale structures even in a supersonic injection flowfield and the instantaneous and time-averaged structures are very different. Since it is quite difficult to directly measure the instantaneous structure quantitatively, it is useful to use statistical approaches with the aid of a promising visualization technique, namely acetone planar laser-induced fluorescence (acetone PLIF).

This research has two main objectives. One is focused on the development of the quantitative measurement of supersonic mixing flowfields using acetone PLIF. Another is focused on the investigation of large-scale turbulent structure inherent in the supersonic mixing flowfield based on the scalar quantity measured by PLIF. The flowfield of interest was a sonic transverse injection into a supersonic air stream.

In Chapter 2 entitled with "Interpretation of Fluorescence Signal from Acetone Molecules and Quantitative Imaging of Supersonic Mixing Flowfield", we examined the fluorescence signal from acetone molecules for quantitative interpretation so as to apply it to supersonic conditions. The LIF signal was linearly related to the acetone molar concentration, which represents number of moles in specific volume, within ± 6.0% error, even though it is affected by local temperature, pressure, and acetone mole-fraction. With acceptance of this level of error, a single-shot PLIF image can be interpreted as an instantaneous jet molar concentration structure.

To demonstrate the advantages of acetone PLIF, we visualized a supersonic mixing flowfield with acetone PLIF. Then we compare the results to those of Mie scattering which has been widely used in past studies with regard to the penetration height of perpendicularly injected jet. We clarified the advantage of acetone PLIF in traceability and capability of precise investigation of flowfield.

In Chapter 3 entitled with "Generalization of Fluorescence Ratio Method", we generalized the fluorescence ratio method, which was originally introduced by Hartfield et al., for the quantitative imaging of time-averaged mole-fraction and density distributions in a supersonic mixing flowfield and examined its validity and applicability. The original Hartfield method was applicable when the tracer seeding rates for both the jet and the main flow are the same. In addition their experiment was done with iodine PLIF. In order to expand the usage of the original method, we deduced the generalized equations. To verify the applicability of the generalized method to other configurations and PLIF with other tracer, we experimentally examined by comparing PLIF data and gas-sampling data for injectant mole-fraction.

Comparison between PLIF and the gas-sampling data with respect to the injectant mole-fraction revealed that the generalized method agreed much better with the gas-sampling data than those obtained with Hartfield's original method. As for the density distributions, the generalized method was well validated by comparison with theoretical values across the oblique shock wave. However, the derived density distribution was validated only in the region where mixing hardly occurred. Quantitative agreement of the mole-fraction distribution strongly suggests that the density in the jet where the mixing occurred well would be appropriate.

We further extended the generalized fluorescence ratio method and deduced equations so as to apply to the multi-component and multi-staged injection cases. Injectant mole-fraction and density distributions from n different injectors can be deduced by use of $n + 1$ sort of PLIF image data sets with different acetone seeding conditions. From the deduced method, we can obtain time-averaged injectant mole-fraction and density distributions for each injector component. We performed a PLIF visualization experiment for staged injection flowfield of which injectants were helium for primary jet and air for secondary jet. In order to apply the extended generalized method, we obtained three sorts of PLIF images with different acetone seeding conditions. Deduced injectant mole-fraction distributions were qualitatively appropriated, and hence the extended generalized method was validated.

In Chapter 4 entitled with "Scalar Spatial Correlation for Sonic Transverse Air Injection into Supersonic Main Stream", we

expanded the usage of acetone PLIF to investigate the large-scale turbulent structure within the supersonic mixing flowfield by using a single-time two-point spatial correlation and probability density function of the PLIF signal intensity, which is proportional to the injectant concentration. The flow conditions were fixed to investigate the large-scale structure in detail. And the structure was precisely investigated by side-view, end-view and top-view analyses. Although the mean distributions in molar concentration and injectant mole fraction differed due to local density change, their averaged tracks agreed very well with each other in the region of $x/D \geq 4$. And the mean concentration profile in the upper half of the jet plume exhibited self-similarity in the entire region of $0 \leq x/D \leq 12$, whereas the fluctuating intensity took $6D$ to develop self-similarity.
A large-scale structure was observed for correlation distributions and appeared most intensely along the upper 50% track of LIF signal intensity. The large-scale structure grew larger as it moved downstream until $x/D = 6$, then shrank gently or maintained a constant size. The structure first had an elliptic shape and rotated in a clockwise direction as it went downstream until reaching $x/D = 6$; its shape changed from an ellipse to a circle and then to another ellipse while switching major and minor axes. The streamwise velocity distribution might determine the shape and orientation of the large-scale structure. The area of the correlated region maintained the same or gently increased in the streamwise direction until $x/D = 6$; however, in the transverse direction, the area became maximum between the 10% and 50% averaged concentration tracks, and sharply diminished below the maximum track.

Large-scale structures appeared in an interval of $3D$ to $4D$, or twice the large-scale vortices. The instantaneous jet plume exhibited a flapping motion and appeared alternately in the upper or lower part of the averaged plume region. In the cross-sections, the upper center and both lower side regions were negatively correlated, and both the right-hand side and the left-hand side of the lower part were positively correlated. These features are consistent with the hairpin model of the large-scale structure.

Vortex structures smaller than those observed downstream appeared around the windward barrel shock and significantly influenced the structures formed in the upstream recirculation zone and upper jet boundary, and inside the jet plume. Fluid behavior in the upstream recirculation zone of the barrel shock has some effect on jet mixing mechanisms. However, the downstream recirculation zone has less effect except for additional mixing enhancement such as shock impingement.

The smaller-scale mixing was investigated by PDF analysis. The PDF results clarified that the best instantaneous mixing in the region $x/D \leq 12$ occurred in the center of the wake region slightly below the maximum concentration track. This region is different from large-scale stirring. The level of mixing improves with downstream distance downstream from the jet exit. The large-scale vortex structures that are observed to periodically pass through the mixing layer are consistent with the trends indicated by the PDFs.

In Chapter 5 entitled with "Effects of Main Flow and Injection Conditions on Supersonic Scalar Mixing and Turbulent

Structure", we studied the effects of the jet-to-mainstream momentum flux ratio, the mainstream Mach number, and the injectant species on the size and shape of the large-scale structures. To facilitate this investigation, we adopted helium and air as injectants, by replacing the tunnel nozzle and changing the injection pressure. In order to clarify these effects on the large-scale structure, the same statistical analyses as Chapter 4 were performed.

The appearance interval, the inclination angle, and the size of the large-scale structure tended to increase as compressibility decreases. The structure was likely to be stretched toward the averaged-velocity direction as the mainstream Mach number increased. This indicates that the velocity field around the jet strongly influences the characteristics of the turbulent structure. The inclination angle of the large-scale structure decreased with increasing main flow Mach number, and the structure was likely to be elongated along the streamline direction. The momentum flux ratio influenced the size and major axes but had almost no effect on the inclination angle.

The penetration of the jet is not affected by the main flow Mach number or injectant species. Also, the large-scale structure appears on the 50% concentration track irrespective of the main flow Mach number and injectant species. The greater velocity difference and air injection develop the turbulent structure in the transverse direction, and the development is slower in helium-injection cases.

In air-injection cases, the shape of the large-scale structure identified by the correlation region was a tilting ellipse, whereas the shape in the helium-injection cases was an ellipse parallel to the mainflow direction. Relatively small-scale eddies appearing at $x/D = -1$ along the upstream side of the barrel shock influence the later development of the large-scale structure in all cases. The inclination angle of the large-scale structure is not affected by J and is larger in air-injection cases. In air-injection cases, the large-scale structure grew until $x/D = 5$ and remained constant in size, whereas that in the helium-injection cases kept growing slowly throughout the whole observed region. The large-scale structure produced by helium injection was smaller than that produced by air injection. The former was likely to be tied together and elongated. In addition, air-injection cases and lower-compressibility cases with higher J produced better mixing.

論文審査結果の要旨

将来の宇宙輸送システム用エンジンとして有望視されているスクラムジェットの実用化に向けて，最も重要な課題の一つに超音速空気流中に噴射した燃料の迅速な混合がある。この流れ場では，亜音速流において乱流混合を支配する大規模な横渦構造の発達が，圧縮性効果によって抑制される可能性がある。しかし，噴射を伴う複雑な超音速流の乱流混合構造の実験による計測は困難であり，これまで十分に行われて来なかった。近年，流れ場にレーザを照射し，気体やトレーサー物質からの散乱光や蛍光を測定して，物質の種々のスカラー量を求める方法が盛んに行われているものの，超音速混合流れ場では，散乱光や蛍光の強度を支配する物質の混合割合，温度，密度が独立に変化するため，発光強度と物理量の対応を定量的に示すことは困難であった。本研究は，アセトン蒸気をトレーサー物質とする平面レーザ誘起蛍光法（アセトン PLIF）について，まず大気条件を淀み状態とする超音速流では蛍光強度がアセトンの濃度にほぼ比例することを理論的に示し，次いで光学系の影響を取り除き平均モル分率を求めることができる蛍光比法の一般化と拡張を行い，その精度を実験的に検証している。また，多数の瞬間PLIF 画像データから噴射気体濃度の空間相関分布及び確率密度関数を求め，それらを使ってスカラー場の乱流構造を解明している。本論文は，これらの研究成果をとりまとめたものであり，全編6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章では，大気吸込み式超音速風洞を用いた実験で想定される温度，圧力及びアセトンモル分率の範囲で，蛍光発光強度を理論的に計算し，蛍光発光強度が±6%以下の誤差でアセトン濃度と比例関係にあることを示している。これはPLIF 画像から物理量を定量的に求める上で有用な成果である。

第3章では，噴射剤の平均モル分率を求めるためにHartfield らが提案した蛍光比法が，暗黙裡に主流と噴流のアセトン混合率を同一と仮定していることを指摘し，その仮定を取り去って一般化した蛍光比法の定式化を行い，モル分率と密度が同時に求められることを示している。さらに同法を異種気体噴射や，多段噴射を行う場合に拡張している。また，同法を検証するために，マッハ2の空気流中に壁面から音速空気流を垂直に噴射した実験を行い，アセトン PLIF の平均画像から一般化蛍光比法を用いて求めた噴射剤の平均モル分率が，プローブで採取した気体をガスクロマトグラフで分析した結果と非常に良く一致することを示し，同法の妥当性を実証している。これは，PLIF 画像により超音速混合流れ場の平均スカラー量の定量計測を可能とする重要な成果である。

第4章では，第3章と同じ条件の混合流れ場に対するアセトン PLIF の瞬間画像から，濃度変動の単一時間二点空間相関および濃度の確率密度関数を求め，スカラー場の構造を調べた。その結果，噴流と主流が接する側には大きな正の相関領域がある間隔で並ぶ大規模構造が見られる一方，噴射孔のある壁側では正の相関領域は小さく大規模構造が見られないことを見出している。また，相関領域の形状を楕円近似して，大規模構造の大きさや形状の主流方向変化を抽出し，従来知られていない噴射に伴う乱流スカラー場の構造と特性を明らかにしている。これは，超音速混合場の乱流構造と燃料の混合過程を知る上で重要な知見である。

第5章では，主流マッハ数，噴射の圧力及び気体種を変えた実験を行い，平均量及びスカラー乱流構造に対するそれらの影響を調べ，低分子量気体を噴射した場合に大規模構造の発達が抑制されることを見出している。これは，実用上有用な知見である。

第6章は結論である。

以上要するに本論文は，アセトン蒸気をトレーサーとする平面レーザ誘起蛍光法の画像から平均のモル分率及び密度を求める一般化蛍光比法を定式化し，その妥当性を実験的に検証すると共に，噴射剤濃度の乱流変動の構造と特性を解明したもので，航空宇宙工学および推進工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。