論 文 の 内 容 の 要 旨

論文題目　Experimental and Numerical Investigation of Hypersonic Flow over a Three-dimensional Backward-facing Step
（三次元後ろ向きバックステップを過ぎる極超音速流に関する実験的数値的研究）

氏　　名　　鐘　策

For development of aerodynamic design of hypersonic vehicles, it is necessary to investigate the hypersonic separated/reattached flow, which have negative effects on the performance of aerodynamic devices. A hypersonic flow is a flow field where the flow velocity exceeds Mach number 5 and above. The hypersonic separated/reattached flow involves the hypersonic effects, including shock wave and expansion wave.

The hypersonic separated/reattached flow has attracted the research attention over last a few decades. From a viewpoint of aerodynamic design, a deep understanding of the flow characteristics of hypersonic separated/reattached flow will be helpful to improve the design of reducing drag, thermal protection and noise/vibration control of hypersonic vehicles. However, the flow physical mechanism of different type of hypersonic separated/reattached flow are very complicated involving shock/boundary interactions, recirculation, reattachment and reattachment shock wave. In order to study the general flow physics of this kind of flow more efficiently, generalized geometries have been employed to investigate the hypersonic separated/reattached flow. For the base drag associated with the wake characteristics, backward-facing step has been considered as an ideal configuration to study the hypersonic wake flow. Furthermore, this geometry can be found in body flap and control surface of orbital vehicles. The flow over backward-facing step is an important benchmark in studying the flow around these devices.

Despite the simplicity of the backward-facing step geometry, the hypersonic flow over a backward-facing step model is complex involving sudden expansion, boundary layer separation, recirculation, reattachment, which play an important role in the wake characteristics of this flow field. In this thesis, the focus of objectives will be on recirculation and reattachment.

The flow over backward-facing step has been studied since 1960s, while the detailed investigation on hypersonic backward-facing step flow can not be found until recent years due to the difficulties of test in such high-speed and high-enthalpy flow.

In study of hypersonic flow, numerical simulation is expected to contribute in providing convenient and efficient ways to study the flow separation and reattachment. However, due to the lack of reliable experimental data at hypersonic condition, systematic validation of CFD methods are rarely seen in the literature.

Most of the studies on hypersonic backward-facing step flow were based on two-dimensional analysis. However, the three-dimensional effects in wind tunnel experiment are indeed needed to be taken into concerned for the limitation of model size in a hypersonic wind tunnel. The experimental validation loses its validity for comparing a 2D numerical simulation with the experimental results involving three-dimensional effects. Furthermore, the experiments and simulations with the consideration of 3D effects are more suitable for the three-dimensional nature of BFS flow in applications.

The major objective of this study is to investigate the three-dimensional flow characteristics of hypersonic flow over a backward-facing step with finite span. The study is conducted by experimental measurements of the three-dimensional flow field in a hypersonic wind tunnel and three-dimensional numerical simulations for the geometries employed in the experiments. Validation of the numerical simulation is conducted by comparison between three-dimensional CFD results to the experimental measuring results. Further, a detailed discussion is presented to clarify the mechanisms of the three-dimensional flow features observed in both experimental and numerical results.

Experiment are conducted in hypersonic flow at Mach number 7 for a backward-facing step mode. The backward-facing step has a model step height at 10mm. In order to obtain the information of the different aspects of the flow field, simultaneous measurements of pressure distribution, temperature distribution, oil flow visualization and schlieren flow visualization have been conducted in this study.

When studying a three-dimensional flow by experiments, measurements of surface distribution must be made over a wide area on the model surface. Pressure-sensitive paint, which can provide global pressure measurement on the model surface, has been applied for the surface pressure distribution on the backward-facing step model. PSP is an optical sensor with high spatial resolution for global pressure distribution measurements. PSP technology gives a luminescence intensity related to the oxygen quenching. When the oxygen collides with the luminophores, the luminophore molecules are deactivated, called oxygen quenching. The intensity of the emitted light depends on several factors including the concentration of oxygen and the intensity of excitation light. The intensity of excitation light decreases with increasing amount of oxygen. The luminescent molecules can be excited by the absorption of excitation light. A porous organic particle, called Godd Ball (Suzuki Yushi), has been considered as one of the promising approaches for enhancing the performance of PSP. A new PSP method for surface pressure distribution in hypersonic wind tunnel, named porous-particle PSP (PC-PSP) is developed and applied for measurements in this study.

Porous particles applied in this study have large surface area and open structure with a unique nanoscale porous structure. The supporting matrix for holding the PSP luminophores is provided by the pores on these particles. By dipping the particles into the solution of luminophore molecules, PSP absorbed particles can be made after drying process. The particles are attached to model surface by PMMA based adhesive.

The simultaneous measurements comprise surface temperature measurements by infrared thermography, surface oil flow visualization and schlieren imaging. Surface oil flow visualization is applied for visualizing the separation and reattachment on the model surface, and the schlieren imaging is applied for visualizing the shock/expansion wave structure in the flow field.

Through these processes, a robust porous PSP method has been developed. This porous PSP has a nano-open porous structure to achieve fast oxygen quenching process and can be sprayed to model surface. PP-PSP is expected to provide pressure measurement in hypersonic wind tunnel.

The measurements have been carried out at the angle of attack 7°. A highly three-dimensional flow pattern has been observed in surface measurements of pressure and temperature. A recirculation region with a curved boundary can be seen clearly in the result of PSP measurements. Another three-dimensional flow feature, called ‘twin peak’ structure in this study, has been found in both surface pressure and temperature distribution. The ‘twin peak’ is peak pressure and temperature on localized regions appears on the model surface. The two regions are symmetric about the center line. The separation lines have been visualized by surface oil flow visualization. Since the oil cannot penetrate the boundary formed by separation, reattachment and recirculation region, the oil flow visualization technique can be used to detect the separation and reattachment. During the experiments, the oil film was strongly blown of by the downwash acting on the model surface. Following separation can be visualized by the separation lines. A closed region surround by separation lines appears at the same position as the ‘twin peak’ structure. The oil within these regions were driven by a strong downwash during the experiments.

High-speed schlieren is inserted for visualizing the shock/expansion wave structure and monitoring the experiments. The reattachment shock wave following the expansion along the step were captured by the schlieren imaging. No significant instability has been observed during the experiments. The discussion of the experimental results and the numerical simulation have been conducted for steady-state flow.

The three-dimensional flow features including ‘twin peak’ structure, recirculation bubble and reattachment have been captured in the experiments. However, the information of the flow field is limited to surface distribution and cross-section imaging. Three-dimensional CFD has been conducted to complement the experimental results to describe the complex three-dimensional flow field of hypersonic flow over backward-facing step.

The numerical simulation is conducted by solving three-dimensional Navier-stokes equations for the same flow condition in wind tunnel test

Before discussing the flow mechanism, validation of CFD simulations has been conducted by comparing the numerical results against the experimental results. It can be clearly deduced that the three-dimensional flow pattern in numerical simulation is same to experimental results. This provides the validation of numerical method applied in this study.

Numerical visualization has also been conducted to obtain further information of the three-dimensional flow field of hypersonic backward-facing step flow. By visualizing the three-dimensional structure of the recirculation, it can be found that the recirculation bubble formed behind the step, has a curved boundary surface. The formation of the recirculation bubble is affected by the separation at the step and both sides. When the flow passes the step and its side edges, the recirculation in both directions are formed following the expansion. As a result, a common recirculation region of flow from upper surface and open sides is form behind the step. The fluid within this region is dominated by the flow mixing, which leads to vortex structures in the recirculation bubble.

Apart from recirculation bubble, the ‘twin peak’ structure, which is key feature of three-dimensional hypersonic BFS flow found in this study, will be discussed in this section. The ‘twin peak’ structure has been found during the experimental measurement and in numerical visualization. The fluid flow from open sides of the model encounters a sudden expansion and flow inboard of the step model. The induced velocity gradient causes the entrainment of fluid from below the surface of the step. The longitude vortices pair forms primarily because of the transverse entrainment. As a result, the fluid flow from open sides twists toward the surface and encounters the flow from the top surface. The interaction between longitude vortices and reattachment enhances the flow impinging on the model surface. The impingement becomes stronger to produce an appreciable adverse pressure gradient, is shown as the peak pressure region. The region of the reattachment is confined by the vortices. This assumption seems to be the evidence of the disappeared reattachment shock wave in schlieren.