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Doctoral Thesis (Abridgment)

博士論文（要約）

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）

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Abstract

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 cannot 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.

Chapter 2-6 (pp. 37 to 136) of my doctoral thesis cannot be made public on the Internet for 5 years from the date of doctoral degree conferral because that part has been accepted for publication. *

In this study, a new PSP technology with high robustness and fast response has been developed by using inorganic spherical porous particles. Experimental technologies comprised of various global measuring methods are applied to the measurements of backward-facing step model in hypersonic wind tunnel.

Based on the experimental and numerical simulation results, the key findings of this study include the three-dimensional flow features: ‘Twin peaks’ structure and recirculation bubbles.

Recirculation bubble is a horseshoe vortex structure generated by the interaction of side expansion and recirculation. The longitude vortices form on both sides of the objects because of the transverse entrainment of the fluid have been detected by numerical simulation. The high-pressure and high-temperature region occurring as a ‘Twin peaks’ structure, is generated by strong down wash produced by the longitudinal vortices and the interaction with reattachment. The flow physics within the domain of three-dimensional patterns and the mechanism of the effect of interaction between hypersonic separated-reattached flow and the longitudinal vortices on the flow field are revealed in this study. This effect results different patterns of interaction between mainstream reattachment and secondary separation flow of longitudinal vortices.

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1 Introduction

1.1 Background

Flow separation is always a challenging topic in the field of fluid dynamics. It describes the flow passes over a sudden discontinuity, which is a common phenomenon throughout the aerodynamic applications. Flow separation has been investigated extensively since 1950s. In early experimental and analytical studies, the basic flow structure and Reynolds flow condition have been focused on[3]. Separation point and reattachment have commonly been considered as the primary parameters. Separated/reattached flows affects the dominant factors of aerodynamic flow field including pressure, heat transfer and skin friction coefficient, which generally have a negative impact on the performance and efficiency of aerodynamic devices. Hence, the separated/reattached flow has received growing research attention over recent years. Among these studies, the separation and reattachment of external flow is closely related to the aerodynamic characteristics and design of aerospace applications.

Since the Wright Brothers made the first successful powered flight in 1903, the dreams of fast transportation began to fade. In recent years, due to the development of design and manufacturing techniques, high-speed vehicles have become a reality. Future aircraft are expected to fly in hypersonic speed. However, efforts are needed to achieve a more efficient and reliable flight. In an aerodynamic perspective, reducing the drag and developing thermal protection system are considered as two of the major aspects of hypersonic vehicle designs. There are several causes of drag. In this thesis, the focus will be on recirculation in the wake area which causes the base drag. Similarly, the impingement in the reattachment region which can cause local heating will be focused in this thesis. Hence, hypersonic flow separation/reattachment are the key factors dominating the wake characteristics of entry/re-entry vehicles.

Apart from the common characteristics with subsonic separated/reattached flows, the existence of expansion and shock wave in hypersonic flow makes it more complex and involves various hypersonic effects, for example, real gas effects and dissociation. In hypersonic flow, the interaction between boundary layer and high-speed external flow dominated the flow field. For a hypersonic vehicle, the flow separation can be found on control surface, the wing/fuselage junctures, splitter plate and body flap, mostly on the after body, in the wake region. The hypersonic separation and reattachment involve the strong shock and expansion waves, which is called hypersonic effects. The interaction between separation/reattachment, shock waves and the geometry lead to a very complicated physics in the flow. Currently there are still no methods provide accurate prediction of the flow field on such complicated three-dimensional bodies. Consequently, there is a requirement for detailed investigations to understand the three-dimensional hypersonic separated/reattached flow.

Among various flow pattern involving flow separation, backward-facing step (BFS) flow is one of the most representative geometries for study on fluid dynamics. BFS flow can be found commonly in various applications, such as the inlet of combustor, flow behind a vehicle, flow over an airfoil at high angle of attack, the flow around spoiler and control surface. BFS has also been widely discussed in studies of the separated/reattached flow as it has a sudden discontinuity and lower wall. The separated and reattached flow is a classic phenomenon which describes the flow passes over a sudden expansion and attaches to the wall again in a downstream region. Despite its simplicity in geometry, the hypersonic flow over a three-dimensional BFS reproduces various flow phenomenon in three-dimensional hypersonic separated/reattached flow, which include three-dimensional recirculation bubble, reattachment, separation and induced longitudinal vortices. For external flow, the interactions of longitudinal vortices with recirculation bubble, reattachment and induced secondary separation can be found in the wake region of hypersonic flow over a three-dimensional BFS. As a consequent, three-dimensional BFS can provide a benchmark for studying the complicated hypersonic separation and reattachment in the wake region.

The basic flow characteristics behind a backward-facing step is shown in Figure 1.1. As the hypersonic flow passes over a backward-facing step, the sudden expansion step causes separation. The flow curves toward the lower surface and reattaches downstream of the step, which results in the production of adverse pressure gradient. Part of the shear layer fluid is deflected upstream, resulting recirculation region, a low-pressure flow made of `dead` air. The reattachment causes the formation of localized high pressure and reattachment shock. The backward-facing step gives an ideal and relatively simple way for investigating the phenomenon of interest occurs in hypersonic separated/reattached flow.

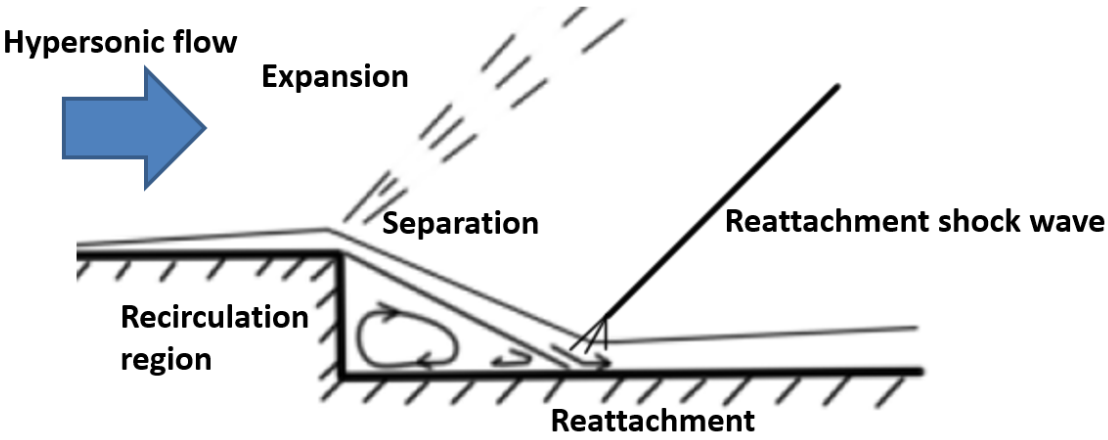

Fig. 1.1. Schematic of hypersonic flow over backward-facing step

The flow over a BFS is known to be related to the enhancement of drag and noise, and additional heat transfer, which usually have a negative impact on overall performance of an aerodynamic device. Therefore, the hypersonic flow over a backward-facing step has been extensively studied by experimental and numerical work.

Although the two-dimensional discussions of hypersonic BFS flow has been widely studied by various methods, its three-dimensional nature in engineering applications as well as experimental models has not yet been much investigated. Bernal and Roshko reported the 3-D structure and its extension after separation observed in experiment of BFS flow [2], which indicates the three-dimensional and complicated happenings in this flow. Different from 2D BFS flow, the 3-D BFS flow involves the flow separation of the mainstream and the effects of lateral flow, which is not included in the flow field of 2D BFS. Three-dimensional BFS in hypersonic flow plays an important role in some aerospace applications, especially for space shuttles, future spaceplanes and Crew Return Vehicle (CRV). BFS configuration which can be found at the flaps or control surface in the vehicle afterbody, as shown in Fig. 1.2. the This requires a further discussion on the BFS flow being tested in hypersonic experiments.

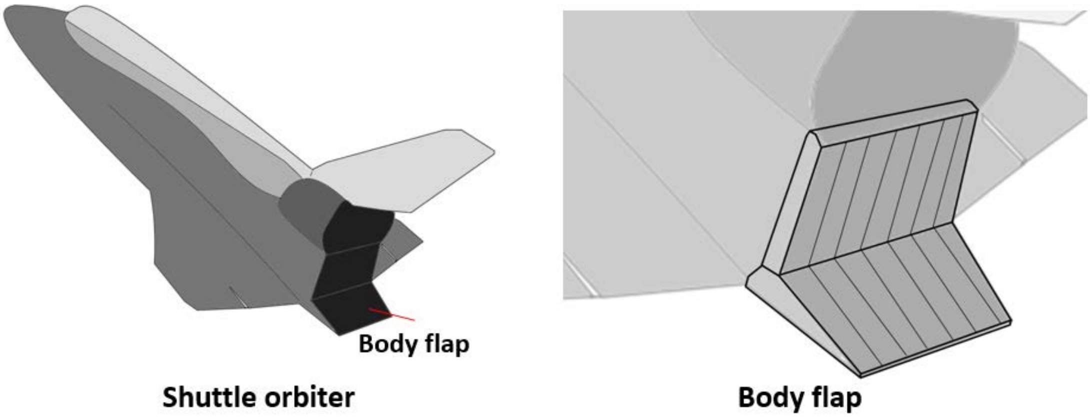

Fig. 1.2. Three-dimensional BFS configuration in space shuttle — body flap

In this thesis, the introduction is divided into four sections. In the following sections, a literature review is performed for the historical background of study on hypersonic separated/reattached flow and a variety investigations of hypersonic backward-facing step flows. An explanation of key findings will be also present.

1.2 Backward-Facing Step

Backward-facing step has been studied as an important configuration in fluid dynamics for more than 50 years. Early experimental studies were conducted on step models in the flow field in 1950s and 1960s [4][5] For example, experiments on the separation and reattachment of a rearward-facing step in a flat plate airfoil were conducted by Moore. The findings related the separated/reattached flow to the stall of the airfoil. In 1970s and 1980s, more detailed studies of the BFS were published, which mainly focused on the parametric study of the effect of step height, freestream velocity and wall temperature, etc.[6][7]. A study on flow over backward-facing steps with different step heights was reported by Thangam[8]. The effect of step height on the reattachment length is demonstrated. Test of heat transfer on a BFS model had also been a hot topic for meeting the needs of the thermal protection design in aerospace industry. In late 1980s and 1990s, with the development of computational capacities, researchers have begun to study the flow field of BFS by applying CFD. Experiments, which can serve as a validation for computational models, were also been conducted extensively for the improvement of numerical methods[9]. In recent years, extensive studies with combination of experiments and numerical simulations of different types of BFS flow(hypersonic BFS flow, microscale flow, chemical flow, etc.) have been reported by many researchers[10][11].

1.2.1 General Properties of BFS Flow

To understand the physics of a complex three-dimensional BFS flow, it is appropriate to start with a two-dimension one with the general properties recognized in many literatures. The major features of BFS is also generally include three regions: separated shear layer, recirculation region and the reattachment region. The flow over a backward-facing step separates from the sudden step. As a result, the flow behind the backward-facing step becomes complicated. In the region of the corner near the step, a low-pressure zone with large separation vortices, called recirculation bubble is formed. Between the recirculation bubble and the freestream, a separated shear layer can be found. After separation, the flow starts accelerating away from the recirculation region then develops, finally form the reattachment on downstream surface.

Under a viewpoint of aerodynamics, the base drag induced by a partial vacuum in the wake region, which contributes a major portion of the drag of a vehicle, has been reported to be connected with the recirculation by many researchers[12][13]. Behind the backward step, it is found that this acceleration and formation of reattachment can cause impingement, buffeting on the vehicle body and increase in heat transfer. The separated shear layer can be also widely seen in study on aerodynamic characteristics of BFS flow[14]. However, due to the different Re numbers, many factors in tests and their complex interactions, the results differ in basic flow features, which indicates that the flow physics of BFS flow is very complex and the flow may also become turbulent in part of the research results. It is therefore difficult for general discussion in separated shear layer within the scope of this study. Therefore, recirculation and reattachment, which are other two key features of the BFS flow, are focused in this study. The recirculation due to the partial vacuum has been discussed in all speed range. For high speed flow, the reattachment following expansion wave and reattachment-induced shock wave are appearing specifically. A detailed discussion of the studies on recirculation and reattachment will be performed in next section.

1.2.2 Recirculation

In the wake of backward-facing step, the vortices in separated shear layer and the paired adjacent vortices form a coherent structure. This structure causes the entrainment of the fluid from below the shear layer, which creates a low-pressure zone and induces the formation of the recirculation. The velocity within the recirculation region is low due to the large vortex structure. This low-pressure region is also referred as the separation bubble, as shown in Fig. 1.3.

Recirculation has significant effect on aerodynamic drag. For example, on an aerospace vehicle, a considerable aerodynamic drag is generated by the low pressure acting on its base. The reduction of this kind of drag, called base drag, plays an important role in the design of high-efficiency vehicles.

To achieve this goal, a deeper understanding of the recirculation region of BFS flow is necessary. Moore was one of the earlier researchers to conduct experiments on the separation bubble at a BFS on an airfoil [15]. This experiment included pressure measurements, Pitot explorations, liquid film and smoke studies on the bubble which forms on a thin airfoil near the stall. He found the critical Reynolds number for the value given by the Owen-KIanfer criterion.

After that, extensive study of the basic recirculation characteristics has been conducted by W.D. Moss and S. Baker [16]. Moss and Baker conducted measurements of recirculating flow with three simple geometries, including a backward-facing step. The flow velocity was measured by the use of pulsed-wire anemometer. Surface pressure and shear stresses are also measured for comparison between these shear layers and the plane mixing layer. The results can be helpful in providing data with which to test the validity of mathematical models applied to recirculating flows.

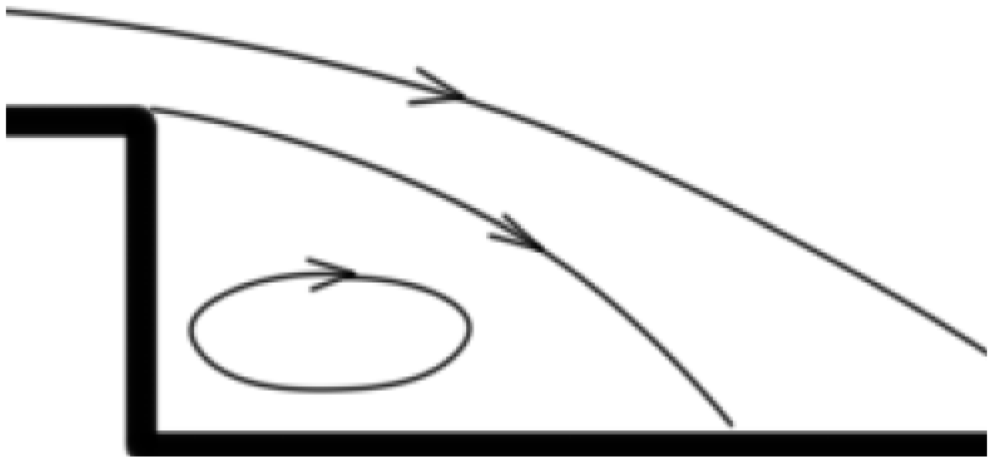

Fig. 1.3. Recirculation of BFS flow

Apart from study on parameters defining the recirculating flows, efforts have been contributed to identify the relationship between base drag and recirculation and its mechanism. Experimental study on detailed flow field have been conducted by many researchers. An extensive measurement including wall pressure distribution and velocity field downstream a BFS was conducted by Hudy using Wall-Pressure Microphone Array and planer PIV [17]. Typical mean velocity distributions have been acquired in this study. The velocity distribution of recirculating region visualized the vortex structure including a primary and secondary recirculation, which indicates the origin of low pressure and its connection with the recirculation.

A comprehensive study on the recirculation and base drag was conducted by Mariotti [18]. The variation of the base drag caused by modifications of separating flow and the induced recirculation is analyzed through experiments, Variational Multi-Scale Large-Eddy Simulations (VMS-LES) and Direct Numerical Simulations (DNS). The results of experiments, VMS-LES and DNS simulations show that an increase of the base pressure and thus a decrease of the base drag may be obtained by increasing the boundary layer thickness before separation, which causes a proportional increase of the length of the mean recirculation region behind the body. The Reynolds number effects on the variation of recirculation length is also reported by Jovic[19], which indicates the relationship between Reynolds number, recirculation region and base drag.

With the advent of CFD technology, more numerical studies can be found in recent years including deeper analysis of the flow physics of the recirculation on backward-facing step[20][21]. These simulations have attained extensive description of the recirculating flow by analyzing the pressure distribution, velocity profile and Reynolds stress components, etc. However, the recirculation of BFS flow is still not fully established and each study tends to explain the flow field under specific conditions, which limits the generalizations in study of BFS flow.

1.2.3 Reattachment

After the separation from the backward-facing step, the flow above shear layer starts accelerating away from the recirculation region behind the step. The streamlines curve

towards the wall until the shear layer reattaches at the reattachment point. This type of flow phenomenon is referred as the reattachment. The acceleration of the reattached flow leads to a local high pressure, which can also form recompression waves in supersonic flow. The adverse pressure gradient induced by the reattachment can be found downstream of the recirculation region, as shown in Fig. 1.4. Part of the shear layer can be deflected into the recirculation. The flow features of BFS flow, including recirculation, reattachment and separated shear layer, are indeed correlated with each other, which make this kind of flow very complicated. Among these flow features, the reattachment and the parametric effects on it are most widely studied. The reattachment length is considered as one of the most representative parameters for investigation of BFS flow for the convenience of visualization and measurement.

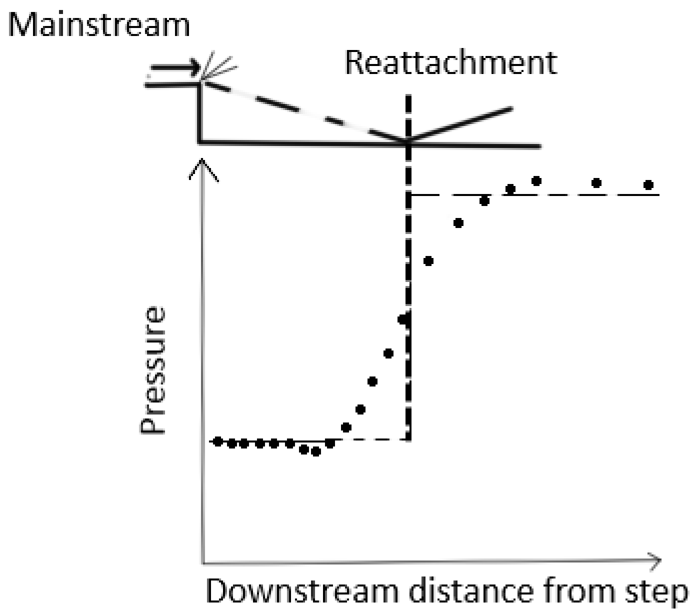

Fig. 1.4. Reattachment and pressure profile

In recent years, both experimental and numerical studies on reattachment of BFS flow has been carried out. Experimental studies are mainly focused on the measurement and discussion of reattachment length. While CFD can provide precise reattachment point. A wide range of Reynolds number based on step height has been tested by many researchers[22][23]. Noriyuki Furuichi conducted measurements of velocity field at reattachment region of a two-dimensional BFS using a multi-point LDV[22]. Isomoto and Honami presented study on the behavior of a separated shear layer over a backward-facing step and its reattachment. The moving path of vortex is observed carefully. They found that the reattachment length is a strongly negative correlated with the maximum turbulence intensity of the flow near the separation region. The mechanism of reattachment length reduced by the shedding of the vortex is also reported in the experimental study by Noriyuki Furuichi[22].

For applications in aerospace industry, the effects of reattachment on heat transfer rate are one of the most important problems for the thermal protection design. However, this aspect of BFS flow has rarely been discussed for lack of experimental results. Guo investigated the heat transfer effects on BFS flow by defining the concept of thermal drag, the thermally induced inertia force[24]. It is found that the falling pressure gradient tends to be proportional to local heat flux.

Besides the studies on reattachment, some researchers reported the correlations between reattachment, recirculation, separated shear layer and other flow features of BFS flow. These flow features are indeed closely related but few studies have been focused on their relationship. In the experimental study of Nadge and Govardhan [25], the multi-factors are discussed for BFS flows. In this study, the reattachment length is seen to increase at lower Reynolds number till around 20,000, above which it saturates and becomes nearly independent of Reynolds number. However, the streamwise length of the secondary bubble decreases for higher Reynolds number, which indicates that saturation of the reattachment length with Reynolds number does not necessarily mean that the mean flow structure has become saturated.

For high speed flow, the reattachment involves the recompression after the expansion due to the compressibility effects on the gas. As discussed above, the recompression of the curving flow in hypersonic generates a shock wave, which significantly affect the flow field behind the reattachment. The recompression leads to local pressure peak and concentrated heating. Roshko has conducted experiments to observe and measure the reattachment behind a BFS in high speed flow. The flow downstream reattachment has been visualized and the peak pressure occurs at the point just after the reattachment.

In summary, the reattachment has been studied via variety of methods. The heat transfer and pressure distribution characteristics, which show different trends under various inflow parameters, have significant effects on the flow field. The flow behind the BFS becomes complicated due to the interaction and correlations between separation, recirculation and reattachment. In high speed flow, the recompression of the reattached flow and induced shock wave play an important role in the flow field of reattachment.

1.2.4 Flow Control

Based on the understanding of BFS flow characteristics, researchers have conducted studies on control of BFS flow, aiming at the reduction of separation and thermal control. Control methods including the plasma actuation, perturbation/excitation, synthetic jet, and g vortex generation and others have been applied to BFS flow. An example of active flow control by jet is shown in Fig. 1.5.

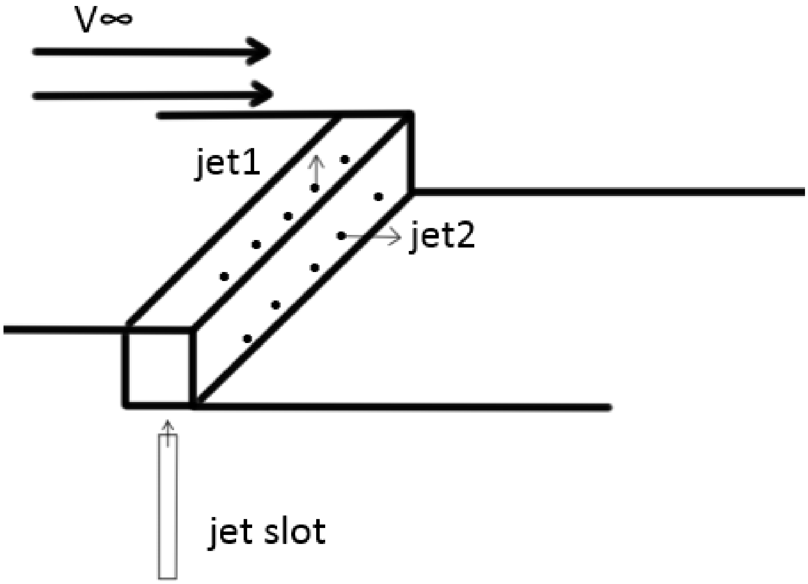

Fig. 1.5. Active flow control of BFS flow with jet

Plasma actuation control for separation flow has also been extended by several groups that focused on the active process with Single Dielectric Barrier Discharge (SDBD) actuators H. Matsuda used DBD plasma actuators to reduce separation bubble size in wind tunnel tests (reduced by 9%) [26]. Adamo reduced the bubble length by 37% using DBD plasma actuator [27].

Flow and thermal control downstream of a backward-facing step has been performed in order to achieve heat transfer enhancement by introducing small disturbance with electromagnetic flap actuators on the step edge [28]. Flap oscillation frequency and amplitude were both changed variously under the laminar flow condition.

Due to a stronger effect of flow separation/reattachment in high speed flow, the flow control of hypersonic BFS flow has become an increasingly topic in this research area. In Guo’s numerical study, the active flow control using supersonic jet on a hypersonic BFS flow has been studied by numerical methods[35]. However, flow control at hypersonic speed started fairly late and remains less studied.

1.2.5 Experimental Studies on Hypersonic BFS Flow

The most commonly investigated characteristics of the BFS flow and the flow control methods have been presented in the previous section. In hypersonic flow, which is generally defined as the flow at speeds of Mach 5 and above, the flow control becomes more important due to the occurrence of the shock wave, the severe aerodynamic heating and impingement. Therefore, a systematic study of the hypersonic BFS flow should be necessary for the future development of related fields.

Early experiments for basic flow structure started in 1960s. However, the detailed experimental and numerical studies on the hypersonic BFS flow characteristics cannot be found until recent years.

The extreme high speed and high temperature of the hypersonic flow pose an obstacle to measurements in the hypersonic flow. Although the new experimental methods have been introduced to the investigation in recent years, reliable experimental data has not been widely seen due to the difficulties of test in hypersonic flow. Apart from the obstacle posed by high enthalpy hypersonic flow, there are only a few hypersonic facilities, especially hypersonic wind tunnel for external flow tests, have been developed by limited organizations. To the best of the author's knowledge, few studies on hypersonic BFS flow have appeared in literature with comprehensive analysis of the flow features.

Reddeppa and Gai conducted detailed measurements of heat transfer rate on backward-facing steps at hypersonic Mach number [29]. Platinum thin-film gauges (PTFGs) have been applied to measure heat fluxes in the applications involving very short duration of the heating environment. The thin-film design of PTFGs can reduce the disturbance of the sensor to the flow field. The measurements of surface convective heat transfer have identified both the flow separation and reattachment points in the hypersonic flow field over backward-facing step models. The variation of measured heat flux values indicates that after flow separation the heat flux values reach the flat plate value. The reattachment length has been measured for two BFS models with different step heights.

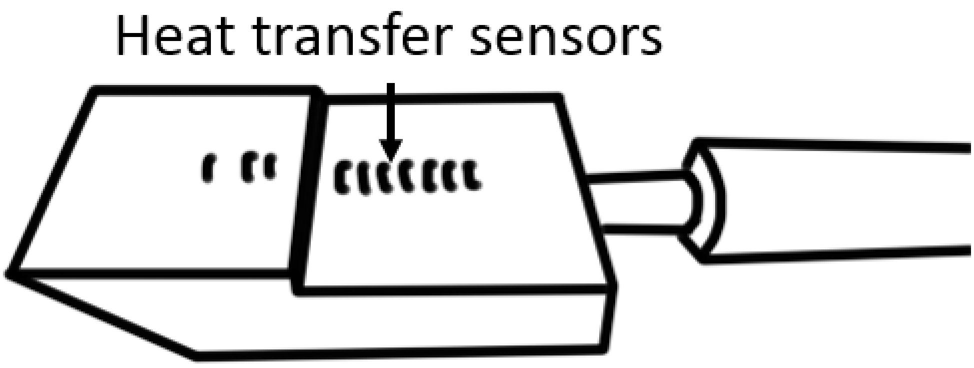

Fig. 1.6. Measurement of heat transfer on BFS[29]

Before the experiment, Gai had conducted theoretical similarity analysis for backward-facing step geometry and the result is compared with heat flux values measured in this experiment [30]. The prediction is consistent with the experimental result. The experimental heat transfer data on the backward-facing step was then used for numerical code validations in the numerical studies.

PIV measurements were widely performed in measuring and visualizing the recirculation for BFS flow. However, in hypersonic wind tunnel, the BFS model is usually mm scale. Due to the low spatial resolution. Nano-tracer planar laser scattering (NPLS) is a new flow visualization technique for measuring fine structures of supersonic and hypersonic flow. The measurement has been carried out by Chen at speed of Mach number 3 and 3.8 [31][31]. The visualization of the flow structures, including supersonic laminar boundary layer, separation, reattachment, redeveloping turbulent boundary layer, expansion wave fan and reattachment shock with high spatial resolution has been obtained. Compression wave and the developing boundary layer behind the reattachment were revealed via NPLS. Although the Mach number in this study is lower than Mach 5, the expansion fan and weak reattachment shock wave in of the flow field of BFS can be recognized clearly, which is useful for understanding hypersonic BFS flow.

In these studies, the inflow parameters, which is generally depended on the hypersonic wind tunnel apparatus, varies with the Reynolds number, speed and temperature. The step size and design variation of the BFS model in the tests also leaded to different flow trends which indicates a more complex physics of hypersonic BFS flow. Assuming hypersonic flow over the backward-facing step, the expansion fan occurs at the corner of the step. After separation, the acceleration of the flow eventually forms a reattachment shock wave away from the boundary layer. A strong adverse pressure gradient is generated by hypersonic reattachment downstream the recirculation bubble. Compared with the general low speed BFS flow, the discontinuities in the hypersonic BFS makes the flow field much more complicated.

However, as discussed above, there is still a lack of experimental data in the hypersonic regions. No general discussion/comparisons have been conducted yet for the detailed mechanism of interactions between separation, expansion, recirculation reattachment, and reattachment shock wave.

From the viewpoint of experimental validation of numerical simulation, the studies mentioned above cannot provide extensive experimental results for quantitative verification of numerical methods. The measurements of heat transfer rate have been confined to several discrete points align on the center line of the BFS model in the studies of Reddeppa and Gai [29][30]. The information of heat transfer variation resulting from the separation and reattachment is insufficient for understanding the whole flow field of hypersonic BFS. Considering the heat transfer rate of hypersonic BFS, the numerical simulation involves the problem of coupled thermal fluid-structure interaction, which is still uncleared for hypersonic flow. Therefore, general comparison between experimental and numerical results has rarely been conducted. For the measurement of flow structure by NPLS, quantitative result is limited to the density field visualized by the tracer particles. Therefore, efforts need to be made to obtain generalized in-depth understanding of hypersonic BFS flow and better validation data set.

1.2.6 Numerical Studies on Hypersonic BFS Flow

The numerical studies of hypersonic flow can be widely seen in literature these years. Different from experiments on hypersonic flow, the inflow parameters are not limited by the hypersonic facilities in numerical simulation. Represented studies include the numerical simulation conducted by Deepak and Gai using compressible multi-block Navier-stokes solvers[30][32]. Solvers applied in their simulation has been experimentally validated. The flow separation and reattachment under both suborbital and super orbital conditions have been analyzed in this numerical study.

It needs to be mentioned that the influence of real gas effects has been identified and shown to be negligible in the numerical simulation discussed above, while some researchers point out that as the rarefaction degree increases, the theoretical assumption in the conventional constitutive relations for continuous flow, such as the Navier-Stokes equation, loses its validity[33], whereas the Boltzmann equation is able to describe the behavior of a gas flow at every rarefaction degree. The Boltzmann equation can be solved by stochastic schemes, commonly known as DSMC. DSMC is widely used to simulate the rarefied hypersonic flow, which can be found in entry/reentry and hypersonic cruise in near space.

Computations of a rarefied hypersonic flow on backward-facing steps have been performed by using the Direct Simulation Monte Carlo method [34]. DSMC has also been employed to numerically investigate the flow characteristics of a hypersonic BFS configuration in near space in detail by considering the cases of the basic BFS at a wide range of altitudes 20–80 km and the BFS baseline under active flow control[35]. The altitude has an important influence on flow characteristics of the basic BFS. The effects of flow control by jet have also been revealed clearly.

It is well known that the cost of numerical simulation on hypersonic flow is much lower than experimental measurements. With the advent of computational capability, more accurate simulation for different inflow parameters and design of BFS model with flow control can be carried out by CFD conveniently. Therefore, CFD is expected to play an important role in generalized and deep-in study of hypersonic BFS flow. However, due to the lack of reliable experimental data at hypersonic condition, systematic validation of CFD methods are rarely seen in the literature. The validation of computational code through comparison of limited experimental data and results obtained by different numerical methods, is insufficient and makes a numerical computation based on this validation questionable. To solve this issue, better validation data set including direct measurements of the separation and reattachment region, pressure and velocity distribution are necessary.

1.2.7 Three-dimensional Effect on Hypersonic BFS Flow

As discussed in prior sections, most studies are focused on the two-dimensional hypersonic BFS flow, in both experiments and numerical simulations.

In hypersonic flow, due to the high cost of energy consumption of the exhausting working air and the restricted inflow conditions in hypersonic wind tunnel, CFD provides a more convenient method to obtain numerical predictions of different flow conditions and geometric designs. However, the validity of a numerical simulation strongly dependent on experimental verification.

The verification in existing research was conducted by comparing the two-dimensional numerical results and quasi-two-dimensional experimental results or flow structure visualization, which are based on two-dimensional flow hypothesis. However, the three-dimensional structure and effects in both external and internal flow have indeed been reported by researchers [36][37].

In the study of water BFS flow by Bernal and Roshko [2], fluid from the sides is entrained at spanwise positions where the induced velocity of the secondary vortices is directed towards the spanwise vortex cores. Similar entrainment of the air flow from the open sides of a 3D BFS model was also reported by Tiney [38].

The BFS model for wind tunnel test is a three-dimensional configuration in the real world. The span size of model will also affect the flow behaviors behind the step. As discussed by Jovic on the multi-factors for BFS flows, the step width in the experimental settings needs to be set relatively large to avoid 3D effects during the measurement [39]. Although such statement can be seen in most 2D studies of BFS flow, it has not been well established in studies on hypersonic BFS flow. Experimental measurements of hypersonic BFS flow encounter an obstacle of limited size in the test section, which usually has a nozzle diameter around 200 mm for educational hypersonic wind tunnel. Increasing spanwise is achieved at the expense of step height on such small-scale model, which is usually under 5 mm. The small-scale model leads to the decrease in reattachment length and size of recirculation region and demands extremely high resolution which is usually out of the specification of current experimental apparatus. For example, the pressure sensors for measurement cannot be aligned too concentratedly. It is also difficult for cameras to capture a flow field within only a few square mm. In this situation, the 3D effects cannot be totally avoided.

The 3D effects observed in general low-speed BFS flow includes entrainment at the separation region near the open side and large vortex structure[40]. In hypersonic flow, 3D effects can strongly affect the flow field, while few studies included discussion on 3D effects on hypersonic BFS flow.

1.3 Motivation and Objectives

The separated/reattached flow plays a key role in hypersonic flow. In most applications and real-world simulation, the separated/reattached flows become more complicated and have an important effect on the aerodynamic characteristics. However, the hypersonic three-dimensional separated/reattached flow has been less well studied, mainly because of the difficulties in experiments and numerical simulations at hypersonic condition.

BFS is one of the key models for studying separated and reattached flow. Investigation have been carried out on hypersonic flow over BFS these years. However, detailed three-dimensional experimental measurement and numerical simulation have not been achieved. Experimental studies are limited to measurements on discrete points. Few detailed quantitative measurements of the whole flow field have been conducted. On the other hand, CFD can be employed for efficient investigation of flow feature variations with various inflow conditions and BFS designs. However, most of the numerical simulations of hypersonic BFS flow are carried out under two-dimensional condition.

In the studies on two-dimensional BFS flow, only the 2D recirculation, reattachment and two-dimensional shock wave structures are included in the flow field to be investigated. Concerning the three-dimensional flow separation in the real life, the flow field is totally different from a two-dimensional one. The three-dimensional flow separation involves three-dimensional effects include lateral flow separation, interaction between the mainstream separation/reattachment and the lateral flow. The three-dimensional effects make the flow field much more complicated and have considerable effects on the flow characteristics, which in turn dictate the performance of high-speed vehicles. However, the three-dimensional effects cannot be evaluated by these results of studies under two-dimensional condition.

In contrast, studying the hypersonic flow over a three-dimensional flow can provide a proper replication for the three-dimensional flow field around BFS. In addition, experiments with consideration of three-dimensional effects, provide a sufficient amount of reliable experimental data can provide fully validation for numerical simulation. The 3D effects can be clarified by global measurements to avoid misleading results due to the unmatched flow field in 2D numerical simulation and experimental results, which is indeed three-dimensional.

The hypersonic BFS flow can be found in aerospace applications, such as the body flap of space shuttle, hypersonic flight control surface and the flow around spoiler. The open side or wing-body interaction involving 3D effects on BFS flow may be dominant in the flow. Knowledge of the physics in hypersonic BFS flow based on studies in 2D is insufficient for understanding the complicated flow field behind the step affected by strong 3D effects. The experiments and simulations with the consideration of 3D effects are more suitable for the three-dimensional nature of BFS flow in applications.

From a broader viewpoint of academic study, research works of hypersonic separation and reattachment are mainly focused on 2D flow. 3D BFS can serve as an ideal benchmark which is expected to contribute in exploring the evolution from 2D fluid dynamics to 3D.

Therefore, in order to gain a further understanding of three-dimensional flow field of hypersonic flow over a backward-facing step, this research has following main objectives:

- To observe and measure the three-dimensional flow features of hypersonic flow over a three-dimensional BFS.
- To understand the flow physics of hypersonic three-dimensional separated/reattached flow over a BFS model

Initially, an experimental system for measurements of three-dimensional flow field in hypersonic wind tunnel has been developed in order to overcome the drawback of conventional measuring methods. Further, flow visualization and three-dimensional measurement of flow field around BFS model have been performed at Mach number 7 in hypersonic wind tunnel. The BFS models with different step height have also been tested for parameter study. Later, in other to understand the three dimensionalities of the BFS flow, numerical simulations have been performed for BFS models with different step heights and span lengths. However, it needs to be mentioned that the objective of numerical simulation is not to replicate the experiment precisely, but to understand the three-dimensional flow field around the BFS model and its flow mechanism. The process to achieve the objectives is as follows:

1. The experimental methods including Pressure-sensitive paint, IR thermography, surface oil flow visualization and Schlieren imaging have been applied in hypersonic wind tunnel for comprehensive three-dimensional measurements and visualization of the flow field.

2. The parameter study has been carried on BFS with different step heights to investigate the effect of the geometry parameter on the flow features and characteristics.

3. Numerical simulation of the hypersonic three-dimensional flow over backward-facing step has been conducted to provide information to explain three-dimensional flow motion around the BFS and the flow physics of the complicated three-dimensional flow field.

1.4 Outline of thesis

In chapter 2, the details of experimental facility, experimental methods and system for surface distribution measurement and flow visualization are introduced. A new global pressure measuring method developed in this study, porous-particle PSP is introduced and explained in detail.

In chapter 3, the experimental results of pressure distribution, temperature distribution, surface oil flow visualization and Schlieren imaging are presented and discussed. The data processing of PSP results from luminescent intensity images obtained by high-speed camera is also explained. Unique three-dimensional flow pattern along with hypersonic flow features and the interaction between them are presented. Experimental parameter study has also been conducted on BFS with 3mm, 6mm and 10mm step height to investigate the effect of step height to the three-dimensional flow field.

In chapter 4, the numerical methods applied for CFD of three-dimensional flow field of hypersonic flow over BFS are presented. Special treatment of the computational domain is discussed.

In chapter 5, the numerical results are discussed for hypersonic flow field around the three-dimensional BFS. The three-dimensional flow features are discussed by visualizing the flow field by post processing the data of numerical results. Three-dimensional flow features on BFS including 'Twin peaks' structure, three-dimensional recirculation and reattachment, lateral separation and longitudinal vortices are introduced.

In chapter 6, a discussion of the mechanism of formation of three-dimensional flow features of hypersonic flow over a 3D BFS has been presented based on the experimental and numerical simulation. Detailed discussion of the flow physics of 3D recirculation bubbles, longitudinal vortices and 'Twin peaks' structure, the interaction between second separation of longitudinal vortices flow and 3D reattached flow is given in this chapter.

In chapter 7, the results are concluded. The road map of the study to achieve the final goal is shown in Fig. 1. 7.

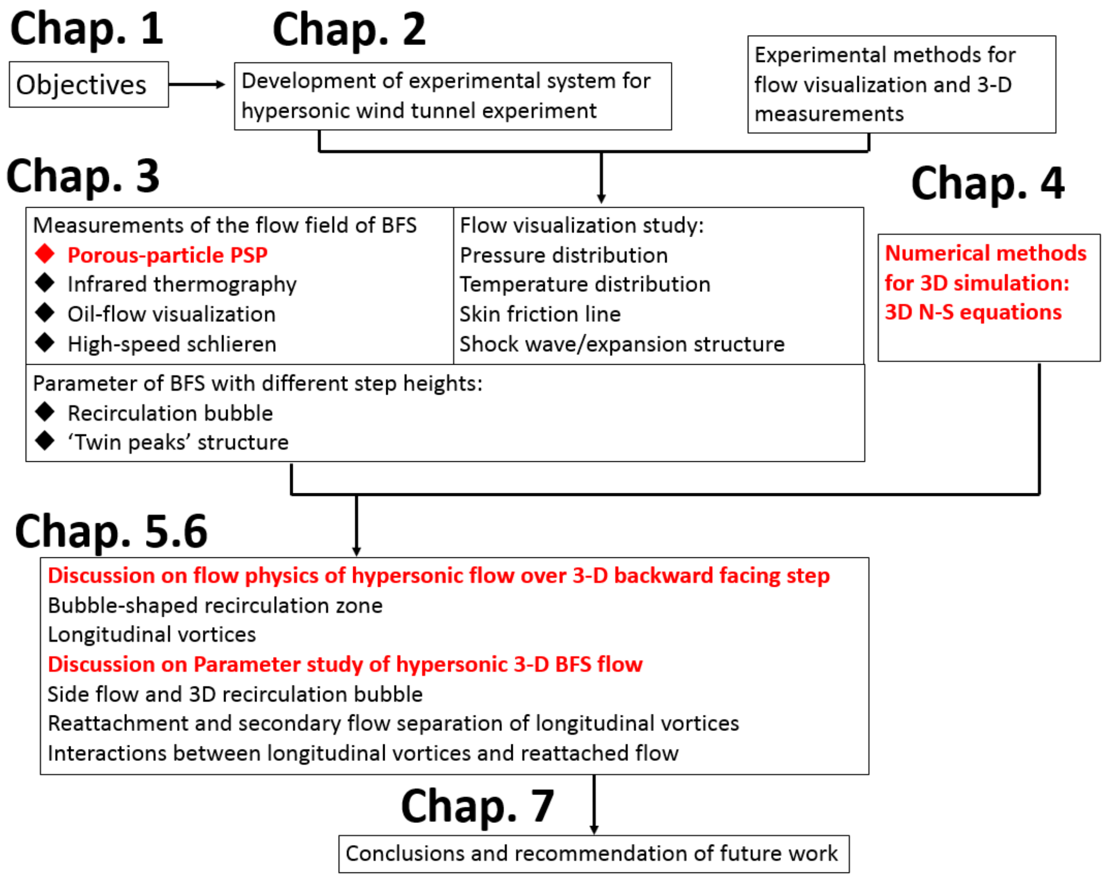

Fig. 1.7. Road map of the study

Chapter 2-6 (pp. 37 to 136) of my doctoral thesis cannot be made public on the Internet for 5 years from the date of doctoral degree conferral because that part has been accepted for publication. *

7 Conclusion

7.1 Summary and conclusion

In this study, the objective is to investigate the three-dimensional hypersonic flow over a backward-facing step. Various experimental methods and numerical simulation are applied to establish the three-dimensional effects on the flow field behind a backward-facing step. The objective has been achieved and conclusions are shown as follows:

1. An experimental system for measurements of three-dimensional flow field in hypersonic wind tunnel has been developed.

- A new PSP technology with high robustness and fast response has been developed by using inorganic spherical porous particles. In this method, the model surface is coated with PSP particles. As a result, this new PSP technique, named PP-PSP is a sprayable method with a good supporting matrix form by porous particles with nano-open structure. This PSP technique is good in ease of use with non-toxic materials and has fast response and high robustness.
- Experimental technologies comprised of various global measuring methods, including IR thermography, surface oil flow visualization and Schlieren imaging are applied to the simultaneous measurements of backward-facing step model in hypersonic wind tunnel.

2. Experimental measurements and numerical simulation have been carried out on the hypersonic flow over a three-dimensional backward-facing step, key findings are concluded as follows:

- The twin peaks structure has been captured in the experimental results. Separation lines of longitudinal vortices are observed. The experimental results indicate that a highly three-dimensional flow is formed. Flow from the open sides of the model has significant three-dimensional effects on the flow structure.
- The flow fields of backward-facing step model with three different step heights are investigated experimentally. The flow patterns of these different backward-facing step models are compared and discussed.
- The flow features, including recirculation bubble, longitude vortices and reattachment, have been visualized by post-processing of CFD results.

- Recirculation bubble is a horseshoe vortex structure generated by the interaction of side expansion and recirculation. The flow within the recirculation bubble exhibits the rotation corresponding to the foci.
- The longitude vortices form on both sides of the objects because of the transverse entrainment of the fluid have been detected by numerical simulation. The high-pressure and high-temperature region occurring as a 'Twin peaks' structure, is generated by strong down wash produced by the longitudinal vortices and the interaction with reattachment.
- The step height and span length affect the recirculation, longitudinal vortices scale and the reattachment of flow over top surface of backward-facing step and longitudinal vortices flow. This effect results different patterns of interaction between mainstream reattachment and secondary separation flow of longitudinal vortices.

In three-dimensional separated/reattached flow, especially for external flow, the flow field involves the separation/reattachment in the mainstream direction and lateral-flow-induced separation/reattachment. These separated/reattached flows from different directions and the interaction between them dominates the flow characteristics. For hypersonic vehicles, this kind of three-dimensional separated/reattached flow can be found around the discontinuities (e.g., corner flow, body flap and control surface) have significant effects on the flight performance. According to the experimental and numerical results obtained in this study, the effects of three-dimensional separated/reattached flow include three-dimensionalities in pressure distribution, temperature distribution, skin friction coefficient and shock/expansion wave structure. This, in turn, leads to issues such as loss in lift, drag, increased heat transfer, oscillation and noise. For investigation on three-dimensional separated/reattached flow, 3D backward-facing step provides an ideal benchmark providing a complicated flow field with separation/reattachment along the step and lateral separated flow, which induces longitudinal vortices and reattaches the model surface. In addition, backward-facing step can be applied to wind tunnel experiments and numerical simulation conveniently for its geometrical simplicity.

The hypersonic flow over three-dimensional backward-facing step has been studied by experimental measurements and visualization in this study. Furthermore, the whole flow field has been obtained by three-dimensional numerical simulation. Key flow features are visualized by post processing of the numerical results. The unique three-dimensional flow patterns of this kind of flow, including 'Twin peaks' structure, 3D recirculation bubble and longitudinal vortices, indicate the importance of three-dimensional measurements of flow over backward-facing step in hypersonic wind tunnel. The three-dimensional effects are needed to be concerned in the study of this kind of model with separated/reattached flows. From the viewpoint of aerodynamic studies, this research demonstrated the flow characteristics of a hypersonic three-dimensional separation/reattachment of mainstream and lateral flow. This study has also revealed the flow physics of interaction between recirc7ulation bubble, reattachment, longitudinal vortices. The understanding of hypersonic three-dimensional separated/reattached flow should be helpful to the aerodynamic design optimization of hypersonic vehicles.

7.2 Recommendations for future study

In this study, the unique three-dimensional flow field of hypersonic flow over a three-dimensional BFS has been investigated by both experimental and numerical methods. The flow physics has been discussed. However, there remains a number of subjects calling for further study, as exemplified below.

1. In this study, various methods of measurements and flow visualization have been presented. However, improvement in the accuracy of measurement is still sorely needed for a quantitative analysis of the three-dimensional flow field.

2. As the vortex structure has been observed in both experimental and numerical results, visualization methods, e.g. 3D-PIV, 3D-LDV, can be applied to visualize the structure of longitudinal vortices developing along the edge of BFS model. By directly visualizing the vortex structure, more information can be obtained for this key feature on 3D BFS flow and its interaction with hypersonic flow features including recirculation and reattachment shockwave.

3. Three-dimensional numerical simulation has been carried out for the hypersonic flow. Based on the 3D flow field obtained in CFD, careful measurements using multi-point probe measurement technique at the location of the three-dimensional features including 'Twin peaks' structure and longitudinal vortices can be made to gain quantitative information of these 3D flow features.

4. Considering the setup of boundary condition at the current stage, there are some discrepancies between the numerical simulation and testing conditions, as exemplified below. Firstly, the inflow condition in the numerical simulation is simplified and the sharp wedge has not been replicated. Secondly, the adiabatic wall condition is applied in this simulation. As has been observed in the results of temperature distribution, the systems of surrounding gas and the BFS model cannot reach thermal equilibrium during the experiment. In order to replicate the experiment, the heat transfer from air to BFS model should be considered.

5. The parameter study of the step heights and span length has been conducted to investigate the effects of these parameters on the 3D flow field. In hypersonic flow, the step height has significant effects on both the reattachment and longitudinal vortices. The span length can change the pattern of interaction between the vortices pair independently from the step height. There is much room for improvement of a deeper study of this parameter by shifting the set of step heights as well as the span length.

6. The aerodynamic characteristics of 3D BFS in hypersonic flow can be quantitatively investigated by measuring or calculating the lift and drag to evaluate the effects of the three-dimensional hypersonic flow separation/reattachment. The results of this study provide helpful information for establishing the design basis of a hypersonic vehicle.

7. The active/passive flow control is an important topic in the study of high-speed flight to deal with possible extreme flow condition. The flow control at hypersonic speed has been extensively studied in two-dimensional. However, the effects of different flow control techniques on three-dimensional hypersonic flow separation have not been well studied. It can be deduced that the three-dimensional flow field with flow control can be much more complicated due to the interaction between various 3D flow features, including 3D recirculation, reattachment and longitudinal vortices. Consequently, there is a need for further understanding of 3D hypersonic flow field with flow control.

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List of Published and Communicated Papers

1. Ce Zhong, Rei Tomita, Kojiro Suzuki, et al. “Effect of Opposing Multiphase Jet on Hypersonic Flow Around Blunt Body”. IOP Conference Series: Materials Science and Engineering. IOP Publishing, 2017, 249(1): 012014.

2. Ce Zhong, Kojiro Suzuki, Yasumasa Watanabe, “Experimental and Numerical Study of Hypersonic Flow over Backward-Facing Step,” Aerospace Technology Japan. <u>Minor revision</u> (Jan. 21, 2020)

Conferences

1. 14th International Conference on Fluid Control, Measurements, and Visualization (FLUCOME 2017), “Effect of Opposing Multiphase Jet on Hypersonic Flow Around Blunt Body,” Paper ID 614, Oct. 12, 2017, the University of Notre Dame, USA.

2. 第 50 回流体力学講演会, “Application of Porous Micro-particles Coated with PSP to Hypersonic Wind Tunnel Experiments,” Paper ID 3B01, July 6, 2018, Miyazaki, Japan.

3. 32nd ISTS, “Experimental and Numerical Study of Hypersonic Flow over Backward-Facing Step,” Paper ID 190241, June 19, 2019, AOSSA and Happiring, Fukui, Japan.

Appendix A

Validation of the CFD code

The CFD code used in this study has been validated with a typical benchmark case, oblique shock wave on a 15-degree wedge at Mach 2.5 in NASA's CFD work[56]. In order to estimate applicability and validity of the 3D CFD code for simulating hypersonic flow over a 3-D BFS, a 3D CFD on oblique shock wave case has been conducted and the results are compared with which in NASA Validation Archive. This case involves a supersonic flow past a wedge with a half-angle of 15 degrees. The Mach number of freestream is 2.5, the freestream conditions are listed in Table 7. An oblique shock forms as the flow meets the wedge. Numerical result obtained by the CFD code in this study is shown in Fig. A.1. T Comparing with the shock wave figure and comparison data given in Ref. [56], it is found that the flow field captured by current CFD code and the flow characteristics calculated by the current simulation are quite consistent with those from Ref. [56] as shown in Table 8. Therefore, the CFD code for 3-D Navier-stokes equation employed in this study can provide reasonable predictions of the cases considered in this thesis.

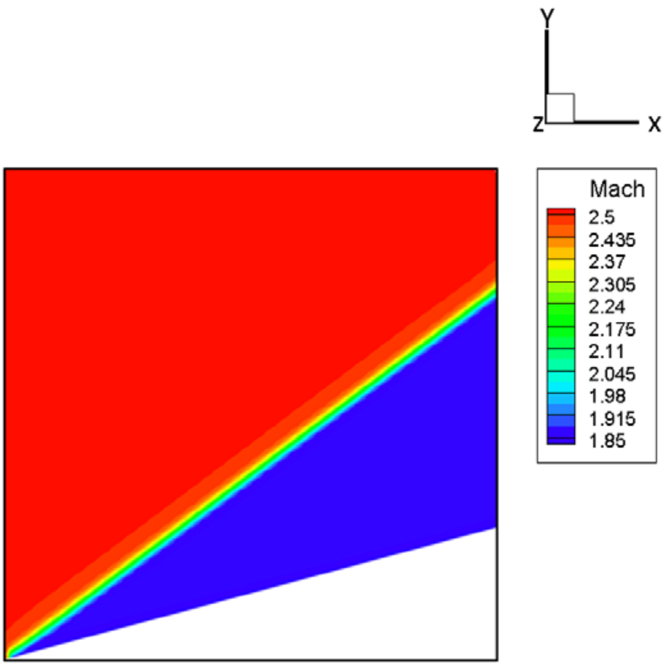

Fig. A.1. Mach number contour for the Mach 2.5 flow past a 15-degree wedge

Mach number	Pressure/kPa	Temperature/K	AoA/deg
2.5	101.3529	288.9	0.0

Table 7. Comparison of the CFD results

	CFD code in this study	NASA Validation Archive
Angle of oblique shock	36.9521 degrees	36.9449 degrees
Mach number behind the oblique shock	1.8752	1.873526
Pressure ratio (p2/p1)	2.4705	2.467500
Density ratio (ρ2/ρ1)	1.8669	1.866549
Temperature ratio (T2/T1)	1.3220	1.321958

Table 8. Comparison of the CFD results