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Experimental Visualization of Hypersonic Boundary Layer Transition

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Abstract

Hypersonic aircraft design faces a significant challenge in the form of aerodynamic heating, exemplified by aircraft like X-51, HGB, and HTV2. Surface temperatures during hypersonic flight can reach extreme levels, up to 2200K, causing severe damage. Aerodynamic heating impacts the aircraft surface and varies with the boundary layer's state. Laminar boundary layers exhibit low heat transfer rates, resulting in minimal damage. However, turbulence drastically increases heat transfer rates, leading to thermal damage. The transition region from laminar to turbulent flow experiences the highest heat transfer rates. To mitigate this, techniques are employed, such as heat shields, surface cooling jets, and porous surfaces, to maintain a laminar boundary layer. The Mack Second Mode instability is a primary trigger for laminar-to-turbulent transition. Delaying this instability through porous surfaces reduces turbulence-related damage. However, applying porous materials across the entire surface increases weight, making selective application crucial. This study aims to visualize the Mack Second Mode and measure surface heat transfer rates to diagnose boundary layer transition.

Keywords Hypersonic Flow*, Boundary layer Transition, Aerothermodynamic, Visualization, Mack Second Mode*

1. Introduction

Aerodynamic heating poses a significant challenge in the design of hypersonic aircraft. Prominent examples of developed or under-development hypersonic aircraft include the X-51, HGB, and HTV2. For instance, the X-51 experiences surface temperatures ranging from approximately 1000 to 2200K, while the HGB can be heated up to 1900K. The HTV2 reaches surface temperatures as high as 2200K, leading to severe damage due to aerodynamic heating during hypersonic operations.

Aerodynamic heating occurring during hypersonic flight has a substantial impact on the surface and is influenced by the state of the boundary layer. In other words, when the boundary layer remains laminar, the heat transfer rate is relatively low, resulting in minimal damage. However, turbulence leads to a significant increase in heat transfer rates, causing severe thermal damage. The transition zone, known as the transition region, where laminar flow shifts to turbulence, experiences the highest heat transfer rates. To mitigate the adverse effects of aerodynamic heating and reduce thermal damage, various techniques are employed either on the entire surface or locally within the transition zone. Common methods for reducing aerodynamic heating include attaching heat shields to surfaces where boundary layer transition and turbulence occur, employing surface cooling through cooling jets across the entire surface or locally, and using porous surfaces to attenuate heat transfer rates. The use of porous surfaces aims to maintain a wider laminar boundary layer instead of transitioning to turbulent flow. One of the primary causes of the transition from laminar to turbulent flow in the boundary layer during hypersonic flight is the development of Mack Second Mode instability. That is, when the Mack Second Mode instability occurs, vibrational activity within the boundary layer increases, leading to turbulence. Delaying the onset of the Mack Second Mode instability redirects instability downstream and delays the transition to high-heat-transfer-rate turbulence. The use of porous surfaces helps reduce this instability by diminishing the vibrational characteristics associated with the Mack Second Mode. However,

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attaching porous surfaces across the entire aircraft surface can increase its weight. Therefore, it is advantageous to apply them selectively to the regions where the Mack Second Mode instability occurs. Predicting the onset of the Mack Second Mode becomes crucial in this context.

Preceding research related to delaying boundary layer transition in hypersonic flow includes the work of Kimmel[1], who researched the use of porous surfaces and localized cooling for controlling heating on hypersonic aircraft. Mack Second Mode instability was confirmed to occur in the 100-500kHz range. Fedorov[2] experimentally verified boundary layer delay by applying a non-uniform mesh coating on a 7-degree half-angle cone.

Most previous research has focused on boundary layer transition flow using models that employ cones and wedges. There need to be more cases that visualize boundary layer transition and provide quantitative analysis in the context of flat plate models without wedge angles. Therefore, this study aims to qualitatively and quantitatively visualize boundary layer transition flow in flat plate models, highlighting the differences in boundary layer behavior compared to cone models using a hypersonic shock tunnel. The observation of boundary layer transition was facilitated using Schlieren techniques, and for quantitative analysis, coaxial thermocouples and PCB pressure sensors were employed.

2. Experimental Setup

2.1. Hypersonic Shock tunnel

The experiments in this study were performed in a typical hypersonic shock tunnel. This facility comprises indispensable components, including a driver tube, a driven tube, a contoured nozzle, a test section, and a dump tank. The facility used are depicted in Fig. 1. The driver tube and driven tube exhibit dimensions of 1.5 m and 7 m, respectively. Concurrently, the remaining tunnel components collectively measure 4.1 m in length. Consequently, the overall extent of the shock tunnel length 12.6 m. The stagnation flow formed at high temperature and pressure values in the driven tube expands through a hypersonic contoured nozzle with a 200 mm exit diameter. The desired hypersonic flow is achieved in the test section. The shock tunnel operating conditions are the stagnation pressure and Enthalpy of 0.8~7.0 MPa and 0.5~2.1 MJ/kg, respectively. The freestream in the test section has a Mach number of 7.0 and Reynolds number of 1e6~1.2e7 /m.

Fig 1. Hypersonic Shock tunnel(IJST2)

2.2. Test Model

In this study, two distinct model configurations were employed. These included a 7-degree half-angle cone shape and a flat configuration. For the 7-degree configuration, both sharp and blunt nose designs were utilized.

3. Result

In this study, experiments were conducted under high Reynolds number and high enthalpy conditions. The experimental visualization was primarily centered, and the flat plate experiments were conducted by varying the Reynolds numbers. Initially, at a low Reynolds number condition (3.51e6 /m), the experimental results revealed the observation of the Speckled Pattern characteristic of the Mack Second Mode at 370mm downstream. At an intermediate Reynolds number condition (6.01e6 /m), the boundary layer was observed to form at 320mm, while at a high Reynolds number condition (1.2*1e7 /m), the boundary layer was observed to form at 295mm. Similar observations were made for the heat transfer rate, which exhibited a sharp increase at specific transition points. In summary, similar observations were made in the flat plate model, and the transition points were observed to shift with changes in Reynolds numbers. The overall transition phenomena are depicted in Figure 2.

Fig 2. Visualizing Boundary Transition on the Flat Model

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