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Mach 3 Turbulent Boundary Layer Measurement over a Flat Plate Using the Particle Image Velocimetry

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Abstract
This study investigates the velocity profile of turbulent boundary layer using Particle Image Velocimetry(PIV) on the flat plate at Mach 2.96. In order to proceed with the study of the boundary layer, Schlieren visualization and PIV are used to confirm whether the oblique shock wave generated from the leading edge affects the flow field on the flat plate. In the turbulent boundary layer, considering compressibility effects, the Van Driest transformed velocity satisfies the incompressible log-law and the log region extends farther in the wall-normal direction compared to the log region in incompressible boundary layer.

1. Introduction

In aerospace, it is very important to accurately measure the friction force and temperature of high-speed vehicle surfaces. Friction and heat load applied to high-speed vehicles are important design factors to reduce weight and increase propulsion efficiency. In particular, shock wave-boundary layer interaction in scramjet results in pressure loss, flow unsteadiness and local thermal loads, which are closely related to flow separation[1]. The flow separation is determined by the strength of the shock wave and the state of the boundary layer (laminar / transitional / turbulent). In general, if the strength of the shock wave is the same, the laminar boundary layer is more likely to be separated than the turbulent boundary layer[2]. It is therefore important to accurately predict the location and size of the transition region to control flow separation in the scramjet.

As a result, a better understanding of the compressible boundary layer is needed to predict complex flow phenomena such as shock wave and boundary layer interactions. Especially, although the study on the compressible boundary layer on the flat plate is a classical subject[3-5], the research is continuing recently.

For decades, research on turbulence has generated considerable interest. However, due to the inherent nature of the turbulence, most studies have been conducted on simple flows such as flat plates. Previous studies have made great progress in the field of turbulence, but most of the work is confined to the incompressible turbulent boundary layer, and the study of compressible turbulence is still lacking[6].

The Reynolds number is the most important variable in the incompressible turbulent boundary layer. However, in the case of compressible turbulent flow, Mach number is also added as an important parameter. The no-slip condition keeps the subsonic region near the wall, and as the Mach number increases, the sonic line is very close to the wall. In addition, viscous dissipation near the wall causes a significant temperature gradient in the boundary layer. Due to this change in static temperature, compressible turbulent flow has a low density and high viscosity near the wall. As a result, the mass flux profile is distorted, the compressible boundary layer becomes thicker than the incompressible boundary layer, and the viscous effect becomes more important than the subsonic flow with the same Reynolds number[7].

Some researchers have simply described the above phenomenon as a change in the flow property due to the temperature gradient of the incompressible boundary layer heated by the surface. Morkovin explained that if the turbulent Mach number in the boundary layer is smaller than 0.3, the compressibility effect does not directly affect the turbulence and the compressible boundary layer is similar to the incompressible boundary layer[8]. Other studies have also shown that supersonic boundary layer and incompressible boundary layer are very similar over a flat plate[9].

Recent experimental results, however, show that the velocity distribution in the compressible turbulent boundary layer is different from the velocity distribution in the incompressible turbulent boundary layer. Lin et al. showed a compressibility effect such that the turbulent Mach number measured in the boundary layer for the Mach 3 was smaller than the value suggested by Morkovin but the position of the end of the log region in the turbulent boundary layer was farther away from the wall than the incompressible turbulent boundary layer[6]. Robinson[10],

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Kistler[11], and Ganapathisubramani[12] also confirmed that the end of the log region in the compressible turbulent boundary layer was further away from the wall. However, it is not yet clear why the end position of the log region in the compressible turbulent boundary layer is farther away from the wall than the incompressible turbulent boundary layer.

2. Experimental Set-up

2.1 Experimental Facility

The experiment was conducted in the Model Aerodynamics Facility (MAF) of Konkuk University. The MAF is a supersonic blowdown wind tunnel. The compressed air inside the reservoir is used at 135 bar, and the run time is approximately 3 seconds. The nozzle exit diameter is 100 mm, and the test section dimension is 360(W) x 200(L) x 226(H) mm^3. In the present work, the stagnation pressure measured in the settling chamber is 762 kPa and the stagnation temperature is 287.85 K. The freestream Mach number in the test section is 2.96. The Mach number was calculated by the ratio of the stagnation pressure in the test section and the stagnation pressure in the settling chamber measured using the Pitot tube. The flow conditions are given in Table 1.

Table 1. Flow conditions

Parameter	Quantity
M_∞	2.96
P_∞ [kPa]	22.03
T_∞ [K]	104.58
Re [m^{-1}]	6.13 x 10^7
U_∞ [m/s]	606.84

2.2 PIV Technique

As shown in Fig. 1, the PIV measurement was performed with the PCO 1600 CCD camera placed on side of the tunnel. The boundary layer is described in a Cartesian coordinate system, where x, y denote the streamwise, wall-normal directions, respectively. The respective velocity fields are denoted by u, v. The instantaneous velocity fields were measured in a streamwise, wall-normal plane(xy) along the spanwise centerline of the test section. The resolution of the CCD camera is 1600 × 1200 pixels, which is cropped in the wall-normal direction from 1200 to 550 pixels to increase the frame rate. The camera was equipped with a 100 mm Macro lens and 13 mm, and 31mm extension

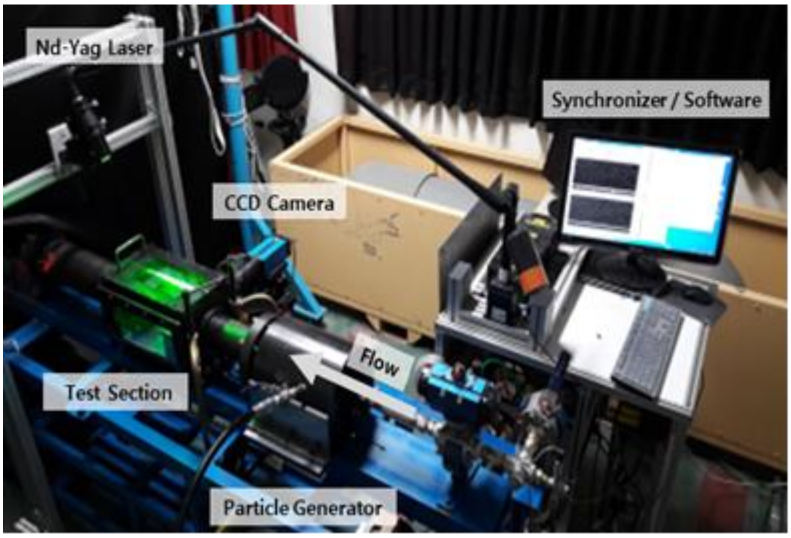

Figure 1 : Configuration of a PIV experiment

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tubes in order to enlarge the field of view by reducing the focal length. The field of view was 12.6 mm × 5.5 mm with a spatial resolution of 127.3 pixels/mm.

Titanium dioxide(TiO_2) particles with a nominal diameter of 200 nm were adopted as the tracer particles, and molar mass is 79.90 g/mol. The seeded flow was illuminated by a double-pulse Nd:YAG laser, which is operated at a laser power of 145 mJ per pulse. The interval between the pulses is 1 μs, and the distance that the particles move during this time is 0.6 mm(77 pixels). The laser beam is adapted by an articulated arm and focused as a uniform sheet with 1 mm thickness by a cylindrical lens.

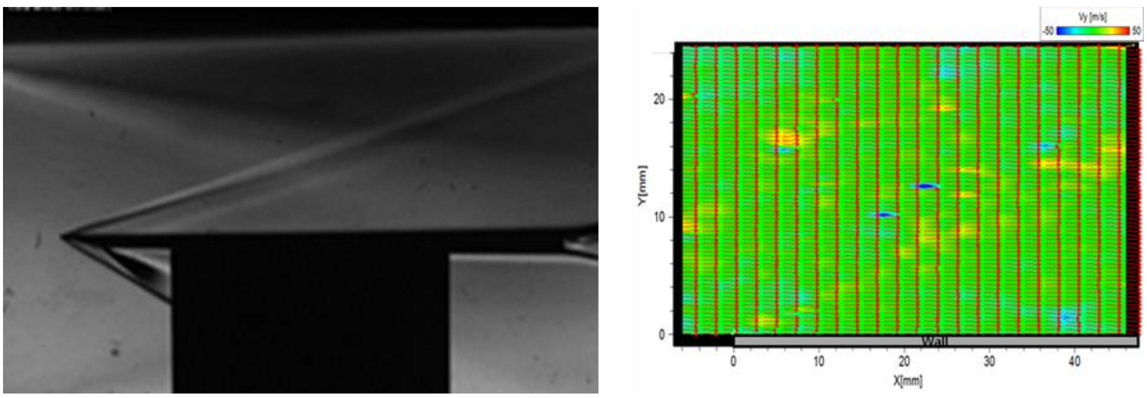
PIVview3c is used as the image correlation software. A thin and elongated interrogation window is set up to have sufficient measurement points in the boundary layer. The interrogated windows of 308 × 6 pixels were used, which corresponds to 2.42 mm in the streamwise direction and 0.047 mm in the wall-normal direction. A window overlap factor of 50% was used, resulting in vector spacing of 1.21 mm and 23.5 μm, respectively.

2.3 Wind Tunnel Model

The experimental model is a flat plate with zero pressure gradient in the streamwise direction. The chord of the flat plate was 110 mm and the span was 160 mm (see Fig. 2). The material of the flat plate was stainless steel 304, and the surface was coated with Teflon to reduce the surface reflection due to laser.

Figure 2 : Dimensions of the flat plate in millimeters

The Schlieren visualization is used to verify that the wind tunnel tests on the flat plate were performed correctly. As shown Fig. 3(a), the weak oblique shock wave is generated at the leading edge of the flat plate. The freestream Mach number is calculated using the angle of the oblique shock wave. The freestream Mach number is 2.99, which is consistent with the Mach number measured using the Pitot tube. The oblique shock wave on the left on the Fig. 3(a) is caused from the nozzle exit.



(a) Schlieren (b) PIV

Figure 3 : Visualization of flow field on the flat plate

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The freestream velocity was measured by the PIV to verify whether the oblique shock wave affects the boundary layer on the flat plate. The velocity vector of the flow field on the flat plate is shown in Fig. 3(b), and Figure 4 shows the ratio of the streamwise and wall-normal velocity to the freestream velocity from -5 to 45 mm when the leading edge of the flat plate is set at 0 mm. The mean freestream velocity is 605.37 m/s, which correspond to the freestream velocity the freestream velocity measured using Pitot tube. Figure 4 illustrates that streamwise and wall-normal velocity are changed to about 1% of the freestream velocity. In addition, since the wall-normal velocity is less than 1% of the freestream velocity, the velocity field on the flat plate is homogeneous in the streamwise direction, and the oblique shock wave generated at the nozzle exit does not affect the boundary layer.

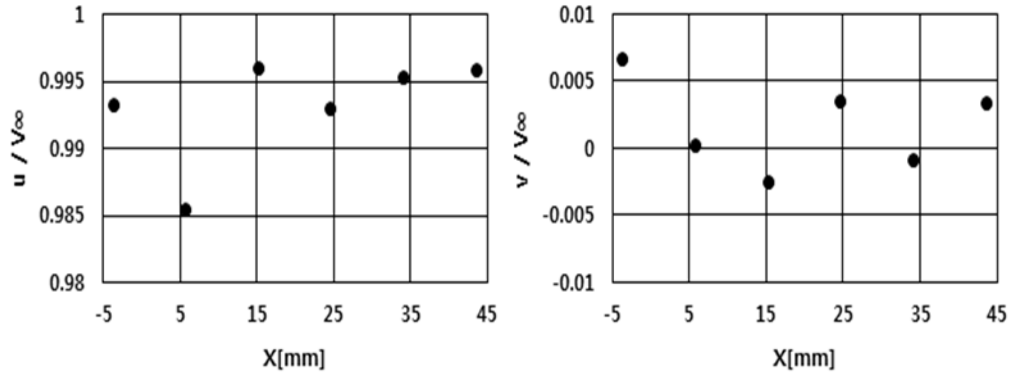

Figure 4 : Ratio of the streamwise and wall-normal velocity to the freestream velocity

3. Results

Figure 5 shows the semi-logarithmic representation of the turbulent profile in terms of the dimensionless variables $u^+ = u_{eq}/u_\tau$ and $y^+ = yu_\tau/\nu_w$ at Re = 4.2 × 10^6. Here u_τ = 30.49 m/s is the friction velocity, ν_w = 6.7 x10^{-5} m^2/s presents the kinematic viscosity evaluated at the wall, and u_{eq} is the Van Driest effective velocity. It is illustrated that the mean compressible streamwise velocity profile and its comparison with the incompressible log law profile (with κ = 0.41 and c = 5) and the Spalding's universal velocity profile from the Fig. 5.

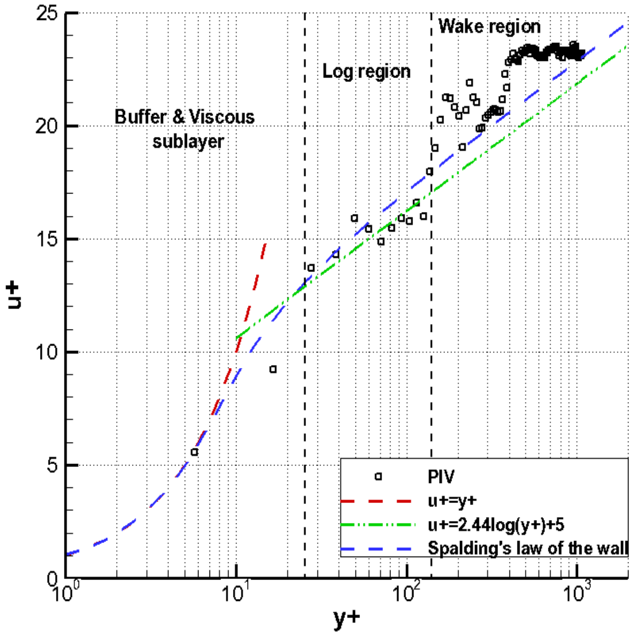

Figure 5 : Turbulent boundary layer profile

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The nearest measurement point on the wall is $y^+ = 5.6$, which corresponds to the viscous sublayer. The result shows that the Van Driest transformed velocity satisfies the incompressible log law profile and indicates a log law behavior in the range between $y^+ = 27$ ($y/\delta = 0.06$) and $y^+ = 124$ ($y/\delta = 0.28$), which is farther away from the wall-normal direction compared to the log-law region which is usually $y/\delta \approx 0.2$ in incompressible boundary layers. This result is consistent with the previous experimental results. However, researchers did not expressly state upon its behavior. The extended log law region might be related to the large velocity gradient in supersonic turbulent boundary layers and the fact that the intermittency profile in a supersonic boundary layer is fuller than the corresponding subsonic profile[13].

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