Measurement of Supersonic Boundary Layer Using Long Range \( \mu \)-PIV with Condensed Water Droplets

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ABSTRACT

Velocity distributions of the supersonic boundary layer on a flared cone model were measured using a long range \( \mu \)-PIV. The experiments were conducted in the JAXA 2m by 2m transonic wind tunnel. The nominal Mach number of the uniform flow was 1.4. The objectives of the measurement were the experimental validation of CFD technique, to confirm the design concept of the natural laminar flow nose of supersonic transport, and to improve the measurement technique for the boundary layer in the large wind tunnel. In order to produce the appropriate condition for the number density of the tracer particles, condensed water droplets produced by controlling the dew point of the air in the wind tunnel were used as the PIV tracer. Influence of the condensed water droplets and the condensation on the boundary layer transition was evaluated from the temperature distribution on the model surface measured with the infrared camera. As the result, the appropriate dew point for the measurement and the flow condition were obtained. The particles images were successfully recorded using a Maksutov-Cassegrain lens. The velocity vectors were calculated with the single-pixel ensemble correlation method. The velocity profiles obtained from the PIV agree with those estimated from the transition pattern observed in the infrared images. An inflection point which promotes the boundary layer transition and was predicted from the CFD was observed in the velocity profiles at the angle of attack of 2.0 degrees.

1. INTRODUCTION

Since boundary layer conditions significantly influence on the drag and the heat transfer of airplanes and rockets, the information of the boundary layer is important in aerospace engineering. In this research, velocity measurement for the supersonic boundary layer was conducted in JAXA 2m by 2m transonic wind tunnel. The objectives of the measurement were the experimental validation of CFD technique, to confirm the design concept of the natural laminar flow nose of supersonic transport [1], and to improve the measurement technique for the boundary layer in the large transonic wind tunnel.

Figure 1 shows the schematic of the experiment setup. The model was a flared cone. The Mach number of the uniform flow was 1.4. At nonzero angle of attack, the boundary layer on the model becomes three dimensional and the streamlines at the surface become curved due to the pressure gradient from the windward to the leeward side. Therefore the crossflow as shown in Fig. 1 occurs on the surface of the model. The convergence of low-speed secondary flow leads to a thicker boundary layer on the leeward line. The thicker boundary layer profiles exhibit an inflectional behavior. The inflection behavior promotes the transition from the laminar to the turbulent on the leeward line. The CFD predicted the thicker boundary layer on the leeward line and the existence of the inflection point of the velocity.

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\begin{align*}
X &= 130 \text{ mm} \\
Mach &= 1.4 \\
\text{Flared cone} &\quad \text{IR Camera} \\
\text{PIV Camera} &\quad \text{Leeward line (Top line)} \\
\text{Windward line (Bottom line)} &\quad \text{about 1 mm}
\end{align*}
\]

Figure 1 Schematic of the experimental setup.
profile [1]. However, these characteristics, especially the existence of the inflection point have not been clarified experimentally. Hence, the velocity profiles of the boundary layer on the flared cone model were measured using long range \( \mu \)-PIV. The existence of the inflection point was clarified from the velocity profiles measured with the PIV.

One of the key techniques of this PIV measurement was the tracer particles. Generally, the oil particle, dioctyl sebacate (DOS) is used as the PIV tracer in the JAXA 2m by 2m transonic wind tunnel. However, the number density of the oil particle was not appropriate for the boundary layer measurement at the Mach number of 1.4. In order to make the appropriate condition for the number density of the tracer particles, condensed water droplets produced by controlling the dew point of the air in the wind tunnel were used as the PIV tracer. Strictly speaking, the condensation changes the flow field in the wind tunnel. In order to avoid the serious damage to the flow field from the condensation and the water droplets, the influence of those on the boundary layer transition pattern was evaluated from the temperature distribution on the model surface measured with the infrared (IR) camera. As the result, the appropriate dew point for the measurement and the flow condition were obtained, and the velocity profile was successfully measured. The measurement methodology and the measured velocity profiles are described in this paper.

2. EXPERIMENTAL METHOD

Experimental condition and setup

The coordinate in Fig. 1 is used in this paper. The measurement was conducted at the Mach number of 1.4. The unit Reynolds number was 13.3 \( \times 10^6 \)/m. The total pressure and total temperature were 100kPa and 327K, respectively. As described below, the appropriated condition of the dew point for PIV tracer was about 253K although the normal dew point of the wind tunnel is lower than 250K. The angle of attack of the model was set at from -2.5 degrees to +2.5 degrees. The result at -2.0, 0.0, and +2.0 degrees are shown in this paper. The working distance of the PIV camera was about 1.2 m. The measurement area included the position of \( X=130\)mm. The thickness of the boundary layer in the measurement area was about 1 mm.

The experimental setup and the measurement systems are show in Fig. 2. The experiment was conducted in JAXA 2m by 2m transonic wind tunnel. A bird’s eye view of the wind tunnel is shown in Fig. 2(a). The wind tunnel is equipped with a 22,500 kW blower, and supersonic operation is achieved using a 8,000kW auxiliary blower. Dry air was supplied from the high pressure air tank. The dew point of the air in the wind tunnel was adjusted controlling the supply amount of the dry air. The wind tunnel has 4 exchangeable rectangle test sections with the reference height and the reference width of 2m. Although the test section #4 is the best for the PIV because of the flexibility of the visualization windows, the test section #3 which had slots on the top and bottom walls was used in order to avoid the disturbance from the porus walls of the test section #4. The pictures of the test section #3 are shown in Fig. 2(b) and (c).

Figure 2(c) shows the flared cone model. The half angle of the flared cone model was 4 degrees. The total length of the model was 330 mm. The flared cone geometry was defined by the following distribution of the model radius, \( R_{g}(X) \):

\[
R_{g}(X) = -1.0478 \times 10^{-8} X^4 + 6.9293 \times 10^{-7} X^3 - 6.1497 \times 10^{-6} X^2 + 6.998 \times 10^{-5} X - 6.2485 \times 10^{-4}.
\]

Where the axial coordinate \( X \) is measured in meters. The model was made of plastic resin except for the tip and the central axis in order to measure the temperature using the IR camera.

IR Camera

Generally, the recovery temperature in turbulent boundary layer is higher than that in the laminar boundary layer. The temperature of the model surface in the turbulent boundary layer region becomes higher than that in the laminar boundary layer region. Although the visualization of the distribution of the temperature on the model surface cannot precisely detect the transition line of the boundary layer, it is convenient to visualize the qualitative transition pattern of the boundary layer. Hence the temperature on the surface of the model was measured during the PIV measurement in order to check the influence of the condensation and the water droplets on the flow condition, especially on the transition pattern of the boundary layer on the model. An infrared camera (FLIR A325, FLIR systems) in the special pressure chamber was used for the temperature measurement. The picture of the IR camera is shown in Fig. 2(d). The camera was set on the roof of the test section and cooled with the supplying air. The infrared images were taken from the slit of the test section.

PIV system

A double pulsed Nd:YAG laser (200mJ/pulse, CFR400, Quantel) was used as the light source for the laser sheet of the PIV. The interval of the successive laser pulse was measured using a photo detector and a high speed A/D converter. The interval of the successive laser pulse was about 270 ns. The laser was set on the roof of the test section. The picture of the laser, the mirror, and the lens systems are shown in Fig. 2(d). Figure 2(e) shows the picture of the camera system. A Charge Coupled Device camera (2048x2048pix, ImageProPlus4M, Lavision) with a Maksutov-Cassegrain lens (QM1, Questar) was used for the recording of the scattering light from the tracer particles. The working range of the QM1 was from 560mm to 1,520mm. Thus the lens was appropriate for this measurement. The picture of the QM1 was show in...
The operation of the PIV system must be conducted from the outside of the plenum chamber in the wind tunnel. The focus of the lens and the position of the CCD camera could remotely be adjusted using the traverse devices. The recording rate of the pairs of pictures was 4 Hz. 2,000 pairs of pictures were obtained for each experimental condition.

**PIV analysis**

Unfortunately, vibration of the camera and the model was observed from the obtained images for the PIV. Before the calculation of the velocity vector, image registration was conducted detecting the surface of the model in the image using the Hough transform. Although the surface of the model was flared, the image registration and the calculation of the velocity vector were conducted assuming that the surface of the model was a straight line because recording was performed with high magnification and the curvature was not recognized from the image. For the calculation of the velocity vector, single-pixel ensemble correlation algorithm [2] was used in order to increase the spatial resolution. The schematic figure of the algorithm was shown in Fig. 3. Analysis software was in-house software and it was written in Matlab® (MathWorks). Calculation was performed using a general-purpose computing on graphics processing unit.

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**Fig. 2**

Experimental setup.
3. RESULT

As described above, the key technique of this PIV measurement was the tracer particles. The dew point of the air in the wind tunnel was very important in this measurement. The appropriate dew point was detected replacing the humid air to the dry air. Figure 4 shows the pictures of the inside of the test section at several Mach number and at the dew point of about 260K (upper figures) and at the dew point from 252K to 255K (lower figures). The target Mach number was 1.4. Hence, the dew point was adjusted for the Mach number of 1.4. At the dew point of 260K, the fog was clearly appeared from the Mach number of 1.2. The model could not be observed at the Mach number of 1.4 because of the dense fog. At the dew point of 260K, the oscillation of the model and the equipments on the roof of the test section was very large. The mirror and lens system for the laser sheet were seriously damaged by the flow passing through the slots of the top wall. It was supposed that the condensation shock wave appeared in the nozzle changed the flow field largely and increased the fluctuation of it. Thus the flow condition at the dew point of about 260K was not appropriate for the PIV. At the dew point of 252K to 255K, the flow condition changed dramatically as shown in Fig. 4 (lower figures). At the dew point around 253 K, the condensed water droplets appear from the Mach number of about 1.3. The number density of the water droplets and the fluctuation of the flow were much smaller than those at the dew point of 260K.

Figure 5 qualitatively shows the temperature distribution of the model surface at Mach number of 1.4 and the...
schematic of the transition pattern of the boundary layer at the angle of attack of +2.0 degrees. The left figures (wet condition) show the temperature distributions at the dew point from 253K to 254K. The right figures (dry condition) show those when the dew point was lower than 250K. As described above, the temperature distributions shown in Fig. 5 roughly show the transition pattern of the boundary layer. Dark color shows the low temperature region and light color show the high temperature region. Namely, the dark region roughly shows the laminar region and the light region shows the turbulent region. The results showed that the influence of the condensation was small on the pattern of the boundary layer transition and the dew point from 253K to 254K was appropriate for the flow condition to investigate the velocity profile of the boundary layer. The transition point on the top line at the angle of attack of -2.0 degrees is located more downstream than that at the zero angle of attack. The transition point on the top line at the angle of attack of +2.0 degrees is located more upstream than that at the zero angle of attack. The characteristic pattern as shown in the schematic figure at the angle of attack of +2.0 degrees was not changed by the condensation and the water droplet. These characteristics of the transition pattern on the wet condition agree well with those on the dry condition especially at the angle of attack of ±2.0 degrees. In addition, the transition patterns do not contradict the prediction described in the section of introduction. At the zero angle of attack, it was observed that the transition line on the wet condition located a little upstream than that on the dry condition. It is considered that the small disturbance produced by the condensation moved the transition line a little upstream than that on the dry condition.

Figure 6 shows the particle images and the velocity distribution obtained by the PIV at the zero angle of attack. Here, the process of the PIV analysis was described. Unfortunately, the vibration of the camera and the model was observed from the obtained images. Hence, the image registration was conducted for the raw images (Fig. 6(a)) detecting the surface of the model in the image using the Hough transform. The velocity vectors were calculated from processed images (Fig. 6(b)) using the single-pixel ensemble correlation algorithm. The search area was ±3 pixels in height and -3 pixels and +30 pixels in the direction parallel to the surface. As the result, the velocity distribution was obtained as shown in Fig. 6(c). Figure 6(d) shows the profile of the velocity component in the parallel direction to the surface, u m/s. As shown in Fig. 6(d), the original velocity profile was noisy because the number of pictures was too small. Hence, the velocity vector was averaged in the direction parallel to the model surface in order to increase the signal to noise ratio as shown in Fig. 6(e). Although the resolution in the X direction become low, the profile of the velocity component become smooth and appropriate for the comparison between the several conditions.

The result of the uncertainty analysis for the averaged velocity was shown in Fig. 7. The uncertainty analysis was based on the method in reference [4]. Precision of the displacement was obtained from the standard deviation of the velocity components at the same height; y. Bias limit of the particle traceability was roughly estimated using the particle motion equation assuming that the diameter of the water droplets was 2µm. The intensity of the scattering light from the water droplets was almost the same as that from the DOS particles whose diameter was about 1µm. Hence, it was assumed that the diameter of the water particle was 2µm in the uncertainty analysis to estimate the worst case. Total uncertainty was estimated at less than 4 m/s.
Figure 8 shows the velocity component in the direction parallel to the model surface $u$ and in the vertical direction to the surface of the model $v$ at the angle of attack of 0.0, $+2.0$, $-2.0$ degrees. The velocity vectors of the boundary layer were obtained at interval of about 5 $\mu$m in the vertical direction to the model surface. The velocity component $v$ was almost zero. The flow speed outside of the boundary layer was about 420 m/s in all cases. The velocity profiles of $u$ and its derivative $du/dy$ were shown in Fig. 9. As the angle of attack increases, the thickness of the boundary layer increases in Fig. 8 and 9. At the angle of attack of $+2.0$ degrees, the existence of the inflection point is observed around $y = 0.35$ mm. The existence of the inflection point is much more easily observed from the line of the $du/dy$ in Fig. 9. This result qualitatively agrees with the prediction of the CFD. Furthermore, the result qualitatively explains the transition pattern of the boundary layer shown in Fig. 5. At the angle of attack of $+2.0$ degrees, the existence of the inflection point
promotes the transition of the boundary layer. Hence the transition point at the angle of attack of +2.0 degrees is located upstream than that in the other cases. Because of the thinner boundary layer, the transition point at the angle of attack of -2.0 degrees is located downstream.

4. SUMMARY

Velocity distributions of the supersonic boundary layer on a flared cone model were measured using a long range μ-PIV. The experiments were conducted in the JAXA 2m by 2m transonic wind tunnel. The nominal Mach number was 1.4. The angle of attack was from -2.5 degrees to +2.5 degrees. The velocity profiles at the angle of attack of 0.0, +2.0, and -2.0 degrees are reported in this paper. In order to produce the appropriate condition for the number density of the tracer particles, condensed water droplets produced by controlling the dew point were used as the PIV tracer. Influence of the condensed water droplets and the condensation on the boundary layer transition was evaluated from the temperature distribution of the model surface. The temperature was measured with the infrared camera. From the monitoring movies and the temperature distribution, it was clarified that the appropriate dew point for the measurement was from 252K to 255K for the present experiment. In those conditions, the transition pattern was not changed by the condensation and the flow fields were appropriate for the investigation of the velocity profile of the boundary layer. The particles images were successfully recorded using a Maksutov-Cassegrain lens. The velocity vectors were calculated
using the single-pixel ensemble correlation method from the 2,000 pairs of pictures. In order to decrease the uncertainty, the velocity profiles were averaged in the parallel direction to the surface. The averaged profiles of the velocity component were appropriate for the comparison between the several cases. The velocity profiles obtained from the PIV agree with those estimated from the transition pattern observed in the infrared images. An inflection point which promotes the boundary layer transition and which was predicted from the CFD was observed in the velocity profiles at the angle of attack of +2.0 degrees.

REFERENCES