

Study on the Transient Behaviour of the Vortex Structure behind Ahmed Body

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ABSTRACT

On a bluff body which has a slant surface on the rear upper part, it is well known that the drastic change of a wake structure behind the rear body occurs at 30° of the slant angle. Originally, this critical phenomenon was pointed out by L.J. Janssen, W.H. Hucho, and H.J. Emmelmann in the middle of the 1970s. In 1984, S.R. Ahmed conducted systematic measurements by changing the rear slant angle of the bluff body, called the "Ahmed Body", to find the critical phenomenon. In the 2000s, D.B. Sims-Williams found that the Ahmed Body had vortex structures which had specific frequencies. However, the relationship between the critical phenomenon and the unsteady behaviour has not been clarified yet.

Therefore, as the first step of this study, we measured the unsteady wake behaviour for various slant angles to find the relationship between the Strouhal number and the angle. The characteristics of the fluctuation were captured with two hot-wires. By analysing the coherence and difference of the phases of their signals, the behaviour of the trailing vortices and the vortex shedding of the wake was investigated. PIV measurements were also performed. As a result, two significant Strouhal numbers of the fluctuation of the wake were measured. The Strouhal number corresponding to the fluctuation of the trailing vortex structure was around 0.1 for various slant angles, while that of the up-wash flow varied in the range of 0.1 to 0.5. Thus, incoherent vortex shedding behaviour was seen in the upper and lower regions of the wake, which was clearly different from the coherent phenomenon behind the body in such a sphere. Furthermore, we captured instantaneous phenomenon when the transition occurred by flow visualisation. Finally, the relationship between those intermittent phenomena and the trigger of the transition was discussed.

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INTRODUCTION

The aerodynamics of the Ahmed body has a long history. In the first place, the beginning of this problem was a chance discovery by Hucho, Janssen, and Emmelmann [1][2][3]. They found a critical change in CD and CL relating to the angle of a rear gate. Around the same time, T. Morel pointed out that the critical change relates to the formation and deformation of the trailing vortices and attachment and detachment of the down wash on the rear gate surface [4]. Eight years later, S.R. Ahmed performed systematic experiments by changing the slant angle and clarified the relationship between the critical change and the flow field in the wake [5]. Through his studies, it was found that CD and CL of the model decrease drastically at a slant angle of 30° and that the critical phenomenon corresponds to the change in the wake and vortex structure behind the body. In 2001, D.B. Sims-Williams found distinctive characteristics of their motion [6][7]. Therefore, the study of the

Ahmed Body has significantly progressed from time-averaged to unsteady problems. G. Vio et al. measured the unsteady characteristics of the pressure fluctuation on a slanted surface for a slant angle of 30°, which corresponds to the phase of the "after transition" [8]. In this case, correlation between the upper and lower part was significant and the phase difference was approximately 180° at a significant peak frequency. As a result, the behaviour of the upper and lower separation bubbles was realised under that condition. S. Krajnovic investigated the very detailed flow structure around the Ahmed Body by LES calculation in 2005 [9][10]. Some findings regarding instantaneous interactions between vortices have been reported, but, as a whole, major investigation has focused on time-averaged phenomenon. Accordingly, the relationship between the critical phenomenon and the unsteady behaviour has not been clarified yet.



Here, since this study is strongly associated with the previous literature of Sims-Williams, further detailed results should be described. Sims-Williams conducted experiments with two different scales of Ahmed model in the different wind tunnels for different slant angles, i.e. 30° and 27.5° . Firstly, he found that there exists a typical wake structure which has a characteristic frequency. He also found that the frequency showed sensitivity to the slant angle. This might have relations with the difference in the characteristics of the wind tunnel, though the exact cause of the difference between them have not been clarified. The other essential result was that the strength and size of a pair of the trailing vortices fluctuated concurrently for both models. However, he did not study in a systematic way for various slant angles and did not refer to the mechanism of the transition of the flow structure. One of the most interesting finding in present study was that the behaviour of a pair of the trailing vortices was "alternately" instead of "concurrently". One of the considerable causes was the difference in the size of the model, i.e. Re . Then authors investigated the effects of Re on the unsteady characteristics of a pair of the trailing vortices. However, in the range of Re in author's experiments, no dependency on Re was proved. Therefore, it was expected that there might be another reason for the difference between Sims-Williams' and authors' results instead of the difference in Re , which would be a future theme.

A primary focus of this study is to explain the mechanism of the drastic change which occurs at 30° of the slant angle. "Which parameters determine the critical angle?" is our ultimate interest. Then, we measured unsteady wake behaviours for various slant angles to find the relationship between the Strouhal number (St) and the angle. The characteristics of the fluctuation were captured with two hot-wires. By analysing the coherence and difference of the phases of their signals, the behaviours of the trailing vortices and the vortex shedding of the wake were investigated. PIV measurements were also performed for a few conditions to support the hot-wire measurement. As a result, two significant St s of the wake fluctuation were found, which indicated a different tendency from that reported by Sims-Williams as mentioned above. The St corresponding to the change in the strength and location of the trailing vortex was around 0.1 for various slant angles, while that of the oscillation of the up-wash varied from 0.1 to 0.5, depending on the slant angle.

The other finding was the trigger of the transition. The transition of the flow pattern looks likely to occur accidentally, but in fact it absolutely occurs at the slant angle of 30° . The indication of the transition was observed even at the angle of 27.5° by flow visualisation. Intermittent but not periodic flow separation appears at the trailing edge of the slanted surface and sometimes develops towards the top of the slope to promote instantaneous separation of the down-wash at the top of the slope. However, in reality, it never promotes the transition below the slant angle of 30° , while it does at 30° . The difference between these cases is the stability of the flow pattern of the separation/reattachment on the slope surface. As

long as the angle is below 30° , the separated pattern is not stable. Then, the relationship between the intermittent phenomenon and the trigger of the separation is discussed.

Accordingly, the interesting point is that St of the down-wash does not significantly depend on the slant angle, though St of the up-wash does. Then, we assumed that some accidental and probabilistic interaction occurs intermittently between the up- and down- wash instead of steadily, and some combination of St might enhance the oscillation of down wash which promotes the transition. This idea is, of course, only a hypothesis yet. However, looking at the behavior of the smoke around trailing edge of the slant surface when the transition occurred, structural movement of the whole wake, i.e. upper and lower region of the wake, was observed. Therefore, we have an interest in the St of both up- and down-wash. This is the motivation of this study.

EXPERIMENTAL FEATURES

The test model was reduced to one-third of Ahmed's original model, as shown in Fig. 1, to adjust for the size of the wind tunnel. The length of the model was 300 mm, the width was 110 mm, and the height was 80 mm. The rear body was prepared for eight variations of the slant angle, i.e., 0° , 12.5° , 25° , 27° .

A series of experiments was conducted in the small wind tunnel at Tokyo City University (TCU), as shown in Fig. 2. The maximum wind speed was 25 m/s, and the turbulence was approximately 0.5% at the inlet nozzle. Measurement of aerodynamic forces was conducted using a three-component balance. Velocity measurements were performed using an I-type hot-wire with a KANOMAX Hot-wire System (Model-1008, 1010, 1013, 1020, 1075) and FFT analyser for the correlation measurement. PIV measurements were performed using a Flow Master 2D PIV system (LaVision). Irradiation was conducted using an 8 W CW-YAG Laser (Omicron Nano Technology). Fig.3 shows measurement systems for this study.

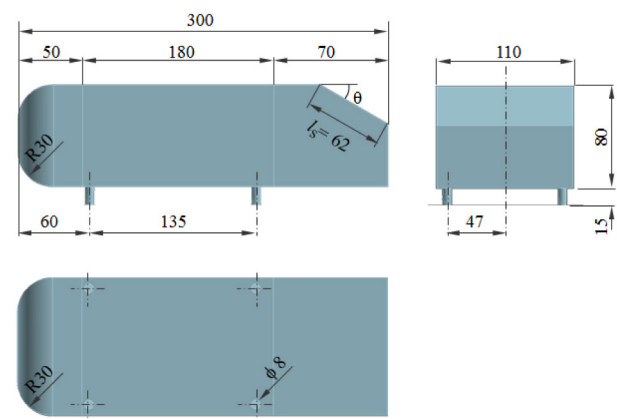


Fig. 1. Test model used in this study; TCU model is 30% of the original Ahmed model.



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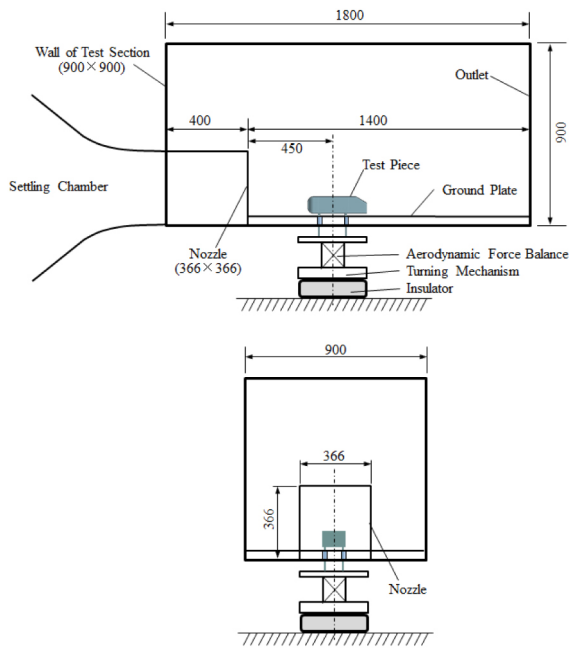


Fig. 2. Test section of wind tunnel for this study; Size of the inlet nozzle is 366(W) × 366(H). Maximum air speed is 25m/s.

TYPICAL CHARACTERISTICS OF AERODYNAMIC DRAG

Characteristics of Aerodynamic Drag

Ahmed conducted the test using a Reynolds number (Re) of 1.38×10^6 in a DFVLR wind tunnel, where Re was calculated based on the square root of the frontal area (A), the free stream flow velocity (U_∞) and kinematic viscosity coefficient (ν);

$$Re = \frac{U_\infty \cdot A}{\nu} \quad (1)$$

Meanwhile, we used an Re of 7.31×10^4 , which corresponded to a wind velocity of 12.0 m/s for regular measurements. Drag coefficient (CD) measured at TCU were remarkably higher than those in the DFVLR, as shown in Fig. 4, where CD was defined as a following formula based on the drag force (D), the square root of the frontal area (A), the free stream flow velocity (U_∞) and the density of the air (ρ);

$$CD = \frac{D}{\frac{1}{2} \rho U_\infty^2 \cdot A} \quad (2)$$

However, the CD trend was similar to that obtained in the DFVLR, and the discrepancy between the CD s seemed to remain almost constant. The transition of the flow pattern at

30° of the slant angle was also seen. Therefore, it was assumed that similar phenomena occurred, even at such a small Re .

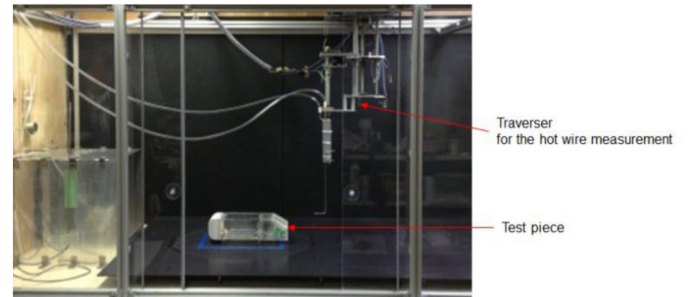


Photo of the test piece in the test section

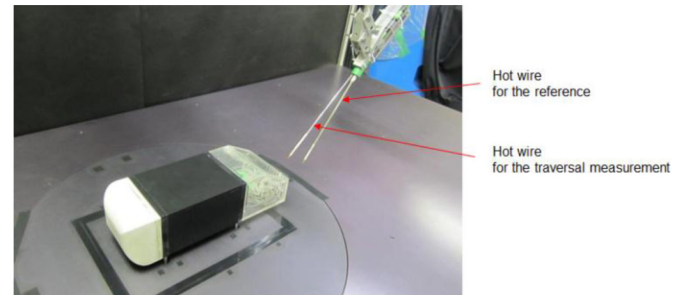


Photo of the hot wire measurement

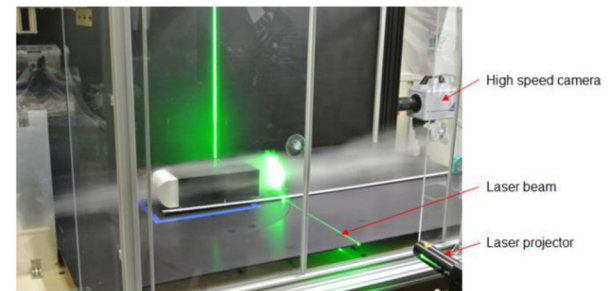


Photo of the PIV measurement



Photo of the PIV measurement system

Fig. 3. Measurement systems for this study; A traverser, hot wires, equipments for PIV and a laptop for the data processing.

Then, we measured the pressure distribution on the slanted and vertical base surface to estimate the pressure drag of the rear body, whose contribution had been shown in Ahmed's paper. As shown in Fig. 5, 324 pressure tap points were installed on the left hand side of the body to measure the pressure drag acting on the slanted and vertical surface. A local component of drag was evaluated by integrating the pressure distribution. Here, the pressure distribution is assumed to be symmetric because the yaw angle is 0° . Comparing with Ahmed's results, where the pressure drag is adjusted at a θ of 0° , good agreement was confirmed, as shown in Fig. 6. It was evident that the famous and distinctive tendency of Ahmed's Body was replicated at such a small Re . Of course, detailed properties, e.g., the thickness of the boundary layer and the turbulence intensity near the wall, might be different. That is, this phenomenon was not sensitive to the nature of the boundary layer, though it was closely related to the separation/reattachment of the flow close to the body surface.

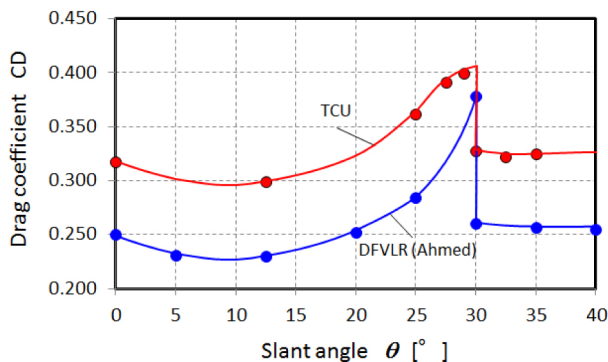


Fig. 4. Coefficient of drag (CD) for various slant angles: Re is 7.31×10^4 for the TCU wind tunnel, while it is 1.38×10^6 for the DFVLR measured by Ahmed.

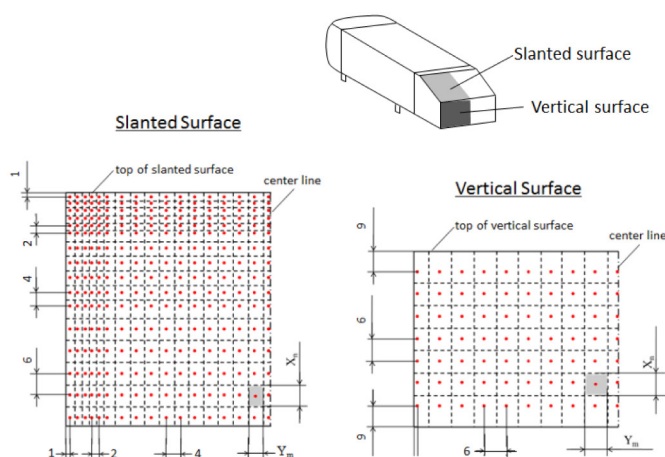


Fig. 5. Location of pressure taps; 324 points of pressure taps points were installed on the left hand side of the body to measure the pressure drag acting on the slanted and vertical surface.

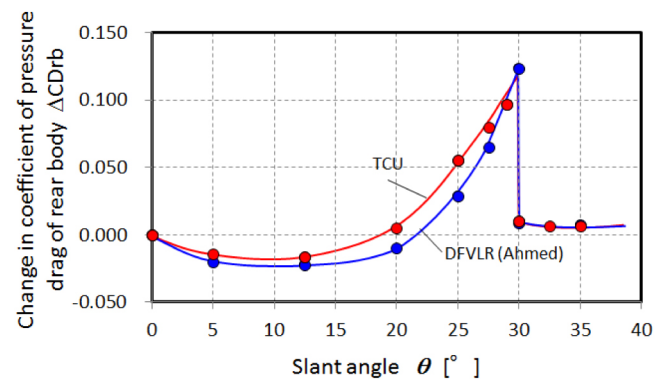


Fig. 6. Change in coefficient of pressure drag of the rear body CD_{rb} for various slant angles; Rear pressure drag is evaluated by integrating the pressure distribution on the slanted and vertical surface of the rear body. In this comparison, both data of from TCU and DFVLR were adjusted to 0.000 at a slant angle of 0° of the slant angle.

Effects of Reynolds Number on Friction Drag

In this section, the discrepancy between the CD measured at TCU and DFVLR is discussed. In fact, the Re , on the basis of which the experiments were performed in the TCU wind tunnel, was located in a delicate condition. It is generally thought that a Re of 7.31×10^4 belongs to the laminar region on a flat plate, so that nature of the boundary layer is much different from that in the turbulent region. Thus, we measured the boundary layer at the rear end of the top surface on different velocities when the slant angle was 27.5° . The free stream velocity was varied from 6 m/s to 18 m/s, which corresponded to a Re from 3.65×10^4 to 1.10×10^5 . In this study, because the reference length for Re is taken as the square root of the frontal area of the body, Re is assumed to be smaller than that on a flat plate, where it is defined as the distance from the leading edge. Therefore, calibrating the reference length to a flat plate, the corresponding Re becomes approximately three times that of the original value mentioned above. Fig. 7 and Fig. 8 show the velocity and turbulence intensity profile of the boundary layer. In Fig. 7, theoretical profile of the laminar boundary layer obtained by Howarth's numerical solution [11] are added for reference. All three velocity profiles are typical turbulent profiles, where velocity decays rapidly very close to the wall surface. The turbulence intensity profiles and levels are also typical turbulent ones. The thickness of the boundary layer decreases with increasing Re . Accordingly, in this study, the boundary layers on the top, side, and bottom surfaces were considered to be turbulent.

Therefore, supposing the 1/7-the power law [12];

$$\left(\frac{u}{U_\infty}\right) = \left(\frac{y}{\delta}\right)^{1/7}$$

(3)

on a flat plate to be roughly applicable to this model, the friction drag coefficient of CD_f became approximately 0.09 for $Re=7.31 \times 10^4$ when CD_f was 0.05 for $Re=1.38 \times 10^6$, i.e., the CD value increased by approximately 0.04 if the pressure drag did not change. In above equation, u , U_∞ , y and δ represent velocity in the boundary layer, freestream velocity, distance from the plate and boundary layer thickness respectively. However, it was difficult to analyse the discrepancy between the CD values from DFVLR and TCU in detail. Thus, we conducted CFD calculations to estimate it quantitatively. ANSYS Fluent 14.0 was adopted as a solver, Realizable- $k-\epsilon$ turbulence model was chosen, and the standard wall function was used, where grids adjacent to the wall were designed for y^+ to be around 20~30 for each case. The number of grids was approximately 8 million. As shown in Fig. 9, at a θ of 12.5° , for instance, the calculated CD_f at $Re=1.4 \times 10^6$ corresponding to the experimental conditions in DFVLR was 0.050, which was close to the experimental result expressed as "Experiment (Ahmed)". Meanwhile, the calculated CD_f corresponding to the experiment at TCU was 0.088, which was the same level as that expected by rough estimation on a flat plate mentioned above.

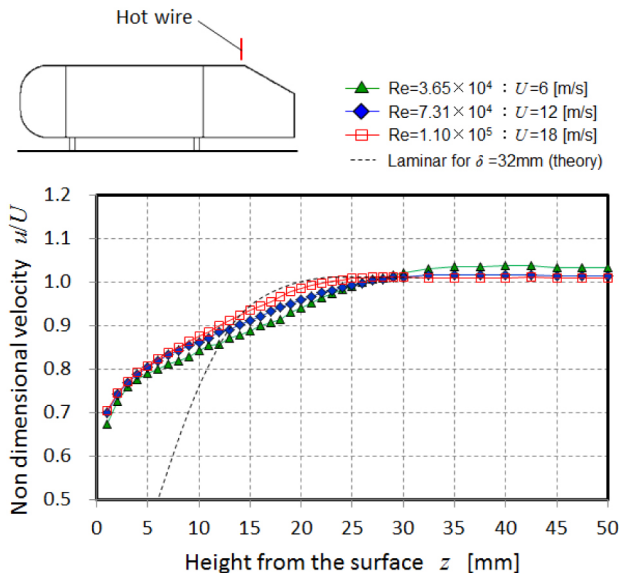


Fig. 7. Velocity profiles of the boundary layer at the end of the top surface; Symbols, i.e., Δ : $Re=3.65 \times 10^4$, $\diamond$: $Re=7.31 \times 10^4$, and $\square$: $Re=1.10 \times 10^5$, are variations of the free stream velocity. The slant angle is 27.5° .

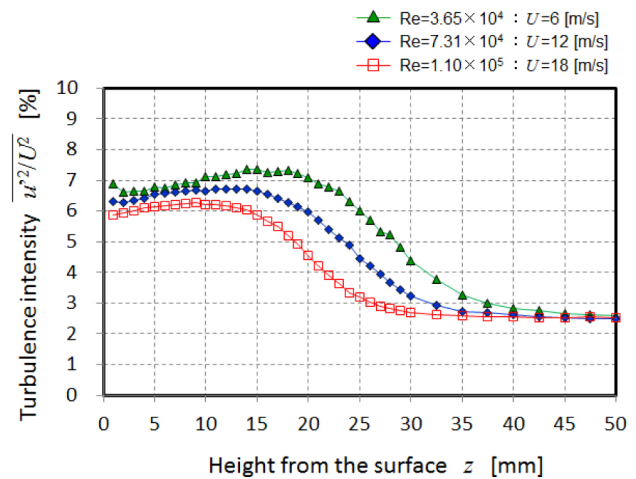


Fig. 8. Turbulence intensity profiles of the boundary layer at the end of the top surface

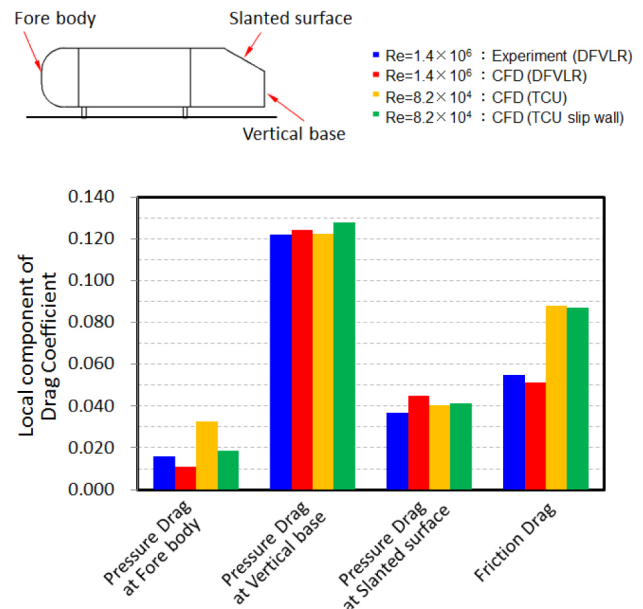


Fig. 9. Local components of drag coefficient estimated by CFD calculation; in this case, the slant angle is 12.5° . The grid structure was set to have the same level of y^+ for different Re .

Effects of Reynolds Number on Ground Boundary Layer

Fig. 10 represents the pressure distribution around the lower front corner. Regarding results using the conditions at TCU, the pressure indicated higher values on the lower corner of the front body, which corresponded to a small local flow separation at the location. To determine the cause of these results, the other calculation was compared, where the boundary condition of the ground wall of the wind tunnel was set to be "slip wall" to eliminate the effects of the boundary layer development.

As a result, the pressure distribution agreed with that of the DFVLR, and the fore-body drag approached that of the DFVLR, as shown in Fig. 9. Therefore, it was assumed that the effect of the boundary layer development on the ground in the wind tunnel was one of the causes of the discrepancy. Additionally, concerning around a θ of 30° , instability of the transitional phenomenon was considered as another cause of the discrepancy. In fact, as shown in Fig. 4, the discrepancy at a θ of around 30° was smaller than that in the lower θ region below 25° .

Consequently, it was realised that approximately 60% of the discrepancy was due to the Re effects on the friction drag. With respect to the remainder, the interference of the boundary layer development on the ground plate was thought to be one of the indispensable factors. The instability of the transition of the flow pattern around a θ of 30° was also a considerable factor.

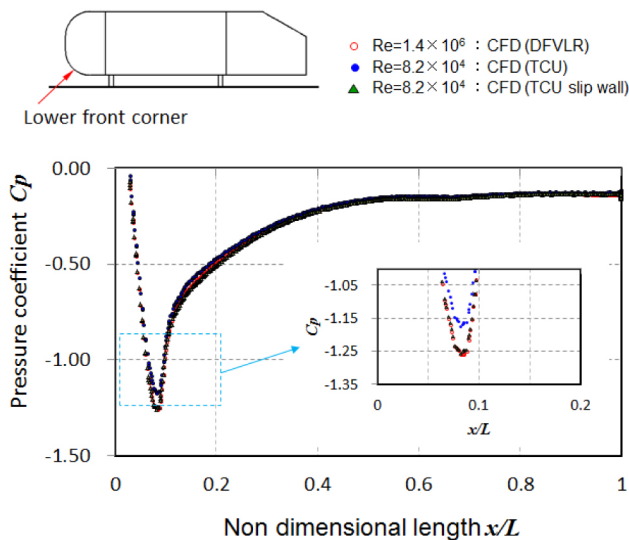


Fig.10. Pressure distribution around the lower front corner estimated by CFD calculation; the slant angle is 12.5° . Because of the boundary layer development on the ground wall, pressure around the lower front corner increases at $Re=8.2 \times 10^4$ at TCU, while it is negligible at $Re=1.4 \times 10^6$ at the DFVLR.

TURBULENCE DISTRIBUTION IN THE WAKE

Turbulence Distribution in the Wake Region

At the beginning of this study, a turbulent structure in the wake was investigated. Fig. 11 shows the distribution of turbulent intensity on the plane located at a distance of 0.24 times the body length behind the rear end ($x=73$ mm). At a θ of 0° , the highly turbulent region indicated that a pair of transversal vortices was being shed from the top and bottom edges. However, around both side edges, no remarkable strong region was seen. This was thought to mean that vertical interaction between the top and bottom vortices was strong due to the ground effects and the aspect ratio of the original model. Increasing the slant angle, a pair of trailing vortices developed and a strong region appeared at the outer edge of the vortices. Associated with development of the trailing vortices, the strong region around the top edge became weak and merged into the trailing vortices at a slant angle of up to 30° .

Above 30° , after the transition, the distribution of the turbulent intensity returned to the initial one. However, around both side edges, the strong region still remained, unlike the initial case. Also, the location of the strong region that developed from the top edge was lower than the roof height, which indicated that a weak down-wash still remained. With further increases in the slant angle, the distribution returned to the initial case.

Fig. 12 shows the distribution of turbulent intensity on the centre plane. At a slant angle above 25° , up to 30° , the thickness of the shear layer along the slope surface developed rapidly. At 27.5° , it was seen that a transversal vortex, which induced down-wash, was generated in the mid-course of the slope surface. Because of the down-wash, the shear layer of the up-wash was suppressed and diffusion was enhanced.

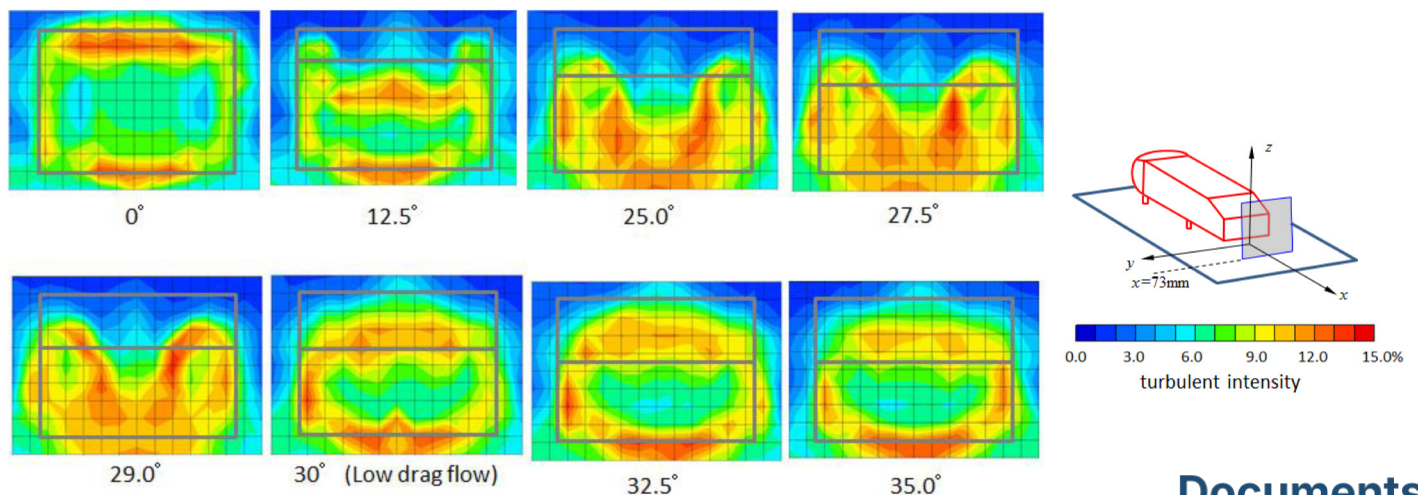


Fig. 11. Distribution of turbulent intensity; measured on the plane located at a distance of 0.24 times the body length behind the rear end ($x=73$ mm).