

Effect of High Blockage Ratios on Surface Pressures of an Inclined Flat Plate

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Abstract

The walls of the wind tunnel test section affect severely the flow characteristics around bluff bodies. In this study, the blockage effect was experimentally investigated in two low-speed wind tunnels (23.0–29.7 m/s). An inclined flat plate, representing blockage ratio of 2.11%–17.64%, was installed on the wind tunnel floor. The mean surface pressures on the upper and lower surfaces in a smooth flow were measured. Compared with the data in the low-blockage tunnel, the effect of the magnitude of blockage ratio on the separated flow over the inclined flat plate was more sustainable. A procedure developed from the dynamic pressure increment around the model was employed. It is observed that the effect of blockage ratio on sectional lift and drag coefficients on the centerline of an inclined flat plate can be corrected through the application of a conventional blockage formula.

Keywords: inclined flat plate; blockage effect; solar collector; wind tunnel

1. Introduction

Wind tunnels have been extensively used in testing bluff bodies, such as cars, bridges, and buildings. However, the presence of wind tunnel walls adds velocities to the flow field around a test model that are absent in an unlimited air flow and must be considered when interpreting force, moment, and pressure measurements (Hackett, 2003). The blockage ratio ($BR = S/C$) is the maximum projected cross-sectional area of the model (S) divided by the area of the tunnel test section (C) (Holmes, 2007).

Ota et al. (1994) indicated that the Strouhal number and force acting on bluff bodies in a confined flow were higher than those in an unbounded flow, because of increased vorticity in the separated shear layer. For a two-dimensional (2-D) rectangular cylinder in a smooth flow, the separated shear layer shifted closer to the wake centerline when the BR increased (Awbi, 1978). For axisymmetric cylinders, Saathoff and Melbourne (1987) demonstrated that an increase in the BR by 5% caused the mean pressure to increase in magnitude by 15% and the standard deviation and peak pressures to increase by 20%. Therefore, estimating the effect of wind tunnel blockage on the test data and correcting them accordingly is crucial.

Maskell (1965) examined the wind tunnel blockage effect on the drag coefficient (C_D) of a finite-span flat plate, at the centerline of a closed wind tunnel, normal to wind (no ground influence). When the moment balance outside the wake is considered, the correction is associated with the dynamic pressure increment around the model, in which

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$$\Delta q/q = \varepsilon C_D BR \quad (1)$$

$$C_D/C_{DC} = 1 + \varepsilon(C_D BR) + O\{BR^2\} \quad (2)$$

Where $\Delta q = q_c - q$ is the effective increase in dynamic pressure of the undisturbed stream due to constraint. C_{DC} is the corrected drag coefficient on condition that the BR approached zero and ε is the blockage factor dependent on the magnitude of the base-pressure coefficient. The factor is shown to range between values slightly higher than 5/2 for an axisymmetric flow to those slightly lower than unity for a 2-D flow. If higher order terms are negligible, then C_D/C_{DC} varies linearly with $C_D BR$. Furthermore, several additional correction equations have been reported according to Maskell's method for rectangular-section prisms (Awbi, 1978), 2-D rectangular cylinders (Laneville and Trepanier, 1996), passenger cars (Mecker, 1986), porous plates and truss girders (Takeda and Kato, 1992), cubes (Utsunomiya et al., 1993) and aircraft configurations (Kang et al., 2005), respectively.

For automotive testing, a model is typically placed on the wind tunnel floor. The pressure correction method was employed to investigate the influence of the boundaries of a wind tunnel test section. At a high BR value, the corrected and measured pressure coefficients (C_{pc} and C_{pm}) generally take the form

$$1.0 - C_{pc} = f(1.0 - C_{pm}) \quad (3)$$

Where f is a correction factor. According to the correlation of the base pressure for a series of rectangular bodies, Sykes (1973) proposed that $f = 1.0 - mBR$, where m ($= 1.90$) is an empirical constant. For a small coupe model ($BR = 15\% - 20\%$), Stafford (1981) suggested a value of $m = 1.22$ to be more appropriate. However, the global correction factor was not applicable in areas of high local curvature. Furthermore, Templin and Raimondo (1986) examined the blockage effect by using notch-back reference models ($BR = 8.3\% - 18.7\%$) and flat plates ($BR = 1.6\%$ and 20%). They proposed a new correction factor A ($= f^{1/2}$). The analysis showed that a q correction that varied axially in the test section was appropriate for correcting the pressure coefficient.

Solar water heaters or photovoltaic systems, which are typically installed on the roofs of low-rise buildings, have been employed worldwide (Chang et al., 2011). Wind loads on inclined flat plates (or solar panels) have been reported (Wood et al., 2011; Kopp et al., 2002; Chung et al., 2008, 2011, 2013a, 2013b). In particular, shifting reattachment points were observed on the upper surface at different tilt angles, imposing a considerable challenge on any correction scheme. In the current study, the influence of a blockage effect on streamwise pressure profiles and aerodynamic characteristics was investigated by comparing data obtained in both large and small wind tunnels. The empirical constant m on q correction was evaluated.

2. Experimental setup

2.1 Wind tunnel and test models

Experiments were performed in two wind tunnels. The constant-area test section of the low-speed wind tunnel (LSWT), located at the Aerospace Science and Technology Research Center, National Cheng Kung University, is 1.22 (height) \times 1.83 (width) \times 2.77 m (length). A honeycomb and five screens are installed, and the contraction ratio is 9. The wind tunnel in the Architecture and Building Research Institute (ABRILWT), Ministry of the Interior was employed to examine the blockage effect on surface pressures by using the same test model; The constant-area test section of the ABRILWT is 2.6 (height) \times 4 (width) \times 36.5 m (length). This tunnel has a contraction ratio of 4.71 and a honeycomb and three screens. The turbulence intensity of both wind tunnels ($\approx 0.3\%$) is approximately the same.

For the test models, two flat plates (Model I: 60% scaled commercial solar collectors, $1.2 \times 0.6 \times 0.05$ m; Model II: 40% scaled commercial solar collectors, $0.8 \times 0.4 \times 0.04$ m) were fabricated. The typical aspect ratio of a solar collector in Taiwan is 0.5. The models were installed on a flat plate that was above the boundary layer of the wind tunnels. Model I was employed in both the ABRILWT (Case 1) and LSWT (Case 3). No correction is required when the BR is less than 3.5% (Holmes, 2007). Case 2 corresponded to the tests of Model II in the LSWT. As shown in Figure 1, the lower surface of the flat plate, in which the tilt angles α were 15° , 20° , 25° and 30° , faced the flow direction. The mean freestream velocity was 29.7 ± 0.5 and 23.0 ± 0.1 m/s in the LSWT and ABRILWT, respectively. The Reynolds number independence for the present test configuration was observed by Chung et al. (2008). The blockage ratios ($BR = 2.11\% - 17.64\%$) for the entire test cases are listed in Table 1.

Table 1: Blockage ratio of test models

| α , deg | Case 1- BR (%) | Case 2- BR (%) | Case 3- BR (%) |
|----------------|----------------|----------------|----------------|
| 15 | 2.11 | 4.38 | 9.93 |
| 20 | 2.68 | 5.57 | 12.61 |
| 25 | 3.22 | 6.71 | 15.18 |
| 30 | 3.75 | 7.81 | 17.64 |

2.2 Measurement techniques

For Case 1, 50 pressure taps were distributed uniformly along the centerline of the upper and lower surfaces of the flat plate. Surface pressures were measured using Scanivalve multichannel modules (Model ZOC 33/64Px 64-port) equipped with differential pressure transducers (Model RAD3200). The full-scale range of sensors was $\pm 2,490$ Pa (or ± 10 inch H_2O), and the accuracy was $\pm 0.15\%$ for the full scale. The sampling rate used for all of the test cases was 256 Hz, and each record contained 40,960 data points. For Cases 2 and 3, 30 pressure taps were distributed along the centerline of the upper and lower surfaces for Models I and II. Pressure transducers (Validyne DP-103-26) were employed.

The sampling rate was 1,000 Hz, and each record contained 60,000 data points. The mean surface pressures were non-dimensionalised with respect to the values of the static pressure, p_∞ , and q , of the incoming flow, in which $C_{pm} = (p - p_\infty)/q$. The sectional lift and drag coefficients (C_l and C_d) were evaluated by integrating the stream wise pressure distributions on the centerline. These generally take the forms

$$C_l = \cos \alpha \left[\int_0^1 (p_u - p_l) d\left(\frac{x}{L}\right) \right] / q \quad (4)$$

$$C_d = -\sin \alpha \left[\int_0^1 (p_u - p_l) d\left(\frac{x}{L}\right) \right] / q \quad (5)$$

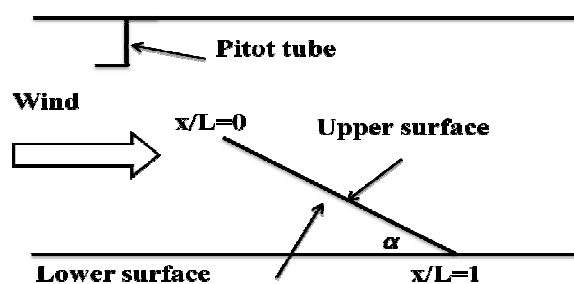


Figure 1: Experimental setup

3. Results and discussion

3.1 Stream wise pressure distributions and aerodynamic characteristics

Examples of stream wise pressure distributions are shown in Figure 2. The front edge of the flat plate corresponded to $x/L = 0$, and the rear edge was located at $x/L = 1$. On the lower surface, there was a mild adverse pressure gradient near the front edge at $\alpha = 15^\circ$, and the level of positive pressure decreased within the one-third of the flat plate at $\alpha = 30^\circ$. The positive pressure then increased moderately close to the rear edge for all of the test cases. The data indicated a minor blockage effect on the flow under the inclined flat plate (attached flow region). On the upper surface, the mean surface pressure distributions revealed an initial expansion near the front edge (flow separation region) and recompression at farther downstream locations.

The level of C_p approached 0 at $x/L \approx 0.5$ ($BR = 2.11\text{--}9.93\%$). For a $BR = 17.64\%$, the location of the maximal C_p moved upstream ($x/L \approx 0.4$), indicating a short reattachment length and remarkably rapid recovery process. In addition, the wind-tunnel blockage effect led to an increase in local flow velocity. The level of C_p decreased as the BR increased, particularly at $\alpha = 30^\circ$. Furthermore, the differential pressure coefficient $\Delta C_p (= (\rho_u - \rho)/\rho)$ corresponded to wind loads on the inclined flat plate. Figure 3 shows examples of ΔC_p distributions. The level of ΔC_p gradually became more negative as the BR increased. For a $BR = 17.64\%$, sufficiently high uplift force (or low ΔC_p) acting on the inclined flat plate was observed, indicating that the blockage correction on the mean surface pressure for an inclined flat plate was definitely required at a BR of more than 10%.

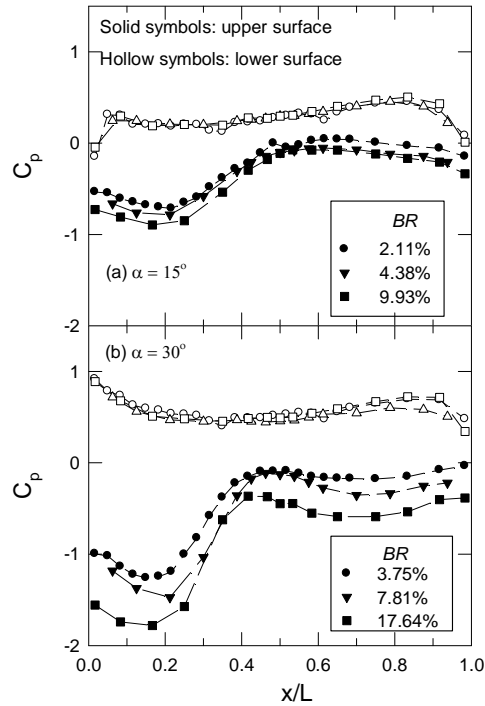


Figure 2: Uncorrected stream wise pressure distributions

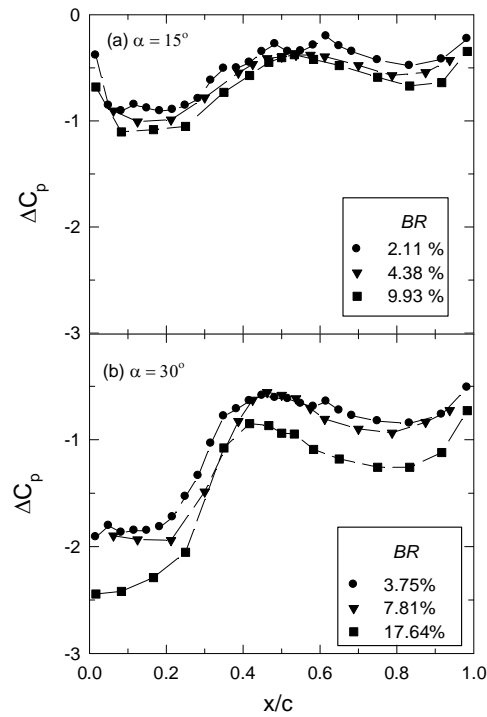


Figure 3: Uncorrected stream wise differential pressure

The data for the sectional lift and drag coefficients are shown in Figure 4. The value of C_d increased linearly as the value of α increased. At a given α , a high BR led to an increase in C_d . Figure 4b shows the variation of C_l with α . In addition, the value of C_l decreased linearly as α increases for each test case. The blockage effect was more substantial at a high BR , in which $C_l = -0.898$ and -1.239 for Case 1 and Case 3 at $\alpha = 30^\circ$, respectively. A BR of 17.64% increased the magnitude of C_l and C_d by nearly 40% compared with the BR in the test case 3.75%.

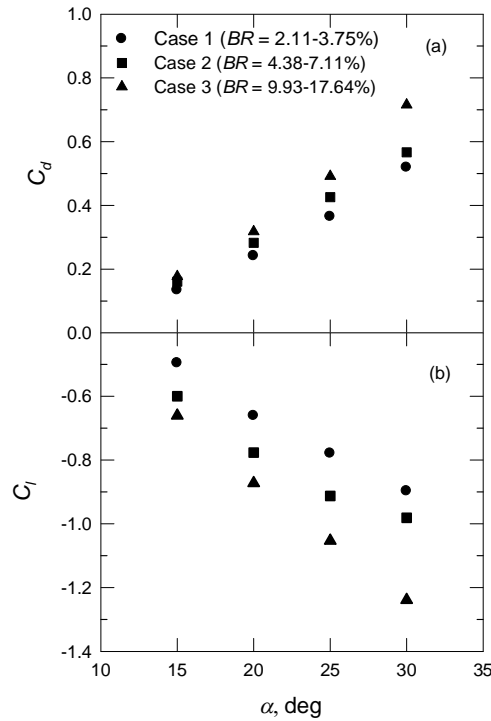


Figure 4 Uncorrected C_d and C_i

3.2 Blockage effect

Templin and Raimondo (1986) demonstrated that the value of the correction factor A can be expressed as a reference pressure or q correction ($q_c/q = 1/A^2$). In the current study, A was deduced from the measured pressure distributions at a high BR ($C_{p,i}$, Cases 2 and 3, $BR = 4.38\%–17.64\%$) compared with the pressure measured at a low BR ($C_{pref,i}$, Case 1, $BR = 2.11\%–3.75\%$). Linear regression was employed to minimise the expression

$$\sum_{i=1}^N \left[(1 - C_{pref,i})^{0.5} - A(1 - C_{p,i})^{0.5} \right]^2 \quad (6)$$

Figure 5 shows A as a function of the BR . At a high BR ($> 10\%$), A decreased as the BR increased. A blockage effect was more evident on the upper surface than on the lower surface. In addition, A was higher than 1 for some test cases on the lower surface (or stagnation flow region), indicating a tendency toward over-correction. Furthermore, the goodness-of-fit can be calculated using the deviation of the pressure coefficient σ_{cp} , which is evaluated according to the corrected pressure coefficient $C_{pc,i}$ and reference pressure coefficient $C_{pref,i}$.

$$\sigma_{cp} = \left[\frac{1}{N-1} \sum_{i=1}^N (C_{pc,i} - C_{pref,i})^2 \right]^{1/2} \quad (7)$$

On the upper surface (separated flow region), σ_{cp} increased for the uncorrected cases at a high BR ; for example, $\sigma_{cp} = 0.46$ for a $BR = 17.64\%$, as shown in Figure 6. When the measured pressure distributions were corrected, the maximal σ_{cp} was 0.11 for a $BR = 15.18\%$. On the lower surface (attached flow region), σ_{cp} was less than 0.1 for all uncorrected and corrected cases. The effect of blockage was only slightly significant.

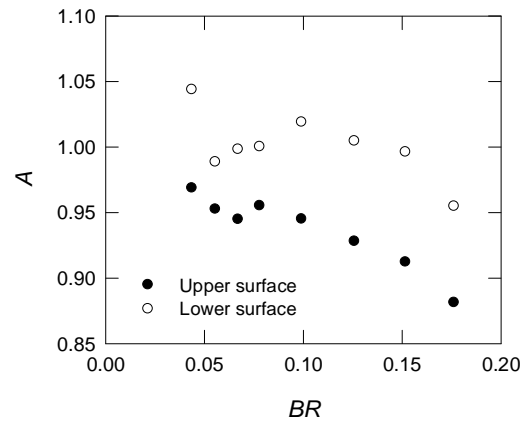


Figure 5: Blockage effect on correction factor A

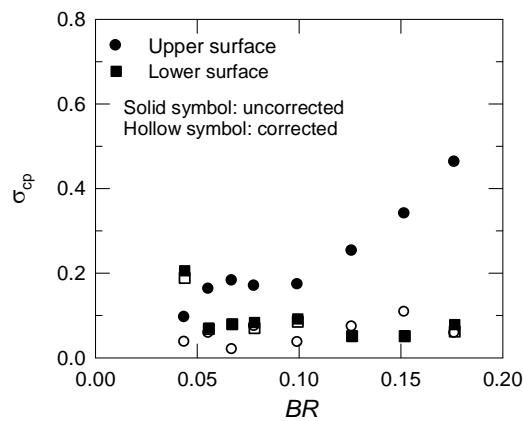


Figure 6: Blockage correction on C_p

As previously mentioned, Sykes (1973) proposed an empirical constant m according to the correlation of the base pressure for a series of rectangular bodies, in which $1-A^2 = mBR$. Therefore, the data were re-plotted to estimate m , as shown in Figure 7. Although the data are slightly scattered, a value of $m = 1.21$ is consistent with the value suggested by Stafford (1981). Furthermore, the correction of dynamic pressure is shown in Figure 8. Because the $BR < 7\%$, a value of $m = 1.90$ (rectangular bodies) was highly consistent with the present experiment. At a high BR , a satisfactory correction can be obtained using Stafford's formula (a small coupe model), implying that the blockage correction depends on the test configuration and blockage ratio. The effect of shifting reattachment points on the upper surface at different tilt angles in the current study might be another concern.

Furthermore, separation primarily occurred at the front upper surface of an inclined flat plate on the wind tunnel floor. Maskell's method for fully separated flow appears to cause the dynamic pressure correction to be underestimated.

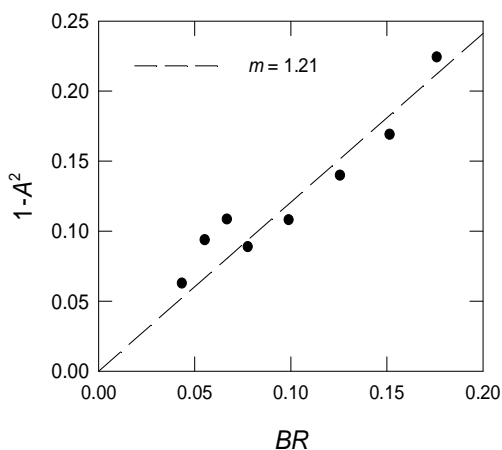


Figure 7: Empirical constant for the test case of an inclined flat plate

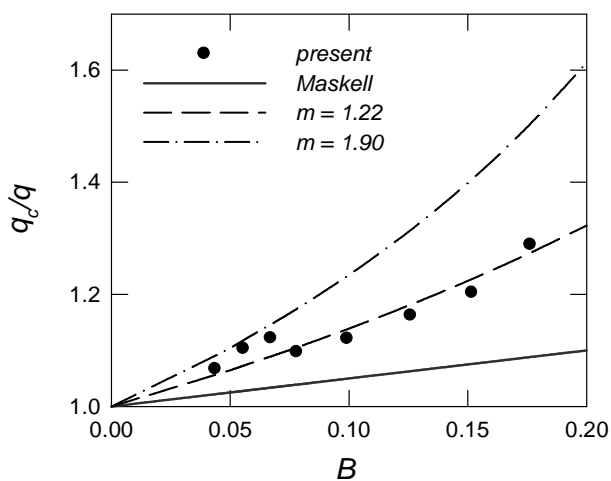


Figure 8: Dynamic pressure correction

Corrected sectional lift and drag coefficients, C_{l_c} and C_{d_c} , plotted against α are shown in Figure 9. The corrected values at a high BR (Cases 2 and 3) are in favorable agreement with the data obtained in the low-blockage wind tunnel (Case 1) at all tilt angles. A deviation in C_d plotted against the BR is shown in Figure 10. As shown in the figure, the magnitude of C_d increased by nearly 40% at high blockage ratios. After the present correction, the deviation was less than 5% for all of the test cases.

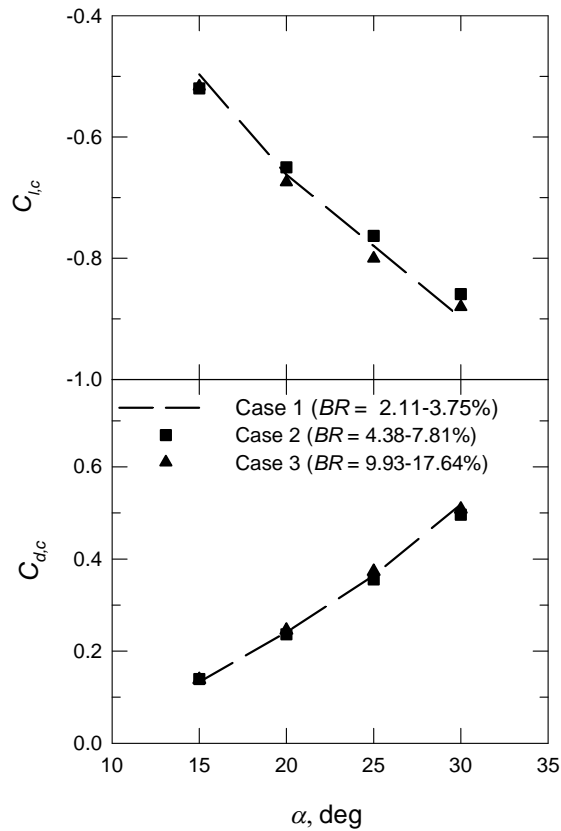


Figure 9 Corrected C_l and C_d

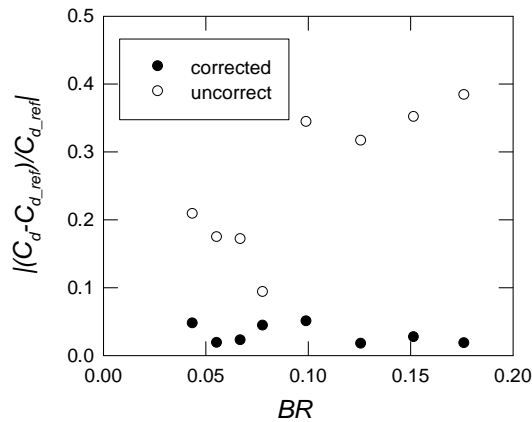


Figure 10 Blockage corrections on C_d

4. Conclusions

The measured pressures along the centerline of an inclined flat plate installed on the wind tunnel floor were compared with the pressures measured in two low-speed wind tunnels. A shorter reattachment length and more rapid recovery process were observed at higher blockage ratios. Deviations in the magnitude of sectional lift and drag coefficients were nearly 40%. In this study, the blockage correction on the mean surface pressure for an inclined flat plate was definitely required at a BR of more than 10%.

A blockage correction method was employed to correct the dynamic pressure. The value of the empirical constant was associated with the test configuration and blockage ratio.

In addition, a tendency toward over-correction was observed in the stagnation flow region. The deviation in the corrected sectional drag coefficient was less than 5% for all of the test cases. However, dynamic flow characteristics (e.g. shifting reattachment points, fluctuating pressures and force coefficients, and Strouhal number) may alter the blockage characterisation.

Nomenclature

| | |
|--------------|--|
| L | length of flat plate |
| C_l | sectional lift coefficient |
| C_d | sectional drag coefficient |
| C_p | pressure coefficient, $(p - p_\infty)/q$ |
| p | mean surface pressure |
| q | dynamic pressure |
| U | wind speed |
| W | width of flat plate |
| x | stream wise distance from the leading edge of the flat plate |
| α | tilt angle of flat plate, in degree |
| ΔC_p | stream wise differential pressure coefficient, $(p_u - p)/q$ |
| C | cross-section area of wind tunnel |
| S | projected area of test model |
| Subscript | |
| low | lower surface |
| up | upper surface |
| ∞ | free stream |
| i | pressure tap number |
| ref | reference state |
| $center$ | centerline |
| c | corrected value |
| uc | uncorrected value |

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