Properties of Flow near a Side-Wall of a Circular Cylinder with Tangential Blowing

(Effects of Slot Shape at Cylinder-Side-Wall Juncture and Angular Location of a Blowing Slot)

By Ryoji WAKA, Funio YOSHINO and Tsutomu HAYASHI

An experiment was carried out to understand effects of the slot shape at the cylinder-side-wall juncture and the angular location of a blowing slot on the spanwise distributions of various characteristic values near the side-wall of a circular cylinder with tangential blowing. The range of the side-wall effects and the characteristic values near the side-wall are much influenced by the slot shape and the location of the slot. When the slot shape like a knife edge, termed "Edge", is used, the range of the side-wall effects becomes narrower as the angular location of the blowing slot is farther downstream.

Key Words: Fluid Mechanics, Circular Cylinder, Tangential Blowing, Characteristic Values, Side-Wall Effect, Vortex

1. Introduction

The authors have carried out systematic investigations on a circular cylinder with tangential blowing, for example, the measurements of various characteristic values such as aerodynamic coefficients, the visualization of flow around the circular cylinder inside the test section and so on. According to these investigations, a strong vortex rolls up near the side-wall in the case of a circular cylinder even if the experiment is carried out on a two-dimensional model. Consequently, a two-dimensional approximation of the flow no longer holds in a wide area near the side-wall and the effect of induced velocity is not negligible even at the mid-span. This is an important problem for a circular cylinder with tangential blowing, because it is difficult to make an aspect ratio of the cylinder large enough.

The area of the side-wall effects is defined as the semi-span minus the spanwise distance from the mid-span to the point at which the two-dimensional approximation does not hold. Then, it is important to understand not only the spanwise distribution of induced angles of attack but also the range of the side-wall effects in order to carry out the experiment on a two-dimensional model. There are, however, only a few investigations on the circular cylinder with tangential blowing \(^{n} \quad^{(n)} \) and even a fewer investigations on the flow near the side-wall. This may have been caused by complexity of this problem and experimental difficulty due to numerous parameters involved.

From these viewpoints, the authors have already published a paper on the range of the side-wall effects and the spanwise distributions of induced angles of attack calculated theoretically\(^{11} \). Moreover, a convenient method using the experimental values at the mid-span was proposed to determine the induced angle of attack at the mid-span. The two-dimensional characteristics of the cylinder were also given from the experimental values by making correction for the effect of the induced angle of attack thus obtained\(^{11} \). After that, the experiment was carried out with the slot shape of the cylinder-side-wall juncture (hereinafter referred to as "slot shape") and the angular location of the blowing slot as a parameter, since the investigation on the side-wall effects was still insufficient.

In this report, the effects of the slot shape and the slot location on various characteristic values near the side-wall are discussed on the basis of known facts in the previous reports.

2. Nomenclature

- \( C_d \): section drag coefficient
- \( C_l \): section lift coefficient
- \( C_{\text{II}} \): lift coefficient normalized by \( C_l \) at the mid-span, \( C_{\text{II}} = C_l / C_l(0) \)
- \( C_p \): pressure coefficient
- \( C_{pb} \): base pressure coefficient
- \( C_m \): momentum coefficient of the blowing jet \( (= \text{momentum of jet per unit span}) / (\rho / 2)(d/2)^2) \)
- \( D \): diameter of the circular cylinder
- \( Re \): Reynolds number \( (= U_d / v) \)
- \( U_0 \): velocity of the uniform flow
\[ y_w : \text{coordinate taken in the port direction from the starboard side-wall} \]
\[ \eta_{sl} : y_w / D \ (\eta_{sl} = 0.5 \text{ at the mid-span}) \]
\[ \theta_{sl} : \text{angle measured clockwise from the leading edge of the cylinder} \]
\[ \theta_s : \text{angular location of the slot} \]
\[ \theta_{sl} : \text{angular position of the separation point on the upper surface of the cylinder} \]
\[ \nu : \text{kinematic viscosity of air} \]
\[ \rho : \text{density of air} \]

Subscripts

ED, ST, SQ : values for the slot shape of "Edge", "Streamline" and "Square", respectively

3. Experimental Apparatus and Method

3.1 Experimental apparatus

The experimental apparatus is the same as one illustrated in the references (1) and (3) except for a height of the slot.

Figure 1 shows a cross section of the model cylinder. A hollow cylinder with an outer diameter of 100mm and a small cylinder with a diameter of 25mm form a blowing slot with a constant height across the whole span. The outer surface of the cylinder is chromium-plated and 335 static pressure holes are circumferentially distributed at 10 spanwise sections. The height of the slot is 0.59mm in the case of varying the slot shape and is 0.58mm varying the slot location.

![Fig.1 Cross section of the model cylinder.](image)

Figure 2 shows a test section of the wind tunnel. The model cylinder is mounted at the center of the test section and passes through two partition-plates of 10mm in thickness inside the test section (hereinafter referred to as "side-wall") and the tunnel walls. The cylinder-side-wall junctions are denoted by the dotted circles in this figure.

Figure 3 shows three kinds of slot shapes used in this experiment. Figure 3(a) shows the slot shape termed "Edge"; the tip of a brass ring of 10mm thickness is sharply shaped like a knife edge over a quarter of its circumference. This brass ring is fixed in the cylinder so that the edged portion of it can contact with the slot. In this case, a jet blown out from the slot flows along the cylinder surface of the both sides of the side-wall after being divided into two parts by the sharply shaped side-wall at the exit of the slot. Next, Figure 3(b) shows the slot shape termed "Streamline"; an epoxy-resin side-wall fairing of 10mm in thickness whose nose is streamlined is put into the inside of the slot at the cylinder-side-wall junction. Then, the side-wall fits in the inside of the slot. A jet flows out from the slot after being divided into two parts by the streamlined nose of the side-wall inside the slot. Finally, Figure 3(c) shows the slot shape termed "Square"; the portion of the brass ring shaped like a knife edge shown in Fig.3(a) is filled up with oil and clay so as to make a tip of the ring 10mm in thickness. A jet is suddenly divided into two parts by a square board of 10mm in thickness at the slot exit. In this report, these slot shapes are identified as "ED", "ST" and "SQ", respectively.

3.2 Experimental method

The experiments were carried out under the conditions of constant \( \Re \) of 2.1 x 10^4 and constant aspect ratio of 8. In the case of varying the slot shape, \( \theta_s \) was fixed at 90° and \( C_0 \) was varied to four different values of \( C_0 = 0.1, 0.2 \) and 0.3 for each slot shape shown in Fig. 3. On the other hand, in the case of varying \( C_0 \), the slot shape of ED was used and \( \theta_s \) was varied to five values of \( \theta_s = 50°, 70°, 90°, 110° \) and 120°. Two experiments for each \( \theta_s \) were carried out; one was a case of varying \( C_0 \) arbitrarily and the other was a case of adjusting \( C_0 \) so as to give the same value of \( C_0 \) for each \( \theta_s \). Two desired values of \( C_0 \) were taken as about 3.6 and 6.2.

The circumferential static pressure distributions were measured with a multtube
manometer for all cases mentioned above.

4. Experimental Results

4.1 The case of varying the slot shape

Figure 4(a) shows the spanwise distribution of upper separation points $\theta_{u}$. $\theta_{u}$ increases over the whole span with an increase of $C_{u}$. $\theta_{u}$ gradually increases with an approach to the side-wall and decreases rapidly after taking a maximum value. Since $\theta_{u}$ takes a minimum value at the side-wall ($\theta_{u}=0$), the separation of flow first occurs there. The effect of the slot shape on $\theta_{u}$ is hardly noticed at the mid-span but clearly noticed near the side-wall. In the cases of ED and ST, the variations of $\theta_{u}$ owing to $C_{u}$ are a little at the side-wall, that is, $\theta_{u}=120^\circ$ at 125$^\circ$ and 115$^\circ$ at 120$^\circ$. However, in the case of SG, $\theta_{u}$ varies in a range of 105$^\circ$ to 120$^\circ$ at the side-wall. The value of $\theta_{u}$ is also smaller than that of $\theta_{u}$ for varying of $C_{u}$ in comparison with the cases of ED and ST.

Figure 5(a) shows the spanwise distribution of the base pressure coefficients $C_{pb}$. Here, $C_{pb}$ is defined as a mean value of $C_{p}$'s at the upper and lower separation points; in the case of $C_{u}=0.1$, it is de-
fixed as a mean value of $C_{p}$ in the separated region. $C_{pob}$ gradually decreases with an approach to the side-wall and increases rapidly after taking a minimum value near the side-wall. As $\theta_{b}$ increases, so does $C_{pob}$. On the contrary, $C_{pob}$ near the side-wall and the minimum value of it decreases. The effect of the slot shape on $C_{pob}$ is observed near the side-wall; $C_{pob}$ near the side-wall decreases in the order of ED, ST, SQ.

Figure 6(a) shows the spanwise distribution of the drag coefficients $C_{d}$. $C_{d}$ increases with an approach to the side-wall and decreases after taking a maximum value. As $\theta_{b}$ increases, $C_{d}$ at the mid-span and the maximum value of it increases and $C_{d}$ at the side-wall decreases. The effect of the slot shape on $C_{d}$ is noticed near the side-wall; $C_{d}$ increases near the side-wall in the order of ED, ST, SQ.

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(a) Case of varying the slot shape

(b) Case of varying the slot location (arbitrary $\theta_{b}$)

(c) Case of varying the slot location (constant $C_{10}$)
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Fig. 6 Spanwise distributions of drag coefficients.

As mentioned above, when the slot shape is varied, the effect of the slot shape on various characteristic values is hardly noticed at the mid-span but clearly noticed near the side-wall. A point or extremum also appears in the spanwise distribution of each characteristic value. The spanwise position of the point of extremum hardly varies with the value of $\theta_{b}$ in ED and ST but varies considerably in SQ (Figs. 6(a) to 6(a)). The spanwise distances from the side-wall to the points of the extremum for each characteristic value $\eta_{w}$ are shown in Table 1. It is found from this table that the positions of extremum move farther from the side-wall in the order of ED, ST, SQ.

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Table 1  Spanwise positions of the extremum of various characteristic values $\eta_{w}$ (case of varying the slot shape).

<table>
<thead>
<tr>
<th></th>
<th>ED</th>
<th>ST</th>
<th>SQ</th>
</tr>
</thead>
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<td>$\theta_{b}$</td>
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<td>0.65</td>
<td>1.65</td>
</tr>
<tr>
<td>$C_{w}$</td>
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<td>0.30</td>
<td>0.64</td>
</tr>
<tr>
<td>$C_{d}$</td>
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<td>-0.65</td>
<td>-0.80</td>
</tr>
<tr>
<td>vortex</td>
<td>-0.50</td>
<td>-0.50</td>
<td>-0.68</td>
</tr>
</tbody>
</table>
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(a) Case of varying the slot shape

(b) Case of varying the slot location

Fig. 7 Spanwise distributions of lift coefficients $C_{10}$ normalized by $C_{1}$ at the mid-span.
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results for the case of ED are drawn by two dotted curves for reference.

Figure 8 shows the static pressure distributions on the cylinder surface for the case of $C_D = 0.3$. This figure is developed surface of the cylinder to give a clearer image of the separated region near the side-wall. The pressure in the separated region near the side-wall becomes lower in the order of ED, ST, SQ and this corresponds to the behaviours of $C_{pb}$ and $C_D$. There is also a particularly low pressure part in the separated region of $\theta = 180^\circ$. According to the observation of the limiting streamlines on the cylinder surface, the spanwise position of this low pressure part is in accord with that of a vortex which shed directly from the cylinder surface and is swallowed up into the center of trailing vortex. The spanwise positions of the vortex center for each slot shape are also shown in Table 1. The position of vortex lies in between those of the extremum of $C_{pb}$ and $C_D$. It hardly changes in the spanwise direction but a little circumferentially with the value of $C_D$ in ED and ST (not shown here).

4.2 The case of varying the slot location.

Figures 4(b) and (c) show the spanwise distributions of $\theta_L$. In Figs. 4 to 6, (b) indicates the case of varying $C_{D}$ arbitrarily for each $\theta_L$ and (c) adjusting $C_{D}$ so as to give the same value of $C_{D_{0}}$ for each $\theta_L$. According to Fig. 4(b), when $\theta_L$ is fixed and $C_{D}$ increases, $\theta_L$ increases over the whole span. The spanwise position of the maximum point scarcely moves with a change of $C_{D}$ but moves toward the side-wall as $\theta_L$ increases. In general, the larger the angle $\theta_L$, the larger is the angle $\theta_L$. In case of the same value of $C_{D_{0}}$ (Fig.4(c)), although the values of $C_{D_{0}}$ are nearly constant irrespective of the values of $\theta_L$, the spanwise distributions of $C_D$ are considerably different among $\theta_L$'s near the side-wall. Namely, in spite of small $C_{D}$, the larger the angle $\theta_L$, the larger is the maximum value of $\theta_L$. Moreover, as $\theta_L$ increases, the spanwise position of the maximum point moves toward the side-wall.

Figures 5(b) and (c) show the spanwise distributions of $C_{pb}$. In Fig. 5(b), $C_{pb}$ increases with an increase of $C_{D}$ for all $\theta_L$'s. For $\theta_L \leq 70^\circ$, the minimum point is not clearly noticed near the side-wall even when $C_D$ is relatively large and $C_{pb}$ decreases slightly toward the side-wall. There is no significant difference owing to $C_D$ among the spanwise distributions of $C_{pb}$. For $\theta_L = 90^\circ$, if $C_D$ is large enough, the minimum point of $C_{pb}$ is clearly noticed. As $C_{D}$ increases, $C_{pb}$ is near the side-wall and at the minimum point decrease. For $\theta_L \geq 110^\circ$, the minimum point of $C_{pb}$ appears near the side-wall even when $C_D$ is considerably small. When $C_D$ increases beyond the value of about 0.1, the minimum value abruptly drops. The spanwise position of the minimum point is nearly independent of $C_{D}$ and is dependent on $\theta_L$ alone; it moves toward the side-wall with an increase of $\theta_L$. In the case of the same value of $C_{D_{0}}$ (Fig.5(c)), the value of $C_{pb}$ are nearly independent of $\theta_L$ for both cases of $C_{D_{0}} = 3.6$ and 6.2. For $C_{D_{0}} = 3.6$, the distribution of $C_{pb}$ is relatively flat and $C_{pb}$ gradually decreases a little near the side-wall. The value of $C_{pb}$ in the case of $\theta_L \geq 110^\circ$ is a little greater than that of $\theta_L \leq 90^\circ$ near the side-wall. For $C_{D_{0}} = 6.2$, however, $C_{pb}$ rapidly decreases and the minimum point is noticed near the side-wall. In particular, $C_{pb}$ decreases remarkably in the case of $\theta_L \geq 90^\circ$ compared with that for $\theta_L = 70^\circ$.

Figures 6(b) and (c) show the spanwise distributions of $C_{D}$. According to Fig. 6(b), $C_{D}$ increases slightly with an increase of $C_{D}$ and the maximum values are noticed in the spanwise distributions near the side-wall for all cases of $\theta_L$. They increase according to $C_D$. For $\theta_L \geq 90^\circ$, the distribution becomes sharper near the maximum point. This tendency becomes stronger when $C_D$ increases beyond the value of about 0.1. Moreover, the spanwise position of the maximum point is independent of $C_D$ and moves toward the side-wall with an increase of $\theta_L$.

Fig. 8 Static pressure distributions near the side-wall (case of varying the slot shape, $C_D = 0.3$).
spanwise distribution of $C_d$ is relatively smooth for each $\beta_j$. For $\beta_j \leq 110^\circ$, the distribution near the side-wall becomes sharper slightly than that for $\beta_j \leq 70^\circ$. The distribution for $\beta_j = 90^\circ$ lies in between those of $\beta_j \leq 110^\circ$ and $\beta_j \leq 70^\circ$. This tendency is more emphasized in the case of $C_10 \leq 6.2$. For $C_10 \geq 6.2$, the distribution curve near the peak becomes particularly steep in the case of $\beta_j \leq 110^\circ$. For $\beta_j = 90^\circ$, $C_d$ becomes larger over a wide range of the span. The spanwise position of the maximum point of $C_d$ moves toward the side-wall with an increase of $\beta_j$ for all cases of $C_10$. Moreover, the value of $C_d$ is smaller than that of $C_40$ very near the side-wall, although $C_40$ does not depend on $\beta_j$. The spanwise distance from the side-wall to the point of the extremum for each characteristic value $\eta_w$ is given in Table 2, where $\beta_j$ is varied for the case of $C_10$.

Figure 7(b) shows the spanwise distribution of $C_1n$. This includes the results of not only the cases adjusting $C_1$ in order to give equal $C_10$ but also of arbitrary $C_1$. If $C_10$ is large enough, the distribution of $C_1n$ is determined by $\beta_j$ alone within the scope of experimental errors. Hence, the spanwise distributions of $C_1$ for various $C_10$ are similar each other except for the case of $\beta_j \leq 110^\circ$ and $C_10 \geq 6.2$.

Figure 9 shows the static pressure distributions on the cylinder surface for $\beta_j = 70^\circ$, $90^\circ$ and $120^\circ$ at $C_10 \geq 6.2$. As $\beta_j$ increases, the vortex moves toward the side-wall and the pressure gradient near the vortex becomes steeper. Hence, the two-dimensional region becomes wider in the left side of the vortex with its rightward movement.

5. Discussion

5.1 The range of the side-wall effects

The spanwise range of the side-wall effects was defined as the range near the side-wall where the flow around the cylinder could not be approximated as quasi-two-dimensional. Then, it is expected that the range of the side-wall effects is closely related to the spanwise position of the rolled-up shed vortex near the side-wall, i.e., this range will become narrower with the movement of the vortex toward the side-wall. The spanwise positions of the vortex $\eta_w$ are already shown in Tables 1 and 2. According to the tables, when the slot shape is varied, the vortex moves toward the side-wall in the order of $S$, $S^*$, $ST$, $ED$. On the other hand, the vortex moves toward the side-wall with an increase of $\beta_j$.

Then, the range of the side-wall effects must become narrower according to the order mentioned above. Since the method of determining this range was already described in reference (1) in detail, it is briefly mentioned here. The range of the experimental scatter of $C_{p_b}$ corresponding to the experimental value of the angular width of the separated region $\theta_b$ at a value of $\eta_w$ is obtained by making use of the experimental relation between $C_{p_b}$ and $\theta_b$ at the mid-span. If the experimental value of $C_{p_b}$ at the same $\eta_w$ falls within this range of scatter of $C_{p_b}$, the flow at that value of $\eta_w$ is

<table>
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<th>$\beta_j$</th>
<th>$\eta_w$</th>
<th>$\eta_w$</th>
</tr>
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<tr>
<td>$5.0$</td>
<td>$7.0$</td>
<td>$9.0$</td>
</tr>
<tr>
<td>$9.0$</td>
<td>$11.0$</td>
<td>$12.0$</td>
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</tbody>
</table>

Table 3 Ranges of the side-wall effects.

<table>
<thead>
<tr>
<th>$\beta_j$</th>
<th>$\eta_w$</th>
<th>$\eta_w$</th>
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<tbody>
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<td>$5.0$</td>
<td>$7.0$</td>
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</tr>
<tr>
<td>$9.0$</td>
<td>$11.0$</td>
<td>$12.0$</td>
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</tbody>
</table>

Fig. 9 Static pressure distributions near the side-wall (case of varying the slot location, $C_10 \geq 6.2$).
determined as "two-dimensional". The range of the side-wall effects is determined as the semi-span minus the spanwise distance of the two-dimensional region. The range obtained by this method is given in Table 3. As mentioned above, this range is also altered according to the variation of the spanwise position of the vortex. The range becomes narrower in the order of St, St, Ed and so does it with an increase of \( \theta_j \). Then, the slot whose shape is Ed ought to be located as far downstream as possible in order to make the two-dimensional range as wide as possible.

5.2 The relations between the slot location, the slot shape and the range of the side-wall effects

As mentioned in the preceding section, the range of the side-wall effects is determined by the slot shape and \( \theta_j \); it is closely related to the spanwise position of the vortex \( \eta_{vw} \).

Figure 10 shows the relation between \( \eta_{vw} \) and \( \theta_j \), obtained from Tables 1 and 2. In Ed, \( \eta_{vw} \) is nearly proportional to \( \theta_j \). Since this relation is independent of \( C_w \), \( \eta_{vw} \) should be determined by \( \theta_j \) alone.

Figure 11 shows the relation between \( C_{10-C1w} \) and \( \frac{C_{pb0-Cpbv}}{2} \), where \( C_{pbv} \) is the minimum value in the spanwise distribution of \( C_{pb} \) and is to be regarded as an approximate value of \( C_{pb} \) at the vortex core on the cylinder surface. \( C_{1w} \) is also the value of \( C_{1w} \) at the side-wall \( (\eta_{vw}=0) \). \( \frac{C_{pb0-Cpbv}}{2} \) is proportional to \( C_{10-C1w} \) in Ed. Now, since \( C_{10-C1w} \) is proportional to the total amount of the trailing vortex shed from the cylinder between the mid-span and the side-wall (hereinafter referred to as "strength of the trailing vortex"), \( \frac{C_{pb0-Cpbv}}{2} \) ought to be proportional to the strength of the trailing vortex. On the other hand, \( \frac{C_{pb0-Cpbv}}{2} \) is approximately proportional to the strength of vortex core (vortex tube), because it indicates a square root of pressure difference between the vortex core and the separated region distant enough from the vortex core. Therefore, if only \( \theta_j \) increases under constant \( C_{10-C1w} \), the vortex core should move toward the side-wall keeping its strength constant since \( \eta_{vw} \) is determined by \( \theta_j \) alone independently of \( C_w \) (Fig. 10). Now, even though \( C_w \) increases under the fixed \( \theta_j \), both the value of \( \eta_{vw} \) and the range of the side-wall effects do not vary as described earlier, but the value of \( C_{10-C1w} \) increases (Fig. 7(b)). Since \( \frac{C_{pb0-Cpbv}}{2} \) increases in proportion to \( C_{10-C1w} \), the vortex core hardly changes in size but increases in strength in this case.

It is concluded from these discussions that the size of the vortex core hardly changes but the spanwise position and the strength of it are affected by \( \theta_j \) and \( C_{10-C1w} \), respectively. Thus it is suggested that only when \( \theta_j \) is varied under the constant \( C_{1w} \), the larger decrease of the minimum value \( C_{pbv} \) of \( C_{pb} \) for \( \theta_j=90^\circ \) than that in the case of \( \theta_j=0^\circ \) (Fig. 5(c)) results from the increase in strength of the vortex core due to the increase of \( C_{10-C1w} \).

On the other hand, when the slot shape is varied under the fixed angle \( \theta_j (=90^\circ) \), the strength of the vortex core is proportional to that of the trailing vortex in Ed. Then, the same discussion also holds in this case. However, even if the value of \( C_{10-C1w} \) is equal to that for Ed, the strength of the vortex core becomes stronger (Fig. 11) and the position of the vortex moves farther from the side-wall (Fig. 10) than in Ed. Since in Ed, the position of the vortex core is varied by \( C_w \) even if \( \theta_j \) is fixed, the same discussion does not hold. The strength of the vortex core, however, becomes greater and its position moves farther from the side-wall than in Ed, even though the strength of the trailing vortex is equal to that in Ed.

6. Conclusions

Experiments were carried out on the spanwise distributions of various characteristic values of a circular cylinder with

![Fig.10 Relation between spanwise position of the vortex and the slot location.](image)

![Fig.11 Relation between the pressure of vortex core on the cylinder surface and the strength of the trailing vortex.](image)
tangential blowing for various locations of the slot, jet intensities and slot shapes. The conclusions from all of these are as follows:

(1) The range of the side-wall effects is determined for each location of the slot and each slot shape as shown in Table 3.

(2) The range of the side-wall effects becomes narrower in the order of SQ, ST, ED. In the case of ED, the larger the angle $\theta_j$, the narrower becomes this range. Also, this range is independent of $C_u$ except for the case of SQ when $C_u$ is large enough.

(3) If $\theta_j$ is fixed, the spanwise distribution of $C_u$ is similar except for the case of SQ but is not similar for the case where $C_u$ is small and $\theta_j \geq 110^\circ$.

(4) The strength of the vortex core is proportional to that of the trailing vortex. In the case of ED, the spanwise position of the vortex core is determined by $\theta_j$ only.

References