Studies on Circular Cascades for Return Channels of Centrifugal Turbomachinery
(2nd Report, Flows and Performances of Cascade)*

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Flow and performances of the cascade designed in the 1st Report were examined experimentally. The main results are as follows.
(1) The flow pattern through the cascade is very complicated owing to the interference between the secondary flow on the end wall and the flow separation on the vane surface.
(2) The pressure on the suction surface recovers slightly even in the region of separation, owing to the secondary flow.
(3) The outlet flow turns into the radial direction near the design point, as expected in the cascade design.
(4) The minimum flow-loss is given at a small positive incidence angle, and the mixing loss downstream of the cascade is considerable.

Key Words : Fluid Machine Element, Return Channel, Cascade, Centrifugal Turbomachine, Internal Flow, Cascade Performance, Secondary Flow, Separation

1. Introduction

In the 1st Report, an inverse method for designing a circular cascade composed of thick-vanes was developed, and the desirable circular cascade for the return channel of a high-pressure large-sized centrifugal turbomachine was designed using this method.

Flow through such a cascade may be accompanied with an intense secondary flow on the end wall and with a flow separation on the vane surface, because of a large deflection angle and a thick-vane. These cause an increase of the flow loss in the cascade. Accordingly, in the 2nd Report, the relations between the through-flow and the cascade performance are made clear experimentally, and the reasonability of the cascade design procedure presented in the 1st Report is confirmed.

2. Experimental Apparatus and Procedures

An experimental apparatus modeling the return channel of a large-sized centrifugal compressor with a high pressure ratio is shown in Fig.1. Eighty rectifying vanes are arranged at the channel inlet and give a swirl velocity component to the inlet flow of the cascade, because it has been made clear that the flow at the return channel inlet (namely, at the outlet section of the upstream cross-over

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Fig.1 Return channel model
scarcely varies in the width direction, though the wake flows caused by the rectifying vanes are observed slightly. The flows and the performances of the cascade were measured under the Reynolds number \(Re=2.6\times10^7\) (based on the mean inlet velocity and the chord length), for various inlet flow angles \(\beta_i\). The measurements at

Sections I-V were done by using a three-holes Pitot-tube. Especially, the flows at Section IV were measured by a five-holes Pitot-tube to know the secondary flow condition in detail. Besides, the boundary layer flow along the vane surface was examined. Its velocity was estimated from the total pressure by an one-hole Pitot-tube and the static pressure on the vane surface. The streaklines on the vane surface were also visualized by the oil-film method.

3. Flow through the Cascade

The flow through the cascade may be complicated owing to the secondary flow on the end wall and the flow separation on the vane surface. Thus, the through-flow conditions at Sections I to IV and the boundary layer flow along the vane surface were examined, under \(\beta_i=\beta_i'\) (\(\beta_i=55^\circ\), \(\beta_i'=36.9^\circ\), \(Re=3.7\times10^7\)). These measuring sections and the main symbols are shown in Fig.3.

3.1 Flows at Sections I-IV

The velocity \(u/v_s\) and flow angle \(\beta\) distributions at each section are shown in Fig.4. The full-line and the dash-line

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Fig.2 Flow condition at the datum section

Fig.3 Measuring sections

(a) Section I (\(u/v_s=0.795\))

(b) Section II (\(u/v_s=0.538\))

(c) Section III (\(u/v_s=0.313\))

(d) Section IV (\(u/v_s=0.41\))

Fig.4 Flow through the cascade
show the experimental result and the calculated one based on the singularity method, respectively. In these figures, the flow condition is shown at the lower-half section (z/L = 0.5), as a symmetrical flow pattern is observed at the upper and lower-half sections (Fig.10). At Section I (Fig.4(a)), the velocity is faster near the suction side of the middle-width section (z/L = 0.5). The flow separation on the vane surface does not appear but the flow angle varies somewhat on account of the secondary flow. The velocity and flow angle of the main flow at the middle-width section are larger than the calculated ones, owing to the boundary layers and the secondary flows. The secondary flow grows markedly at the farther downstream section because the flow deflection angle becomes large, as shown in Fig.4(b). At Section II, a distinct velocity defect region due to flow separation on the suction surface appears. This defect region makes the main flow faster as compared with the calculated one and pushes the flow from the suction side to the pressure side. Moreover, the main flow region with a nearly constant velocity becomes wide. Similar flow pattern is observed at Section III [Fig.4(c)], but the discontinuous surface of velocity is observed near the trailing edge in the pressure side (z/L = 17.8). Such a dead region disappears at Section IV (Fig.4(d)), because of the turbulent mixing downstream of the cascade. The width and velocity defect of the wake flow are remarkable and the flow angle β becomes large near the middle-width section, corresponding to the flow conditions at Sections II and III.

3.2 Boundary layer flow along the vane surface

As mentioned above, the velocity defect region due to the separation varies in the channel-width direction. Thus, the boundary layer flow along the vane surface was examined in detail. The pressure distribution on the middle-span section of the vane is given in Fig.5, in which the full-line shows the calculated distribution and the actual separation point is one obtained by flow visualization based on the oil-film method.

The secondary flow on the end wall affects markedly the flow along the suction surface of the vane. As shown in Fig.6, the flow toward the middle-span from both sides of the vane is observed and the region of separation near the trailing edge shows a triangular profile with the maximum length near the middle-span. Such phenomenon is understood from the velocity distribution shown in Fig.7, in which v∞ and v are the velocities in the boundary layer and at its outer edge (Fig.3). The

Though it is difficult to determine its point strictly, the point where the oil begins to stagnate is adopted here. It coincides considerably well with the point where the pressure recovery along the vane surface begins to decrease suddenly (Fig.5).

Fig.5 Pressure distribution on the vane surface (λ = 1')

Flow direction

Fig.6 Flow on the suction surface of the vane visualised by the oil film method (λ = 1')

Fig.7 Velocity distribution on the suction surface of the vane (λ = 1', Re = 3.7×10^5)
symbol $\delta$ denotes the thickness of the boundary layer defined by a position of $y$ where $u_{w}/w_{m}=0.99$ ($x$: distance from the vane surface). As an abrupt pressure rise scarcely occurs near the leading edge with comparatively small roundness when $\text{Re}=10^5$ ($UL=0.51$ in Fig.5), the transition from laminar to turbulent flow due to the local separation does not occur. Moreover, the experimental Reynolds number is comparatively small, too. Therefore, the laminar flow is kept along the middle-span surface ($z/b=0.5$) and it already separates at $UL=0.16$ [Fig.6(c)]. On the contrary, the transition to the turbulent flow occurs near the vane side ($z/b=0.17$) and no separation occurs even at $UL=0.16$. It seems to be induced from the turbulent fluctuations caused in the boundary layer on the surface by the secondary flow on the end wall. Corresponding to such flow condition, the displacement thickness $\delta'$ of the boundary layer varies obviously in the span direction as shown in Table 1. Where, $\delta'=\int_{0}^{h}(1-u_{w}/w_{m})dy$. The layer on the vane side becomes thinner than on the middle-span, as $UL$ decreases (that is, farther downstream). As mentioned above, the separation begins on the middle-span surface and its region comes to spread gradually into both sides of the vane. Consequently, the pressure on the vane surface recovers slightly even in the region of separation (Fig.5).

In Figs.7(a) and (b), the theoretical velocity distributions on the middle-span surface are also drawn. Though many analytical methods for the boundary layer flow have been reported, the approximate method presented by A. Wallis[20] was applied conveniently without considering the displacement and secondary flow effects. In this analysis, the pressure distribution on the surface was estimated by the singularity method[8]. The analysed velocity distribution is in comparatively good agreement with the results presented at $L=0.3$ [Fig.7(a)]. At $UL=0.2$ [Fig.7(b)], however, the actual velocity near the surface is higher than the analytical one on account of the secondary flow effect. The analytical separation point ($l/L=0.17$) where the shape factor $K$ reaches 3.5, however, coincides well with the actual value $l/L=0.17$ (Fig.5).

As the experiments were carried out under a comparatively small Reynolds number $Re$, the effects of $Re$ on the separation point were predicted using the above mentioned method for the incompressible flow (Table 2). The separation is delayed with an increase of $Re$, because the laminar flow along the vane surface reaches the critical Reynolds number $Re$, and translates into a turbulent flow.

On the contrary, the flow along the pressure surface is hardly affected by the secondary flow. As shown in Fig.5, the laminer flow translates into a turbulent flow near the leading edge, owing to the local separation caused by a marked pressure rise ($UL=0.54$ in Fig.5). In this case, the flow separates from the surface close to the trailing edge and its region does not vary in the span direction.

Table 1 Displacement thickness of the boundary layer on the suction surface of the vane ($l_{w}=1''$, $K_{w}=3.7\times10^{5}$)

<table>
<thead>
<tr>
<th>$UL$</th>
<th>0.3</th>
<th>0.2</th>
<th>0.16</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\delta'$ (mm)</td>
<td>0.5</td>
<td>0.248</td>
<td>0.622</td>
</tr>
<tr>
<td></td>
<td>0.34</td>
<td>0.225</td>
<td>0.586</td>
</tr>
<tr>
<td></td>
<td>0.17</td>
<td>0.312</td>
<td>0.424</td>
</tr>
</tbody>
</table>

Table 2 Effect of the Reynolds number on the suction side separation point of the vane ($l_{w}=1''$, $K_{w}=3.7\times10^{5}$)

<table>
<thead>
<tr>
<th>$Re$</th>
<th>Transition point $l/L$</th>
<th>Separation point $l/L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3.7\times10^{4}$</td>
<td>0.187</td>
<td>0.379</td>
</tr>
<tr>
<td>$8.1\times10^{4}$</td>
<td>0.329</td>
<td>0.422</td>
</tr>
</tbody>
</table>

Fig.8 Velocity distribution on the pressure surface of the vane ($l_{w}=1''$, $K_{w}=3.7\times10^{5}$)

Besides, the boundary layer is as thin as $\delta'=0.22mm$ at $UL=0.9$.

4. Effect of the Incidence Angle on the Cascade Outlet Flow

As the incidence angle affects the appearances of flow separation and secondary flow, the separation on the suction surface and the flow at Sections IV and V were investigated for various incidence angles.

4.1 Separation point

The separation points on the middle-span surface of the suction side are shown

\[ l_{w}=1''/\lambda_{w}=6\times10^{5} \] for the flat plate[2-6x10^{5}] and $\eta=1.8$ as the initial conditions, the turbulent boundary layer was analyzed using the momentum- and energy-integral equations, and the equation for the skin-friction due to Dudley-Tillman[20]. The separation point was located at the position where $\eta=1.8$. 

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in Fig.9. They were obtained by the flow visualization based on the oil-film method, and the ordinate gives the non-dimensional length from the trailing edge to the separation point on the vane surface. For the negative incidence angle \( i_1 \), the region of separation is narrow, but it has a tendency to spread gradually as the incidence angle increases and \( i_1 \) takes the maximum value at \( i_1 = 13^\circ \). When \( i_1 \) increases more, the region becomes narrow again because the separation mode changes from the laminar separation to the turbulent one. Such transition is caused by the local separation owing to an abrupt pressure rise near the leading edge. The region, however, spreads suddenly for \( i_1 > 13^\circ \).

In this figure, the separation points predicted by the above laminar and turbulent analyses are also given. In the range of \( i_1 < 3^\circ \), the predicted point is in acceptable agreement with the experimental one. For \( i_1 > 3^\circ \), however, both do not coincide because the reattachment condition after the local separation is not clear and the secondary flow seems to affect markedly the flow along the suction vane surface.

### 4.2 Flow condition downstream of the cascade

The iso-velocity lines and the velocity vector giving the velocity component parallel to the \( (Z, \phi) \)-plane at Section IV ( \( R/R_s = 0.4 \), Fig.9) are shown in Fig.10, in which the abscissas \( \phi = 0^\circ \) and \( 18^\circ \) correspond to the positions of the trailing edge. Irrespective of the incidence angle, a pair of large circulations caused by the secondary flow are observed. Besides, the velocity distribution in the section for \( i_1 = 13^\circ \) much differs from the case for \( i_1 = 1^\circ \). As recognized in Figs.10 and 4(d), the thickness of the boundary layer on the end wall varies in the angular direction. The layer becomes thinner at \( \phi = 14^\circ \) near the pressure side of the vane and its thickness depends on the incidence angle \( i_1 \). Figure 11 shows the velocity distributions in the width direction \( (z \)-direction) at \( \phi = 15^\circ \). Here, \( x_{max} \) is the maximum velocity in Section IV. In the case of \( i_1 > 8^\circ \), the growth of the boundary layer is suppressed obviously by the displacement effect due to the flow separation on the vane near the middle-width section ( \( x/b = 0.5 \)). The thickness, however, grows with a decrease of \( i_1 \) because of the decrease of such displacement effect.

To know the wake flow pattern in detail, the velocity and flow angle distributions at the middle-width section are shown in Fig.12. Figure 13 shows the maximum velocity defect \( u_{max} \) and the half width of the wake \( W \), measured along the angular direction. It can be known from these figures that the maximum defect and the half width increase gradually and the wake region moves to the pressure side with an increase of the incidence angle, though the region of separation becomes narrow once in the range of \( 3^\circ < i_1 < 8^\circ \). The

\[ * \text{The turbulent boundary layer flow is analyzed by the same method as described in the footnote of 3.2.} \]
Fig. 12 Flow distribution in the angular direction on the middle-width section (Section IV)

The main reason for this phenomenon seems to be that the wake region is shifted to the pressure side by an intense secondary flow toward the pressure side near the middle-width section when $i$ becomes large.

Though the flow pattern at the cascade outlet is very complicated, the velocity distribution farther downstream becomes uniform, as shown in Fig. 14. The flow angle, however, varies slightly in the channel width direction. In this figure, the velocity and flow angle distributions at the section, which divides one pitch into three equal parts, are indicated with a different mark.

5. Cascade Performances

5.1 Outlet Flow Angle

The flow angle downstream of the cascade is discussed by using the mean flow angle $\delta$ weighted by the flow rate, as the flow angle $\delta$ varies markedly in Section IV. The relation between $\delta$ and the inlet flow angle $\beta$ is shown in Fig. 15. The deflection angle is given by $\delta = \beta$. In this figure, the inlet setting angle of the vane is also marked by $\beta = 0^\circ$ and the right side from its mark shows the distribution for the positive incidence angle. The downstream flow angle is decided practically by the flow at the cascade outlet and is nearly equal to one at Section IV. The value of $\delta$ is independent of the inlet flow angle $\beta$ in the range of $55^\circ < \beta < 68^\circ (-1^\circ < \beta < 12^\circ)$, and the outlet flow turns into the radial direction as expected in the cascade design. When the inlet flow angle comes to decrease from this range, the outlet flow angle increases because the flow through the cascade does not turn sufficiently. On the contrary, with an increasing inlet flow angle, the outlet flow angle decreases conversely because of an intense secondary flow on the end wall.

In Fig. 15, the flow angles for Aerofoils A and B presented in the 1st Report are also given. Those three distributions have the same tendency in spite of the different profiles, but the deflection angle for Aerofoil B is smaller and its downstream flow has a comparatively large whirl component.

Fig. 13 Characteristics of the wake flow on the middle-width section (Section IV)

Fig. 14 Flow at Section V

(a) At Section IV

(b) At Section V

Fig. 15 Flow angle downstream of the cascade
4.2 Loss coefficient

The flow-loss coefficients $\xi_m$ between the datum section (Section 0) and Sections IV, V are shown in Fig.16. Where, $\xi_m = (P_2 - P_1)/(1/2 \rho V_1^2)$. $P_1$ is the mean value of the total pressure weighted by the flow rate and the subscript 0 means the value at the datum section. The loss from Section 0 to IV does not include the downstream mixing loss whose value is affected mainly by the flow separation on the vane surface. Accordingly, the evaluation of the loss between Section 0 and Section V, where a pretty uniform flow is observed, is more reasonable though the bend loss is also included. The loss coefficient becomes minimum at a small positive incidence angle where the region of separation on the suction surface becomes narrow. Under a large positive incidence angle, $\xi_m$ increases owing to an increase of the secondary flow and separation losses. Under the negative incidence angle, the loss also increases because the boundary layers on both end walls grow considerably and the scale of local separation near the leading edge enlarges. Though these phenomena are independent of the evaluated section, the value between Sections 0-V is naturally large. Especially, the loss from Section IV to V is considerable, which shows that the turbulent mixing and bend losses can not be disregarded.

The loss in the tested cascade is less than that in Aerofoil A for the same deflection angle. The minimum loss in Aerofoil B is almost the same as that in the tested aerofoil, as the former has an undesirable whirl component and a comparatively high velocity head downstream of the cascade.

6. Conclusions

The flow conditions and performances for the cascade designed by the inverse method were examined experimentally, continued from the 1st Report. The following results are induced mainly from the experiments:

(1) The flow condition at the cascade outlet is very complicated because the secondary flow on the end wall interferes with the flow separation on the vane surface in the cascade. Besides, the flow predicted by the singularity method does not coincide with the actual one, when the through-flow is affected by the separation on the vane surface.

(2) The secondary flow on the end wall affects markedly the flow along the suction surface of the vane. The flow along the suction surface begins to separate from the middle-span surface and its region spreads into both vane sides (end walls). Accordingly, the pressure along the suction surface recovers slightly even in the region of separation.

(3) The maximum velocity defect and its region caused by the flow separation on the suction surface of the vane are remarkable near the middle-width section. As its displacement effect decreases with a decrease of the incidence angle, the boundary layer on the end wall becomes thick.

Fig. 16 Flow-loss coefficient

(4) The flow downstream of the cascade turns into the radial direction near the design point, as expected. The inlet flow angle to the next-stage impeller is decided by the flow angle at the cascade outlet.

(5) The flow loss becomes minimum at a small positive incidence angle, and is less than that for the cascade used in the preliminary experiments, which gives the same deflection angle. The mixing loss downstream of the cascade is considerable and can not be disregarded.

Continuously, the through-flow with the separation is discussed theoretically in the 3rd Report. Besides, the authors have reported in the Proc. IAHR 1984 Symposium held in Stirling that the performance of the return channel may be improved more successfully by using the tandem cascades.

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References


