Experimental Research of the Secondary Flow in Rectilinear Turbine Cascades

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ABSTRACT

For studying the secondary flow in a turbine cascade, the flow field is measured in detail. The measurements of pressure and velocity are taken at various axial planes upstream of, within, and downstream of the cascade by a 4-hole probe. The static pressures are taken on the endwall, suction and pressure surfaces. By treating the experiment data the mechanism of the secondary flow field and the loss model are proposed in this paper.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>b</td>
<td>axial chord</td>
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<tr>
<td>c</td>
<td>chord</td>
</tr>
<tr>
<td>E</td>
<td>energy deficit</td>
</tr>
<tr>
<td>L</td>
<td>circumference of airfoil</td>
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<tr>
<td>l</td>
<td>length along airfoil surface nondimensionalized on L</td>
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<tr>
<td>P</td>
<td>pressure</td>
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<tr>
<td>P</td>
<td>static pressure coefficient</td>
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<tr>
<td>P_o</td>
<td>total pressure</td>
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<tr>
<td>P_o</td>
<td>upstream inlet pressure to cascade</td>
</tr>
<tr>
<td>u</td>
<td>velocity</td>
</tr>
<tr>
<td>U_o</td>
<td>upstream inlet velocity to cascade</td>
</tr>
<tr>
<td>X</td>
<td>coordinate normal to cascade leading edge (axial direction)</td>
</tr>
<tr>
<td>Y</td>
<td>coordinate parallel to cascade leading edge (pitchwise)</td>
</tr>
<tr>
<td>Z</td>
<td>coordinate normal to endwall (spanwise)</td>
</tr>
<tr>
<td>ti</td>
<td>outlet angle</td>
</tr>
<tr>
<td>e, f</td>
<td>density</td>
</tr>
<tr>
<td>b, s, a</td>
<td>boundary layer</td>
</tr>
<tr>
<td>f, l_o</td>
<td>total pressure loss coefficient</td>
</tr>
<tr>
<td>g_o</td>
<td>pitch averaged total pressure loss coefficient</td>
</tr>
<tr>
<td>z_o</td>
<td>in the new endwall boundary layer</td>
</tr>
<tr>
<td>z_s</td>
<td>in the secondary flow region</td>
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Subscripts

- ps = pressure side
- s = suction side
- a = atmosphere
- i = measured point
- 1 = inlet
- 2 = outlet

INTRODUCTION

Losses in two-dimensional turbine cascades are usually obtained by experiment. A number of studies on two-dimensional cascade losses i.e. profile losses have been done. Ref. [1] produced a formula of estimating the loss coefficient of a turbine cascade on the basis of experiments. Several experimental correlations of the cascade losses of transonic turbines have been obtained [2]. However two-dimensional cascade losses only are a small part of the total losses for the design of an advanced turbine. So it is very important to find out the rule of the endwall effect and the secondary flow loss model.

The experiment have been done for finding out the physical nature of secondary flow losses in Gas Turbine Lab of Tsinghua University. Measurements of the flow structure and the loss distribution were taken behind the cascade and tests were made with a natural inlet boundary layer. Results were shown in Ref. [3]. The experiment verifies that the vortex core is in existence and its approximate position can be found. Measurements of outlet flow field also were taken with an artificial thickening inlet boundary layer generated by means of adding a turbulent network. Comparison of outlet flow fields obtained by various inlet boundary layer was presented in Ref. [4]. It shows that the thickness of the artificial inlet boundary layer doubles, but it does not cause the change of the nature of the outlet flow field. The loss distribution of outlet plane just verifies that the cascade secondary flow is the renewed distribution of the inlet boundary layer at outlet plane as it mentioned in [5]. Some information of new endwall boundary layer was also obtained. However we deem it very difficult to propose a secondary loss model without the inner flow field in whole cascade passage.
Langston [6] and Sieverding [7] have measured this flow field in their own Labs. Their results can be regarded as a good foundation to describe the nature of the secondary flow in turbine cascade and the new endwall boundary layer near the outlet of the cascade. Gregory-Smith [8] gave a prediction method of the secondary losses by estimating three components and adding them together. Three component losses are the loss core, the new endwall boundary layer loss and the kinetic energy loss of the secondary flow, they all can be calculated or estimated simply. So that based on Gregory-Smith's method, it is possible to predict the secondary loss distribution along blade span without complex calculations or experiments. However the agreement between the estimated and the experimental losses is to be improved. According to our experience it seems that the secondary flow kinetic energy loss is too high on Fig. 3 in reference [8]. In this paper we will try to present a loss model according to detailed experiments of a turbine cascade in our own Lab.

EXPERIMENT

Experimental Apparatus
Experiments were conducted in a low-speed cascade wind tunnel with M=0.2. The test cascade consists of six blades. A cross sectional sketch of the test section is shown in Fig. 1.

The blade profile is the hub of the stator blade of a high pressure turbine first stage. For accurate measurements the blades were enlarged adequately. The cascade geometry is as follows:

Chord c=120.4 mm
Chord/ Axial chord=1.696
Pitch/Chord=0.7568
Aspect ratio (Span/chord) =1.047

There are 5 slots in the upper endwall of the cascade, which can accept a probe to measure the inner flow field of the cascade passage. The probe can be traversed along pitchwise (Y) and spanwise (Z). The lower endwall is instrumented with 25 static pressure taps (0.5mm) at 5 quasi-streamlines.

There are two rows of static pressure taps on both suction and pressure surfaces at 50 percent and 13 percent of two blade spans measured from the lower endwall.

Inlet Boundary Layer Measurements

The inlet boundary layer is the main factor causing the cascade secondary flow. It is necessary to measure accurately the velocity distribution of inlet boundary layer. The velocity measurements were made in the plane 47mm upstream of the cascade (See Fig. 1). 60-65 points along spanwise were taken from 0.15mm of the endwall to midspan. Fig. 2 shows the velocity distribution of inlet boundary layer. By using least squares to fit, the velocity distribution is found divided into three parts. Their analytical relations are:

1. \( \frac{u}{U_o} = \left( \frac{Z}{4.71} \right)^{1/4.55} \) 0<Z<1.2,
2. \( \frac{u}{U_o} = \left( \frac{Z}{15.5} \right)^{1/14.36} \) Z*3.55, U_o = 19.15m/s
3. \( \frac{u}{U_o} = \left( \frac{Z}{15.5} \right)^{1/6.61} \) Z<15.5

The boundary layer thickness is 15.5mm. From the velocity profile, it can be considered that the boundary layer is a turbulent flow boundary layer. It consists of layer flow region (near the endwall), transition region and full-developed turbulent flow boundary layer. This is in agreement with the characteristics of the turbulent boundary layer of a plane. The measurement accuracy close to endwall is slightly lower because the probe blocks up in that region.

Profile Surface Static Pressure Distribution

Fig. 3 shows the distribution of the nondimensional static pressure coefficient \( P \) along the blade surfaces. It can be seen the variation of the profile surface static pressure is not large along spanwise, although the secondary flow exists. \( P \) has also been obtained by calculating in Ref. [9], which agrees with by measuring.

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Exit Flow Field Measurement
Detailed measurement of the three-dimensional flow field were made at 13.5mm downstream of cascade. 10 points in span-wise (midspan to 1.5mm of the endwall) and about 45 points in pitchwise were taken (including one pitch and two wakes). The results obtained by data processing shown in Fig. 4 indicate that the loss characteristics at the trailing edges of two blades are similar and the high losses appear near the endwall and the corner where the endwall interacts with the suction surface. The profile losses is concentrated at wake, and the loss is extremely low at midsnan. The pitch averaged loss coefficient was calculated from the definition:

\[ \bar{\omega} = \frac{1}{V} \int_0^V \omega \, dv \]

Its spanwise distribution is shown in Fig. 5. There are two peaks in it. Close to endwall, the curve is very precipitous, namely the first peak, which is caused by new endwall boundary layer. The secondary peak, namely the secondary flow region, extends widely from 10 to 30mm. In midspan region, \( \bar{\omega} = 0.05 \), which is agree to \[2\] in high speed testing.

Outlet angle spanwise distribution averaged with pitch conforms to triangular model of the secondary flow angle correction (Ref. [10]). Near the endwall, there is a deviation, but this region is a small part out of the whole passage and the velocity is lower in it. So there is little effect on the work distribution of a turbine stage. (See Fig. 6).

Measurements of Flow Field in cascade passage
It is necessary to measure whole three-dimensional flow field in cascade passage for studying growth and development of the secondary flow. The measurements were made with four-hole probe at axial plane I, II, III, IV, V (See Fig. 1). The detailed experimental data is in [11].

In each plane 7-10 points (along Y) and 10-12 points (along Z) were taken. From Fig. 7(a) the isobar plots are horizontal in plane I and the losses are extremely low expect close to endwall region (about one thickness of inlet boundary layer). Following the fluid forward the high loss region is getting extended i.e. the secondary flow growth and development. In plane II, see Fig. 7(b), the high loss region extends widely and the flow begins to roll up. The losses of the suction surface are larger than the pressure surface. The isobar plot close to midspan is getting vertical. Unfortunately, when a strong pressure gradient exists, the problem of a probe characteristic correction has not been solved yet. So the secondary velocity profile has not obtained accurately. It will be further researched.

The secondary flow is defined that the two-dimensional isentropic flow parameters, which are calculated by time-marching method [9] are subtracted from the measured parameters.

ANALYSIS

Secondary Flow Pattern
The blade used by test is typical stator blade. Its turning angle is 70° and the secondary flow is not too serious. But the secondary flow characteristics can be obviously distinguished according to flow field measured.

The secondary flow velocity field is shown in Fig. 8. As seen, the vortex center is located in the interacting...
The distance of vortex center from the endwall is of the order of the thickness of inlet boundary layer as it mentioned in [8] and [10]. The distance is equivalent to the second loss peak as shown in Fig. 4.

The secondary velocity close to the endwall is not very strong, this is because of the stagnant effect of viscosity of the new endwall boundary layer on vortex. Judging from the secondary flow velocity of trailing edge near pressure surface, the existence of opposite vortex is possible.

The kinetic energy loss of the secondary flow is slight, well below 0.01 so it does not much affect the triangular loss distribution.

The loss coefficient of the new endwall boundary layer is defined as

\[ \frac{U_e}{U_2} = 1 - \left( \frac{U_{2}}{U_2} \right)^2 \]

Because of the accelerate flow, the new endwall boundary layer in cascade is not very thick. It can be calculated easily by integral equation along the mean curved streamline from plane III (the maximum turning plane to exit plane). The parameters on the mean streamline is taken from the two-dimensional isentropic flow through a rectilinear cascade passage using program in [9]. For this example \( \delta_c \) is equal to 10mm and the velocity profile is assumed 1/7 law, so the loss coefficient distribution within 0 to 10mm is obtained
Fig. 7 ISOBAR PLOT OF TOTAL PRESSURE LOSS COEFFICIENT IN PLANE I & PLANE III

Fig. 8 SECONDARY FLOW VELOCITY FIELD
The loss distribution with spanwise is obtained by summation of the three components. Comparison between the estimated value and the experimental value is shown in Fig.5. The prediction of loss by the model is rather useful to turbine designers, although it is not quite satisfactory and needs improvement.

Certainly, in the real turbine cascade, the flow pattern near the endwall is very complex and a lot of aerodynamic and geometric parameters can effect on secondary losses. The interaction of components can play an important role sometimes. In this estimate method, the passage convergence, incidence and the flow turning can be taken into account in the calculation of new end wall boundary layer loss, but it can not effect on the redistribution of the inlet boundary layer. The interaction effect is not considered at all. It will be studied and developed in future.

CONCLUSIONS

Summing up the results of experiments and analysis, the following descriptions of the flow through the turbine cascade passage present.

The inlet boundary layer roll up at the maximum turning of the cascade passage.

The distance between the center of the secondary flow vortex and the endwall is about equal to the thickness of inlet boundary layer.

Because the endwall boundary layer and the secondary flow do not disturb strongly each other in relative long blading, the cascade loss spanwise distribution may be assumed to be the sum of three components. These components can be predicted individually.

The secondary flow loss may be predicted by redistributing kinetic energy deficit of inlet boundary layer over the secondary flow region of the passage exit according to triangular model.

The thickness of outlet endwall boundary layer determines the loss model accuracy to a great extent. Further study is therefore necessary.

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REFERENCES