Three-Dimensional Fluid Flow Phenomena in the Blade End Wall Corner Region

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ABSTRACT

The three-dimensional flow in the blade end wall corner region was investigated. The techniques used in the investigation included flow visualization, static and total pressure measurements with conventional probes, and mean velocity profile measurements with a single sensor inclined hot-wire probe. Six critical axial stations along the blade chord were chosen for detailed measurements based on the flow visualization results. A large number of data points were obtained very close to the corner walls at each axial location including all the components of the mean velocity. Based on the measurements, three vortices were identified. A horseshoe vortex started near the leading edge. A corner eddy was formed between the horseshoe vortex and the corner. Another vortex was formed at the rear portion of the corner due to the secondary flow of the second kind. The relative size and the rate of spread of the vortices in the streamwise direction are discussed.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>( P_{op} )</td>
<td>Total pressure at the peaks</td>
</tr>
<tr>
<td>( P_{oc} )</td>
<td>Constant total pressure in the traverses parallel to the flat plate</td>
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<tr>
<td>( P_{om} )</td>
<td>Total pressure at minima</td>
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<tr>
<td>( P_{om} )</td>
<td>Total pressure at maxima</td>
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<tr>
<td>( P_{o} )</td>
<td>Total pressure</td>
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<tr>
<td>( P_{oc} )</td>
<td>Constant total pressure in the traverses parallel to the flat plate</td>
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<tr>
<td>( P_{om} )</td>
<td>Total pressure at minima</td>
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<tr>
<td>( P_{oa} )</td>
<td>Free stream total pressure</td>
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<tr>
<td>( P_{s} )</td>
<td>Static pressure</td>
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<tr>
<td>( R )</td>
<td>Reynolds number</td>
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<td>( R_{sp} )</td>
<td>Reynolds number based on momentum thickness</td>
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<tr>
<td>( \bar{U}, \bar{V}, \bar{W} )</td>
<td>Components of mean velocity in ( X, Y ) and ( Z ) directions, Fig. 1.</td>
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<tr>
<td>( \bar{U}<em>{1}, \bar{V}</em>{1}, \bar{W}_{1} )</td>
<td>Components of mean velocity as shown in Fig. 1.</td>
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<tr>
<td>( \bar{U}_{\infty} )</td>
<td>Undisturbed mean free stream velocity</td>
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<td>( U^* )</td>
<td>Friction velocity</td>
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<td>( X, Y, Z )</td>
<td>Coordinates, Fig. 1.</td>
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<tr>
<td>( Y_{p} )</td>
<td>Distance of the position of peak total pressure from the airfoil surface</td>
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<tr>
<td>( Y_{d} )</td>
<td>Distance of the position of depression on total pressure profile from the airfoil surface</td>
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<tr>
<td>( Z_{M} )</td>
<td>Height above the flat plate at which maximum occurs</td>
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<tr>
<td>( Z_{m} )</td>
<td>Height above the flat plate at which minimum occurs</td>
</tr>
<tr>
<td>( \delta )</td>
<td>Distance at which ( \bar{U}/U_{\infty} ) is 0.995 (boundary layer thickness)</td>
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<tr>
<td>( \Theta )</td>
<td>Momentum thickness</td>
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<tr>
<td>( \nu )</td>
<td>Kinematic viscosity</td>
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Superscript

\( ^{RMS} \) RMS value of the fluctuating quantity
INTRODUCTION

A substantial portion of the losses in compressors and turbines are due to the secondary flows. The contribution of the mainstream secondary flow loss to the total secondary flow loss is relatively small, Lakshminarayana and Horlock [1]. The major part of the secondary flow loss is due to the interaction of the wall boundary layers with the blade rows in the blade end wall region. Sieverding [2] has extensively reviewed the experimental results on the blade end wall flows and provided related physics of the mechanisms involved. He indicated that the formation of horseshoe vortices in front of the leading edge of the blades due to the rolling up of the end wall boundary layers, is a complex phenomenon. The physics of horseshoe vortex formation and its displacement and diffusion in cascades has also been described by the investigations of Binder and Romey [3], Langston [4], Herzog and Hansen [5], Langston, Nice and Hooper [6], Moore and Ramsay [7], and Moore and Smith [8]. Losses near the tip of rotors were studied by Pandya and Lakshminarayana [9,10] and Hunter and Cumpsty [11]. The flow along streamwise corner has been studied by many investigators: Zamir [12,13], Zamir and Young [14,15], Perkins [16], Brundrett and Baines [17], Launder and Braggs [18], Perkins and Braggs [19], Gessner and Emery [20], Hanjalic and Launder [21], to mention a few. In the case of a turbulent flow along a streamwise corner, inhomogeneous and anisotropic Reynolds stresses produce a pair of contra-rotating vortices, while the effect of prevailing turbulence on the horseshoe vortex is to diffuse it. However, the effect of the solid walls on the horseshoe vortex is not fully known.

The study of the flow near a simplified wing-body junction is an intermediate step between the flow in an actual streamwise corner and the flow in the blade end wall corner region. To improve the integral method, East and Hoxey [22,23] conducted flow visualization and pressure measurement experiments near the leading edge of a simplified wing body junction. Sepri [24], Chu and Young [25], and Young [26] reported investigations carried out in a simplified wing body junction. Flow visualization studies showed that the formation of one or more vortices depends on the Reynolds number. Stanbrook [27] studied the combined effects of nose and wing leading edge shape on the flow in the wing-body junction at sonic and supersonic free stream velocities. Shabaka [28], from his experimental investigation and subsequent analysis, concluded that eddy viscosity and mixing length models are not suitable for the flow in the wing body junction where asymmetric boundary layers interact. He found that the secondary flow in this case was of skew-induced type and there was no evidence of the double vortex pair, characteristic of stress induced secondary flow. Recently, Moore and Forlini [29] measured the flow in the horseshoe vortex around a Rankine half-body in a duct. Moore and Moore [30] used a numerical technique for the calculation of a horseshoe vortex flow and compared the results with Moore and Forlini [29]. Gorski et al. [31] developed a method using a k-ε model to predict flow in the simplified wing body junction and verified the results by comparing the predicted secondary flow velocities with the measurements reported by Shabaka [28].

In this paper the experimental results on fluid flow phenomena in the blade end wall corner region are presented and discussed to explain the distortion of the total pressure profiles, streamwise velocity profiles and the limiting streamlines.

EXPERIMENTAL METHOD

The Model and The Wind Tunnel. The model consisted of a flat plate and two NACA 65-015 base profile airfoils fixed to either side of the flat plate along the center line as shown in Fig. 1. The flat plate was of double walled construction; 46 cm wide, 91 cm long, and 1.9 cm thick due to the interaction of the wall boundary layers. The airfoils had a 21.9 cm span and a 25.4 cm chord with a 1.27 cm leading edge diameter and a 0.254 cm trailing edge diameter. There were two rows of static pressure holes on each side of the flat plate. The initial 7.0 cm of the flat plate was made rough by affixing a piece of sand paper with 0.2 cm grit size and 15 grits/cm² to promote a thick boundary layer. The airfoils were attached to the plate with its chord parallel to the centerline and the span normal to the surface of the flat plate.

A low subsonic open circuit wind tunnel was used for the experiments. The velocity of air at the 46 cm x 46 cm test section can be varied from 5 m/s to 35 m/s with the help of the inlet guide vanes. Non-uniformity in the mean velocity profile was less than ±0.5% and the turbulence intensity was less than 0.1%, in the absence of any model and near the maximum velocity of the air stream.

A combination of two grids was used to create 1.5% free stream turbulence at a distance of 107 cm downstream of the grid to avoid separation on the airfoil surface. Non-uniformity in the mean free stream introduced by the grid was less than 0.5% at a test section velocity of 27 m/s. The test model was bolted to the test section with the flat plate in a horizontal position and the leading edge of the airfoil at 107 cm downstream of the grid. The leading edge of the flat plate was 45 cm downstream of the grid. The top and bottom walls of the test section were removed from 10 cm ahead of the airfoil leading edge of facilitate the probe traverses. In the present case, the tunnel velocity was adjusted as close to 27.3 m/s as possible, giving a Reynolds number of 4 x 10⁶ based on blade chord and 10⁸ based on the length of flat plate upstream of the leading edge of the airfoil.

Probes and Instruments. A Kiel probe having a 1.59 mm diameter sensing head was used to measure the reference total pressure of the free stream. The total pressure probe used for the total pressure surveys had a square nose and was made from 0.81 mm outer diameter, 0.6 diameter ratio, stainless steel tubing. A static pressure probe having a 1.59 mm sensing head, made by United Sensor and Control Corporation, was used for the static pressure surveys.

The inclined single sensor hot-wire probe, used for velocity measurement, had a 0.45 mm long 4 micron diameter sensor at 45° to the probe axis. The probe was connected to a constant temperature anemometer (CTA). The output of the CTA was linearized by a linearizer and displayed on an integrating digital voltmeter.

Measurement Procedure. The flat plate was set in the test section at zero angle of incidence and verified from the wall static pressure measurements. The boundary layer on the flat plate without the airfoil was measured at the axial location of the airfoil leading edge which is located 62 cm downstream of the flat plate leading edge. Total pressure,
were no noticeable variations in the profiles. The survey was made at the centerline and 50 mm either side of the centerline. There were no noticeable variations in the profiles. The results of the survey over the flat plate and the plane of the prongs normal to the boundaries are shown in Fig. 2. These results will be described in more detail in the next section of the paper.

Surface oil film flow visualization was carried out using lamp black mixed with #2 Diesel and Oleic acid as a dispersing agent, for the initial investigation. Subsequently, the surface streamline flow visualization was carried out using Polyurethane Enamel paint and Mineral Spirits, a technique similar to the one used by Langston [32]. The results of the surface streamline flow visualization are shown in Fig. 3.

The static and total pressure measurements were made at six axial locations (X/C = 0.1, 0.3, 0.5, 0.6, 0.8, 0.985) in the corner region. At each axial location the axes of the probes were kept tangent to the walls while traversing. The static and total pressure readings were normalized with the reference total pressure readings. The reference total pressure readings were taken with the Keil probe placed 50 mm ahead of the airfoil leading edge and 75 mm above the flat plate centerline. Some representative results are illustrated in Figs. 4, 5, 6 and 7.

The mean velocities were surveyed at the same axial locations as the pressure measurements. The three components of the mean velocity in the corner region were measured with single sensor inclined hot-wire probe, rotated about its own axis in four planes. The hot-wire response equations were developed incorporating corrections for the tangential and normal sensitivity coefficients, k and h, respectively, and were similar to Ref. [33,34]. The k and h corrections for the probe were obtained from the calibration of the probes in two planes. The details of the hot-wire response equations and calibration procedure are presented in Ref. [35]. The velocity components were normalized by the reference velocity which was calculated from the reference pressure readings. Some representative results are shown in Figs. 9, 10 and 11.

RESULTS AND DISCUSSION

The measurements in the corner region were carried out at six axial locations as mentioned in the previous section. However, the results at only three stations, namely X/C = 0.1, 0.3, 0.5, and 0.985 are presented in this section because of the large volume of data. The experimental data at these three stations reflect the general trends found in the corner flow measured in the present investigation.

Initial Conditions. The initial conditions of the incoming boundary layer were investigated to confirm that the flow structure near the artificially thickened boundary layer was no different from the turbulent boundary layer over a horizontal smooth flat plate at the point of entry to the blade corner. The momentum thickness (δ) was obtained from the mean velocity profile (Fig. 2a) and the Reynolds number based on this momentum thickness was then calculated to obtain the value of the friction coefficient (Cf), from Prandtl-Schlichting law and hence the friction velocity U*. Non-dimensional parameters U/U* against 2U*δ/µ for the measured points were plotted on a semi-log graph paper and compared to the log-law, U/U* = A log (U*/δ) + B, with widely accepted constants A = 5.75 and B = 5.5. The results are shown in Fig. 2c, where the values for the two curves were at a free stream velocity of U0 = 27.5 m/s, δ = 2.56 mm, R9 = 4.36 x 109 and U* = 1.106 m/s. It is clear from the figure that there is excellent agreement between the measured profile and the standard log-law profile for a two-dimensional turbulent boundary layer even at the edge of the boundary layer. The results of the turbulence measurements, shown in Fig. 2c, indicate that the turbulence levels are also of the same order as those generally observed in two-dimensional boundary layers except at the edge, where grid induced turbulence tends to yield higher levels in the free stream.

Flow Visualization. A general view of the flow patterns on the surface of the present model is shown in Fig. 3. Close up views of flow streamlines on the flat plate and the airfoil streamlines on the surface of the airfoil leading edge. Two separation lines originate from this point and go around each side of the airfoil. The perpendicular distance from the airfoil surface to the separation line at first increases to a maximum of 13 mm and then starts decreasing to a minimum of 6.5 mm at an axial distance of 204 mm from the airfoil leading edge. The distance again starts increasing and becomes 9.5 mm near the trailing edge. In the region between the blade and the separation line, ahead of the leading edge, surface streamlines on the flat plate are of reverse flow type. Up to about 76 mm downstream of the leading edge, the surface streamlines inside the horseshoe vortex region are either away from or parallel to the corner. Downstream of this region, the streamlines bend towards the corner. The trend is more pronounced in the airfoil leading edge, the streamlines start moving away from the corner.

The surface streamlines on the airfoil are less spectacular (Fig. 3c). Near the leading edge, 20 mm above the flat plate, the streamline has about 1° of inclination towards the corner; as it proceeds downstream the inclination decreases. At about 100 mm downstream of the leading edge it becomes parallel to the flat plate and then gradually moves away from the flat plate. At about 150 mm downstream it makes approximately 2° angle away from the flat plate. In the vicinity of the plate, streamlines point away from the corner. The distances of the separation line on the flat plate from the corner and the associated streamlines ahead of this face 2 mm above the flat plate could be correlated to the profiles of static and total pressure and velocity to understand the physics of the vortices in this region as indicated in the subsequent sections.

Static and Total Pressure Profiles. Variation of static pressure parallel to the flat plate (constant Z) and parallel to the airfoil surface (constant Y) are shown in Figs. 4 and 5, respectively. The static gage pressures are plotted as fraction of un-
disturbed free stream dynamic pressure \((\frac{P_s - P_a}{P_{oo} - P_a})\). Away from the corner, the static pressure decreases towards the airfoil in the forward part of the airfoil (Fig. 4a). This is typical of an accelerating flow over a curved surface. In the corner a decrease in static pressure is opposed by the horseshoe vortex. In Fig. 4a, away from the corner the pressure coefficient drops below -0.3 but in the vicinity of the corner the minimum value encountered is -0.28. At stations downstream of the maximum thickness section, the flow on the surface decelerates and the static pressure on the surface starts increasing, slowly reversing the inclination of the profiles (Fig. 4b and c). The effect of the horseshoe vortex is considerably reduced in this case. Away from the corner normal to the flat plate the static pressure does not change significantly (Fig. 5a, b, c). However, near the corner in the forward part of the airfoil the static pressure profiles show a gradual increase towards the flat plate due to the action of the horseshoe vortex (Fig. 5a). Further downstream, weakening of the vortex leads to no significant variation near the corner (Fig. 5b and c).

The total pressure profiles parallel to the flat plate (constant \(Z\)) and parallel to the airfoil surface (constant \(Y\)) are shown in Figs. 6 and 7, respectively. These curves are also plotted in terms of gage total pressure as a fraction of undisturbed free stream dynamic pressure \((\frac{P_{oo} - P_a}{P_{oo} - P_a})\). At a constant height above the flat plate and near the flat plate, in the direction away from the airfoil, the total pressure sharply increases to a peak then gradually reduces to attain a constant value away from the airfoil. The constant value is determined by the height above the flat plate and the flat plate boundary layer profile. As the height from the flat plate increases, the peak pressure as well as the constant value of the total pressure increases. The later increases at a faster rate and outside the corner region they become equal. At this point the total pressure profile becomes a typical boundary layer profile over an airfoil. The position of the peak first moves away and then moves closer to the airfoil as the height above the flat plate increases. At large axial distances the peaks are further away from the airfoil surface. At \(X/C = 0.8\), for the profile measured close to the flat plate, a depression appears on the positive gradient part of the profile (Fig. 6b). This depression becomes more prominent at the subsequent axial locations. The values of the peak and constant total pressures of these profiles and the position of the peaks at the three axial locations are compiled in Table 1. From this table it is apparent that maximum difference in the value of the peak and constant pressures \((\frac{P_{oo} - P_a}{P_{oo} - P_a})\) for \(X/C = 0.3, 0.5, 0.7, 0.8\) and 0.985 are 0.335, 0.319 and 0.15, respectively and occurs on the profiles at \(Z = 0.41, 2.95\) and 4.22 mm, respectively. The reduction in this pressure difference with increasing \(X\) indicates the dissipation of the horseshoe vortex resulting from the combined effects of turbulence and deceleration of flow.

The most prominent feature of the total pressure variation with \(Z\) at constant \(Y\), near the airfoil surface, is the appearance of a peak (maximum, \(M\)) followed by a deep valley (minimum, \(m\)) and a boundary layer type of profile (Fig. 7). With increasing \(X/C\), the steepness of pressure variation decreases and the distance from the flat plate surface to the maximum and minimum points gradually decreases. Away from the airfoil surface (increasing \(Y\)), the difference between maximum and minimum values decrease and ultimately the total pressure profile approaches that of a boundary layer profile over a flat plate. The difference between maximum and minimum pressure \((\frac{P_{oo} - P_a}{P_{oo} - P_a})\) on the profile measured nearest to the airfoil \((Y=0.41 mm)\), at \(X/C = 0.3, 0.8\) and 0.985 are 0.14, 0.02 and 0.01, respectively.

The axial variation of the distances of the peak \((Y_P)\) and depression \((Y_d)\) from the airfoil surfaces for the profile nearest to the flat plate \((Z=0.41 mm)\) as well as the variation of distances of the maximum \((2Y)\) and minimum \((Y)\) from the flat plate for the profile nearest to the airfoil \((Y=0.41 mm)\) are shown in Fig. 8.

Mean Velocity Profiles. In the plots of mean velocity profiles the values of velocities are normalized by the undisturbed free stream velocity \(U_\infty\). The mean velocity profiles of the streamwise component \(U_1\) in \(Y\)-direction and at constant heights \((Z)\) above the flat plate are shown in Fig. 9. The general shape of these profiles closely follows the total pressure profiles at the same locations (Fig. 6). It was also found that the numerical values are also in good agreement. For example, at \(X=203\ mm, Y=7.5\ mm\) and \(Z=2.95\ mm\); the values of \((P_{oo} - P_{oo})\) \(=0.74\) and \((U_1^1 + U_1^2 + U_1^3)\) \(=0.74\), the difference is within 1%. The position of the peaks in the streamwise velocity profiles at the corresponding heights \((Z)\) are also in good agreement with those of the total pressure profiles. When the data were plotted against \(Z\) at constant \(Y\), it was observed that the variation of \(U_1\) normal to the flat plate also follows the general shape of the total pressure profiles in Fig. 7.

The variation of mean velocities normal to the airfoil surface \((V_1)\) and normal to the flat plate \((W_1)\), in the \(Y\) direction at fixed \(Z\) are shown in Figs. 10 and 11, respectively. For the traverse nearest to the flat plate, at \(X/C=0.3\), \(V_1/U_\infty\) starts with a value of -0.01, increases to a value of 0.075 at \(X=0.1\ mm\) and gradually reduces to zero (Fig. 10a). \(W_1/U_\infty\) on the other hand, starts with a value of about 0.15, reduces to about 0.05 at \(Y=5\ mm\), and then asymptotically increases to about 0.10 (Fig. 11a). This general shape continues up to a height of \(Z=6.76\ mm\) for both \(V_1/U_\infty\) and \(W_1/U_\infty\). At \(Z=9.3\ mm\), \(V_1/U_\infty\) remains constant \((\sim 0)\) and \(W_1/U_\infty\) starts with a value of about -0.05 and asymptotically increases to 0.01. Above this height, \(V_1/U_\infty\) starts with a small positive value (0.01) and asymptotically reduces to a small negative value (-0.04). At the same location \(W_1/U_\infty\) starts with a value of about 0.05 and asymptotically reduces to a slightly smaller positive value. At \(X/C=0.8\) and 0.985, \(V_1/U_\infty\) distribution near the flat plate, starts with a small value \((\sim 0.01\ to\ 0.02)\) gradually increases to a peak value \((\sim 0.075)\) and then asymptotically attains a slightly smaller value. Away from the flat plate, the asymptotic reduction is not observed, instead the value slightly increases (Figs. 10b and 10c). At these stations the profiles of \(V_1/U_\infty\) (Fig. 11b and 11c) near the flat plate are similar to those of \(V_1/U_\infty\). Slightly away from the flat plate \((Z=4.22\ to\ 9.3\ mm)\), the values decrease slightly and then asymptotically increase to a slightly higher value. Above this, the \(V_1/U_\infty\) profiles again take the general shape of \(V_1/U_\infty\) at the same heights.
The distance of the saddle point of separation when normalized by the boundary layer thickness is in good agreement with the results of Shabaka’s [28] flow visualization experiment. The present experiment gives a value of \( \delta_0/\delta = 0.448 \), whereas Shabaka's experimental results give a value of about \( \Phi \approx 0.450 \). At \( X/C = 0.8 \) (\( X = 203 \) mm) the peak in the velocity profile, in the present experiment, occurs at \( Y_p/\delta \) (flat plate) = 0.21. From Shabaka's results, it appears that this value is of the same order as \(~ 0.187 \) mm. Also, the general shape of the velocity profiles are very similar to those given in Shabaka [28].

Bernoulli Surfaces. The distortion of Bernoulli surfaces, show the effect of the secondary flows on the flow field (Fig. 12). These Bernoulli surfaces were obtained from the total pressure profiles of Figs. 6 and 7. At \( X/C = 0.3 \), in the immediate vicinity of the corner, the Bernoulli surface for \( (P_0 - P_d)/(P_{ref} - P_d) = 0.4 \) (Fig. 12a) has an outward bulge which is the characteristic shape for a laminar corner flow. Away from this region, the Y-direction, the surface resembles the flat plate and then gradually move away from it. In the Z-direction, they first move away and then gradually move towards the airfoil. At \( X/C = 0.8 \) and 0.985, the shape of the Bernoulli surfaces, away from the immediate vicinity of the corner, are similar to that of Fig. 12a. However, in the immediate vicinity of the corner, the characteristic bulge of the laminar corner flow no longer exists. Instead there is a hint of bending towards the corner which is a characteristic of a turbulent corner flow. Away from the corner, the spacing between the Bernoulli surfaces parallel to the airfoil rapidly increases as the flow proceeds downstream. The rate of increase of the spacing between the Bernoulli surfaces parallel to the flat plate is much slower.

The distortion of the total pressure profiles and the Bernoulli surfaces at \( X/C = 0.3 \) are believed to be caused by a combination of vortices shown in Fig. 13a. The largest of these vortices is the horseshoe vortex generated by the distortion of the vortex sheet of the incoming boundary layer. This distortion is due to the presence of the thick airfoil leading edge. In the first octant (\( X, Y, Z \) all positive) this streamwise component points towards the downstream direction (positive \( X \)). Away from the corner region, the boundary layer formed on the airfoil gives rise to a vortex sheet with the vector pointing towards negative \( Z \)-direction. However, in the corner region the vortex is distorted to produce a streamwise component pointing in the upstream direction (negative \( Z \)). This vortex is enclosed between the walls forming the corner and the horseshoe vortex. The vortex in the corner (hereafter referred to as a corner eddy) and the horseshoe vortex rotate in opposite directions. On the flat plate, the limiting streamlines move away from the corner due to the influence of the horseshoe vortex and move towards the corner due to the influence of the corner eddy. This is verified by the flow visualization traces. The surface streamlines on the flat plate between the airfoil and the position of the peak of the total pressure profile nearest to the flat plate, lean slightly towards the corner. If the shape of the corner eddy is a slightly distorted form of circular cylinder, the height \( z_p \) at which the minimum occurs in the total pressure profile nearest to the airfoil surface, and the distance \( (Y_p) \) at which the peak occurs on the total pressure profile nearest to the flat plate should be roughly equal. This was the case near the leading edge (Fig. 8). The corner eddy was also observed by Gorsky et al. [31]; however it could not have been the secondary flow of the second kind as it was present near the leading edge of the airfoil where characteristic bulge of the laminar corner flow was observed.

As the flow proceeds downstream, the stress induced secondary flow is generated. In a simple corner it would have appeared as a pair of contra-rotating vortices. In the present case the vortex with the vector pointing upstream merges with the corner eddy. The system of vortices formed in this manner is shown in the Fig. 13b. The appearance of the secondary vortex of the second kind does not alter the general shape of the total pressure profiles in the \( Z \)-direction. At \( X/C = 0.8 \) and 0.985, total pressure profiles nearest to the flat plate show a depression on the portion of the profile where the gradient is positive thus indicating a pair of vortices of the second kind. The secondary vortex does not alter the total pressure profiles in the \( Z \)-direction because the vortex has the same direction as the corner eddy and merges with it.

Magnified plots (Fig. 14) of total pressure in the vicinity of the corner at \( Z = 0.41 \) mm and at \( Y = 0.41 \) mm at six axial stations reveal further information pertinent to the corner eddy and the stress induced vortices. In both the figures, the profiles flatten out up to the axial distance of \( X/C = 0.6 \). This trend is due to the dissipation of the horseshoe vortex and the corner eddy by the action of Reynolds stresses. But at \( X/C = 0.8 \) and 0.985 the total pressure profiles in both the figures show that they become fuller. Unlike velocity profiles, which can become fuller due to the change in static pressure, the only way the total pressure profiles can become fuller is when the high energy particles from the outer region is ingested into the flow near the surface. From these figures, it is evident that the profiles in both the directions are energized near the corner, which is possible with a set of contra-rotating vortices. The profiles parallel to the flat plate (\( Z = 0.41 \) mm) also show a depression appearing on the profiles. The peak values in the profiles at \( Y = 0.41 \) mm monotonically decrease along the axial direction. However, in the case of profiles at \( Y = 0.41 \) mm, the maximum value decreases up to \( X/C = 0.6 \). In the last two stations (\( X/C = 0.8 \) and 0.985) the maximum value of total pressure near wall starts increasing. This indicates that the corner eddy which created the maximum value in pressure profiles is being strengthened by the new phenomena.

The changes in the positions of peak in the total pressure profile along \( Y \) and minima in the total pressure profile along \( Z \) are a measure of the distortion of the vortices. These are presented graphically in Fig. 15 as a function of \( X \). The variation in the rate of change of distance in the front and the rear part of the airfoil can be explained from the fact that the accelerating flow reduces the size of streamwise vortices and the decelerating flow increases it. Therefore the rate of change of the positions of maxima and minima with \( X \) is smaller in the front part of the airfoil than when compared with the rear part of the corner. These combinations of eddies were reported for two different initial conditions in reference [36].
CONCLUSIONS

The effect of streamwise vorticity on the static pressure in the blade end wall corner region is marginal. The effect is more pronounced on the total pressure, mean velocity and the Bernoulli surfaces. The following conclusions were drawn from an analysis of these profiles in conjunction with the surface streamline flow pattern.

1. The horseshoe vortex formed in front of the leading edge has a size of the order of the boundary layer thickness on the flat plate away from the corner region. Within a short distance, in the region between the corner and the horseshoe vortex, a corner eddy is formed. The direction of vorticity of the corner eddy is opposite to that of the horseshoe vortex and the size is of the order of the boundary layer thickness on the airfoil surface far away from the corner region at the same axial location (Figs. 6, 7 and 13). The horseshoe vortex and the corner eddy are diffused by the action of the Reynolds stress, and acceleration and deceleration of the flow. The rate of spread of the corner eddy upstream and downstream of the maximum airfoil thickness section are not the same. The rate of spread is slower in the portion where the flow is accelerating compared to the rate of spread in the portion where the flow is retarding. These rates of spread with axial distance are of the order of 1/80 and 1/40, respectively for this experiment (Fig. 8, slope of the line for the position of minima).

2. As the flow proceeds downstream, due to the action of inhomogeneous and anisotropic turbulence, a pair of contra-rotating vortices are formed in the immediate vicinity of the corner. The vortex with the same direction as the corner eddy, formed near the airfoil, merges with the corner eddy. The other vortex, formed near the flat plate, has a direction opposite the corner eddy (Fig. 13b). The appearance of the depression, on the total pressure profiles in the direction parallel to the flat plate, is the result of this vortex. The size of the vortex is about half the size of the corner eddy and the rate of growth is the same order as that of the corner eddy (Fig. 8).

REFERENCES


ACKNOWLEDGEMENT

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**TABLE 1. Comparison of Data from Total Pressure Profile**

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<th>X/C</th>
<th>Zmm</th>
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<td>2.25</td>
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<td>(P_{oo}'-P_a)/P_{oo}</td>
<td>0.655</td>
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<td>0.735</td>
<td>0.76</td>
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(a) Mean velocity

(b) Comparison with log-law profile

(c) Turbulence intensity

Fig. 1. Schematic of the model and the coordinates

Fig. 2. Initial conditions on the flat plate with no airfoil (X=0, Y=0)
Fig. 4. Static pressure variation parallel to the flat plate.
Fig. 5. Static pressure variation parallel to the airfoil surface

Fig. 6. Total pressure variation parallel to the flat plate
Fig. 7. Total pressure variation parallel to the airfoil surface.

(a) $X = 76$ mm, $X/C = 0.30$

(b) $X = 203$ mm, $X/C = 0.80$

(c) $X = 251$ mm, $X/C = 0.985$

Fig. 8. Variation of positions on the curves closest to the surfaces ($Y = 0.41$ mm, $Z = 0.41$ mm).

Symbols
- Peak
- Minimum
- Maximum
- Depression
Fig. 9. Variation of streaming mean velocity parallel to the flat plate

Fig. 10. Profiles of component of mean velocity normal to the airfoil
Fig. 11. Profiles of component of mean velocity normal to the flat plate.

(b) $X = 203$ mm, $X/C = 0.80$

(c) $X = 251$ mm, $X/C = 0.985$

Fig. 12. Bernoulli surfaces in the corner.

(c) $X = 251$ mm, $X/C = 0.985$
Fig. 13. Vortex system leading to the distortion of the Bernoulli surfaces.

Fig. 14. Development of total pressure profiles near the corner.