EXPERIMENTAL CONTRIBUTION ON THE SIGNIFICANCE AND THE CONTROL BY TRANSVERSE INJECTION OF THE HORSESHOE VORTEX

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ABSTRACT

The present study addresses two aspects of the horseshoe vortex, namely its significance in the secondary flow in a turbine blade passage and the possibility of reducing its strength by an active flow mechanism, i.e. the transverse injection of coolant air through a slot in a cylinder-endwall junction. The study reports on the results of two experiments in low speed wind tunnels, which employed a calibrated five-hole Pitot tube to measure the velocity vectors and the resulting secondary flowfields. The first aspect was studied in a 90° square cross section bend duct. The two horseshoe vortex legs were simulated by two half-Delta wing vortex generators. The results showed that the horseshoe vortices influence two regions of the secondary flowfield, i.e one near the passage entrance, where the pressure side leg forces a three dimensional separation of the endwall boundary layer, and the other is in the exit plane, where the coupling of the horseshoe with the passage vortex redistributes the flow with total pressure losses, without affecting the total loss, and increases the secondary kinetic energy by about 20%.

For the second aspect, a rectangular bluff body, with a cylindrical leading edge, was positioned over the tunnel endwall and the transverse air injection was implemented through a thin slot, covering the 180° arc in the leading edge-endwall junction. The results showed that, for an average injection velocity equal to 35% that of the mainstream, the size and strength of the horseshoe vortex leg were reduced by nearly 60%. On the other hand, for stronger injection rates the vortex size and strength were increased.

NOMENCLATURE

- \( m_s \): The air mass flux (equ. 2)
- \( p_s \): Local static pressure
- \( P_{\infty} \): Local total pressure
- \( q \): Dynamic pressure (= \( \sqrt{2p_{\infty}} \))
- \( u \): Streamwise velocity component
- \( v \): Velocity component along the y direction
- \( w \): Velocity component along the z direction
- \( x \): Local streamwise direction
- \( y \): Direction normal to the endwalls
- \( z \): Direction parallel to the endwalls

Greek
- \( \Gamma \): Circulation
- \( \delta \): Thickness of the endwall boundary layer
- \( \zeta \): Streamwise vorticity component

Superscript
- \( * \): Non-dimensionalized parameter

Subscript
- \( DW \): Delta wing vortex generator
- \( HS \): Horseshoe vortex
- \( IN \): Injection parameter
- \( o \): Conditions in the inlet of the test section

INTRODUCTION

The main contributors to the observed difference between the thermal efficiency of a Gas Turbine and the equivalent Brayton cycle are the so called "Secondary" flows, that are characterized by the streamwise rotation imparted on parts of the fluid in a blade passage. This rotation transforms the fluid kinetic energy in such a form that it cannot participate in the work exchange process of the component, so that it is considered as a loss (Denton, 1993). There are three main secondary flow structures, all of them in the form of streamwise vortices, i.e the horseshoe, the passage and the tip leakage vortices (Sieverding, 1985). All of these flows have been studied extensively in the last twenty years, but our ability of controlling them is still quite limited.

Presented at the International Gas Turbine and Aeroengine Congress & Exhibition
Birmingham, UK — June 10-13, 1996
The horseshoe vortex has been studied either as an isolated phenomenon, in bluff body-endwall junctions, or in conjunction with the passage vortex in turbomachinery blade channels. Baker (1979, 1980, 1992) has provided extensive visualization data on the symmetry plane of the horseshoe in a cylinder-endwall junction. He noticed the presence of various recirculating eddies of either steady or transient nature. Thomas (1987) has provided similar data, while Visbal (1991) has solved the three dimensional flow equations in the laminar flow limit. Similar results have been reported for various bluff bodies with cylindrical leading edges, e.g. Moore and Forlini (1984), Pierce and Tree (1990) and Davenport and Simpson (1992). Eckerle and Langston (1987) have measured the development of the secondary flow, in a number of planes, as the fluid bypasses the cylinder, and they report that the horseshoe vortex leg is created between the 5° and the 25° planes due to the amalgamation of the vorticity in the symmetry plane recirculation eddies.

The evolution of the two horseshoe vortex legs inside the blade channel is quite different. The pressure side one, driven by the transverse pressure gradient, bends almost immediately after the blade leading edge and travels inside the endwall boundary layer towards the opposite suction side. Along its trajectory the vortex forces a boundary layer separation, which leads to the creation of a new boundary layer downstream. The suction side leg travels close to the blade-endwall corner. After the point the trajectories of the two legs meet, the pressure side one is being absorbed by the stronger passage vortex, while the counter rotating suction side one forms a vortex couple with it. The evolution of the turbine secondary flow has been measured in various studies (Langston, et al, 1977, Moore and Smith, 1983, Gregory-Smith et al, 1988, Harrison, 1990, etc), while various efforts have attempted to solve the three dimensional flow equations (Hah, 1984) and obtain an estimate of the secondary flow component significance (Hah, 1990, Niehuis et al, 1990). Extensive reviews have been provided by Sieverding (1985) and Denton (1993). Parallel studies on bend ducts of various geometries (Humphrey et al, 1981, Chang et al, 1983, Jacovides et al, 1990, Kim and Patel, 1994) report similar secondary flows, even though no horseshoe vortices existed in these ducts. Finally, a study by Blair (1973) in a duct simulating the pressure loading of a turbine blade channel has, again, produced similar secondary flows. The general conclusion of the above studies is that the horseshoe legs do not contribute significantly to the secondary flow in the exit plane. Their main contribution is focused in the boundary layer separation. Direct quantitative data for this contribution, however, have not been provided so far.

Efforts to develop methods for the reduction of the size and the strength of the horseshoe vortices have been attempted by various people. Most of them have focused their efforts on the "passive" mechanisms, i.e. various nose shapes, such as fillets, swept fairings, etc (Kuherdar et al, 1984, Mehta, 1984, Davenport et al, 1989), and wall profiling, such as the ice-formation method (Langston and Langston, 1993). The effectiveness of these methods has been rather limited. Two "active" control methods have been reported so far. McGinley (1987) introduced two counter rotating vortices through vortex generators with limited success, while Philips, Cimbala and Treaster (1992) attempted suction of the incoming boundary layer, just in front of the junction. The last did report an almost complete elimination of the horseshoe vortices but the air bleeding was significant. In addition, this method is not applicable in turbine blades, since the mainstream temperature is too high.

The present study investigated experimentally two aspects of the horseshoe vortices. In the first, the significance of the horseshoe vortex-passage vortex interaction was studied by employing a square cross section 90° bend duct, where the two horseshoe vortex legs were simulated by two delta wing vortex generators. The results do show that the horseshoe vortices do not influence the total pressure losses but they contribute to the secondary kinetic energy in the exit plane. The second aspect concerned the possibility of reducing the size and strength of these vortices by an applicable method, i.e. the transverse injection of coolant air through a thin slot in the blade-endwall junction. Although the configuration has not been optimized yet, the results show that for very small injection rates it is possible to reduce the size and the strength of the vortices by 60%.

PART I : THE HORSESHOE VORTEX IN THE BEND DUCT SECONDARY FLOW

The main objective in this part was the experimental evaluation of the quantitative contribution of the two horseshoe vortex legs on the structure of the secondary flow in a square cross section 90° bend duct, simulating a turbine blade channel. In such flows it is known that the main contributor to the secondary flow is the total blade loading and not the specific static pressure distribution around the blade aerofoils. In addition, this duct permitted the separate introduction of the two horseshoe vortex legs, through delta wing vortex generators.

II: THE EXPERIMENT

This experiment was conducted in the low speed wind tunnel of the Thermal Engines Lab., with a test section cross section of 0.14 x 0.14 m^2. The mainstream velocity inside the test section, just after the nozzle exit plane, was monitored by a Pitot tube and was sustained at the 16 m/s value through an electric motor speed controller. A Hot Wire Anemometer measured a turbulence intensity of less than 1% in the nozzle exit core. The bend duct (figure
Fig. 2 The static pressure in the bend duct

(a) Without vortex generators

(b) With vortex generators

Fig. 3 The endwall oil visualization

The main measurements were taken in two planes, the 15° and the 90° (i.e., the exit) planes. The first was selected after oil-ink-milk droplet visualization (figure 3) showed that the two horseshoe vortex legs limiting wall trajectories crossed each other just downstream. So, this was considered to be a proper plane to check the effectiveness of the Delta wing vortex generators, since near the 0° plane there existed the possibility of the presence of smaller, additional counter vortices that would dissipate quickly inside the endwall boundary layer. The grid of the measurement points is illustrated in figure 4, where each of the secondary velocity vectors starts at the corresponding grid point. The points closest to the walls were 5 mm away. Near to the walls the grid spacing was 2 mm, while the inner spacing was increased to 5 mm. The grid size was 21 points along the y direction (normal to the endwalls) and 27 points along the z direction. The (y-z) plane origin was at the center of the cross section.

The flowfield parameters in these two planes were measured by a calibrated Five-Hole Pitot tube, which was homemade out of 0.63 mm (OD) stainless steel tubes, with a 45° cut in the tip, and calibrated after the Wickens and Williams (1989) method. A MODUS electronic Micromanometer, with a range of ± 1000 Pa and an uncertainty of 1 Pa, measured the pressures. An error analysis of the measurements gives the following estimate:

(i) Since the typical pressure reading was around 160 Pa, the 1 Pa uncertainty gives a 0.3% expected error for the velocity, although this increases proportionally inside the shear layers. (ii) The inversion of the calibration equation fitting polynomials produced errors up to 1.5 % against known velocities. (iii) The linear positional uncertainty was 0.1 mm, while the angular one was 0.2°. The last could generate 0.6% additional errors in the secondary velocities. Thus the total velocity expected error was about 3 %, being nearly double for the pressure and the vorticity values.

The two horseshoe vortex legs were produced by two half-Delta wing vortex generators, illustrated in figure 1a, which were positioned just in front of the 0° plane, near the two sidewalls. Each wing had a 17.5 mm base and a 35 mm height, while it was inclined at a 25° angle of
attack against the mainstream. The base was 5 mm above the endwall, while the tip was 19.8 mm above it. The wing was supported by an L type support, which permitted the wing to be positioned 15 mm away from the nearest sidewall. The selection of the vortex generators was based on the following criteria, resulting from the Eckerle and Langston (1987) and our own data for horseshoe vortices in the 90° plane and for an endwall boundary layer with a thickness δ:

(i) The vortex core was to be 0.8δ away from the sidewall, 0.2δ from the endwall and its size to be of order 0.5 x 0.5 δ².

(ii) The strength of the vortex should be similar to that of the horseshoe one. This was estimated on the following. The average non-dimensional vorticity of the horseshoe vortex is defined by equation (1)  
\[ \zeta = \frac{\zeta \delta}{u_o} = \Gamma_{HS}/A_{HS} = 2. \]  

Here, Γ_{HS} and A_{HS} are the horseshoe vortex cross section circulation and area respectively. Then, it was assumed that the lift per unit length of the delta wing is given by the relationship \(L = \rho \Gamma u_0\), where \(\Gamma\) is the circulation of the produced vortex. The selected geometry gave a strength estimate nearly 2/3 that of the expected, when the Lee and Ho (1990) data were incorporated for the wing lift coefficient.

The endwall droplet visualization was done after drawing a grid on the endwall surface. After the test, a transparent paper was introduced into the duct and the droplet trajectories were copied on it. The data in figure 3 were the result of size reduction in a photocopying machine.

II: RESULTS AND DISCUSSION

The data analysis was based on two aspects (i) The distribution of a number of flow parameters (streamwise velocity and vorticity, secondary kinetic energy and total pressure loss coefficient), expressed in non-dimensional form, and (ii) the integration of these parameters over the area covered by the measurements, in the corresponding planes. The parameters studied and the corresponding integration quantities were:

(i) The streamwise velocity \( u' = \frac{u - u_o}{u_o} \), which on integration leads to the mass flux \( m_a \), where  
\[ m_a = \int \rho^* u^* dy^* dz^* \]  

The average streamwise velocity over the integration area \( u_{AV}^* \) was defined by the equation (3). The density ratio \( \rho^* = \rho/\rho_e \) was taken equal to unity.

(ii) The streamwise vorticity \( \zeta^* = \frac{\zeta H}{u_o} \), whose area integration gives the corresponding circulation \( \Gamma^* = \Gamma u_o H \)

\[ u_{AV}^* = \frac{m_a^*}{\int \rho^* dy^* dz^*} \]  

, as shown below  
\[ \Gamma^* = \int \zeta^* dy^* dz^* \]  

(iii) The secondary kinetic energy  
\[ E_{SKE} = V'^2 + W'^2 = \frac{1}{2} [V^2 + W^2] \]  

which yields the mass averaged secondary kinetic energy \( e_{SKE} \)  
\[ e_{SKE} = \frac{\int \rho^* u^* E_{SKE} dy^* dz^*}{\int \rho^* u^* dy^* dz^*} \]  

(iv) The total pressure loss coefficient \( C_{PR} \), which yields the corresponding mass averaged coefficient \( C_{PR}^* \), where  
\[ C_{PR}^* = \frac{\int \rho^* u^* C_{PR} dy^* dz^*}{m_a^*} \]  

The first testing of the bend duct flowfield was based on the static pressure loading between the suction and the pressure sides. Figure 2 shows that the loading is quite uniform over most of the bend arc, as expected.

(a) The structure of the horseshoe vortices in the 15° plane

The significance of the horseshoe vortex was examined initially by considering the endwall droplet results, illustrated in figure 3. It is quite clear that the horseshoe vortex influences the endwall flow mainly near the entrance region of the bend, especially on what appears to be the trajectory of the two vortex legs. This influence is manifested not only by the limiting, endwall, streamlines around the pressure side leg (which is known to force a boundary layer separation) but near the suction side-endwall corner as well, where the counter rotating suction side vortex leg throws the flow away from the corner (on the endwall). Thus, the incoming endwall boundary layer fluid is being thrown against the corner downstream of the vortex "collision" point. In the simple duct case, the fluid is thrown towards the corner right at
the beginning of the bend.

The resulting secondary flowfield, in both planes is exhibited in figure 4. The results for the 15° plane (figure 4a) verify not only the presence of the two vortices, but it shows clearly the expected asymmetry between the two legs resulting from their different trajectories. The streamwise vorticity component, in figure 5, shows that these vortex structures are indeed the result of two main vortices, although smaller vortex structures are also present. The last vortices originate in the interaction between the fluids thrown in the opposite transverse directions by the two main ones. Figure 7 presents the secondary kinematic energy distribution, which again proves the presence of two large rotating fluid masses. The $C_\text{SKE}$ and $E_\text{SKE}$ maxima in the suction side leg are nearly double the corresponding values of the pressure side one. Figure 6a shows the distribution of the transverse velocity $w$ (parallel to the endwall) along lines passing through the two vortex cores. The maximum $w^*$ magnitude occurs in the two core centers, which tend to collide with a relative velocity of order $u_0/2$. The fluid angular velocity $(V_{\text{ROT}}^*)$ near the two vortices, along the same two lines, was calculated by the equation

$$V_{\text{ROT}}^* = \frac{[w_{\text{CORE}}^* - w^*]}{[y_{\text{CORE}}^* - y^*]}$$

where $w_{\text{CORE}}^*$, $y_{\text{CORE}}^*$ were the transverse velocity and the corresponding height above the endwall of the vortex core. Figure 6b shows that both cores rotate almost as solid bodies, since the $V_{\text{ROT}}^*$ value is nearly constant above and below the core center. The $V_{\text{ROT}}^*$ sign, of course, changes as one passes the core centers. The magnitude of this velocity is nearly double in the suction side vortex leg, when compared to the pressure side one. These data agree with the observations made by other studies, which showed that the vortices are of the Rankine type (Binder and Romey, 1983). The $E_\text{SKE}$ data, in figure 7, show that the typical value of this parameter, over most of the vortex area, is of order 0.02 to 0.04, although it increases sharply inside the vortex core centers. The overall transverse flow inside the endwall boundary layer, which ultimately leads to the creation of the passage vortex, forms an accelerating wall jet over most of the $z$ direction, as shown in figure 6c. Both legs have their cores near the maximum velocity point of these jets. The pressure side leg appears to be convected by the jet, while the suction side one appears to move against it. Due to the duct bending, the entire mainstream flow has a negative transverse velocity ($w^*$). The transverse flow inside the endwall boundary layer is additional to that. The excess transverse mass and momentum fluxes were calculated by the following two equations:

$$m_{\text{TR}}^* = \int \left( \frac{w^*(y^*)}{w_{\text{CL}}^*} - 1.0 \right) dy^*$$

$$M_{\text{TR}}^* = \int \left( \frac{w^*(y^*)}{w_{\text{CL}}^*} - 1.0 \right) \frac{w^*(y^*)}{w_{\text{CL}}^*} dy^*$$

where the velocity $w_{\text{CL}}^*$ is the transverse velocity in the duct centerline. The distribution of these two quantities, as functions of $z^*$, is given in figure 6d, which shows that
the passage vortex - horseshoe vortex interaction is quite significant. In the 15° plane most of the transverse flow appears to take place between the two vortices. The cross flow in the two edges is much smaller. This gives an estimate of the modifications on the endwall flow imposed by the two horseshoe legs in this region. In addition, the data suggest that the transverse flow in the region between the two vortices is associated with the feeding of the two vortices with fluid originating in the incoming endwall boundary layer. Figure 7 shows also that the two rotating fluid masses are very coherent and well separated in this plane. The intermediate fluid posses very little rotation, even inside the endwall boundary layer.

Figures 8 and 9 exhibit the streamwise velocity \( (u') \) and the total pressure loss coefficient \( (C_{PT}) \) distributions. Both give very similar distributions near the endwall, indicative of the fact that the main total pressure loss mechanism is the viscosity inside the boundary layer. The small \( C_{PT} \) deviations around the vortex cores are not significant, although the vortex cores apparently are formed by low total pressure fluid. Figure 8 shows that the endwall boundary layer in the two edges is much thinner when compared to that between the two vortices. The \( C_{PT} \) data in figure 9 agree with this too.

The integration of the flow parameters over the area of the measurements in the 15° plane showed that the average streamwise velocity was around 1.12. In other words, there appeared a small acceleration of the mainstream flow. The mass averaged \( C_{PT} \) value, over the same area, was around 0.1. If one considers the total pressure losses in the incoming endwall boundary layer, in
the 0° plane and for the section covered by the above area, the above value is more than double in magnitude, apparently due to the accumulation of low total pressure fluid in this region of the endwall. The circulation (Γ') of the flow around the pressure side vortex (by employing equation (4)) was 0.03, which by transforming it into the Γ'=Γ/ω_0 form gives the value Γ'=0.16. This value agrees very well with the corresponding value measured in the horseshoe vortex leg, as shown in the next section. The corresponding values for the suction side vortex were nearly double.

The general conclusion of the above data is that the two vortex generators have produced a system of two well defined counter rotating vortices, well embedded in the endwall boundary layer. These vortices interact with this layer as expected for the horseshoe ones, since they appear to possess similar sizes and strengths as they do.

(b) The exit plane data

The exit plane data were employed as the main platform for the estimation of the horseshoe vortex significance. The secondary flowfields, as shown in figure 4, give a picture similar to the one produced by the similar previous studies. A more clear picture, however, emerges from the secondary kinetic energy (E_{sk}) distribution, in figure 10. The results show that the flow in the simple duct case is almost exactly symmetric between the upper and the lower half of the exit plane. In each half it appears that two main vortices exist, one corresponding to the passage vortex and the other to a small corner one. In addition, the cross section center fluid appears to possess a significant degree of rotation. Hence, the resulting picture corresponds to that of low aspect ratio blade channels, found usually in high pressure turbine stages. The E_{sk} magnitude may exceed the 0.15 value in the core of the rotating masses. The picture in figure 10b is somewhat different. The upper part, without vortex generators, appears to be almost exactly the same with the previous one. The lower part, however, has been modified considerably, a first indication of the horseshoe vortex significance. The integrated quantities in these two cases showed that:

(i) The u_{AV} value was around 1.02 for both cases. The small difference between u_{AV} and u_0 originates probably in the integration of the wall boundary layer fluxes, for which linear velocity profiles were assumed between the solid wall and the nearest measurement point. The u_{AV} magnitude between the two cases varied only after the third decimal point. When integrating the mass flux in each half separately, the u_{AV} was again producing a value very close to 1.02 for all four cases, indicative of the small interaction between the two halves. The mass averaged secondary kinetic energy (e_{sk}) in each half was 0.0465 in the case with the vortex generators and 0.04 in all the cross section halves without the vortex generators. This means that the two horseshoe vortex legs increase...
the $e_{SKE}$ magnitude by nearly 20%. This increase appears to originate mostly in a corresponding widening of the flow region where the $E_{SKE}$ magnitude is large.

The vorticity distribution in the lower half of the cross section is presented in figure 11. The distribution near the solid walls does not appear to be influenced by the horseshoe vortices. On the other hand, a significant redistribution of $C_\text{m}$ appears in the middle of the cross section. The presence of the two vortices, however, could not be verified. Apparently, the strengths of the two horseshoe vortices were reduced significantly, well before the 90° plane, so that they were absorbed by the main vortex structures associated with the transverse endwall flow, which created the passage vortex as well. The two legs, however, increase the rotation of the duct "mainstream" and this rotation persists well after the horseshoe vortices. This means that for blades with large aspect ratios the horseshoe influence on the $e_{SKE}$ magnitude will be smaller, due to a smaller blockage effect.

The total pressure losses are given by the distribution of the $C_p$ values in figure 12. Here, the horseshoe vortices appear to increase the area around the cross section center where the $C_p$ magnitude is small but non-zero (for $C_p$ values in the range $0.2 < C_p < 0.4$). The mass averaged $C_p$ values, however, showed that the two horseshoe vortices produced no change at all. In the lower half, with the vortex generators, $C_p = 0.227$, while for the other halves, without vortex generators, $C_p = 0.219$ everywhere. This remarkable agreement (the small rise is probably due to the drag of the delta wing vortex generators) shows that the horseshoe vortices interact only with the mainstream core in an inviscid mode. As far as the boundary layer fluid is concerned, the two horseshoe vortices simply redistribute only its upper layers (where the $C_p$ has a small value) inside the mainstream, without enhancing the dissipation. This redistribution, however, changes the mainstream flow blockage, as shown in figure 13. Thus, the exit $u^*$ profile becomes somewhat more uniform, and this could lead to reduced mixing losses downstream.

**PART II : CONTROLLING THE HORSESHOE VORTICES BY TRANSVERSE INJECTION IN THE BLADE ENDWALL JUNCTION**

The main objective in this part was the investigation of a method that will lead to a reduction of the horseshoe vortex size and strength and which could be applied in a high pressure turbine stage. The basic idea behind this method was the injection of fluid in a direction opposite to the flow of the mainstream near the blade leading edge towards the endwall, which creates the recirculating eddy. In addition, the injected fluid may act as a coolant for the endwall surface.

**III : THE EXPERIMENT**

The experiment was conducted in the low turbulence, low speed wind tunnel of the Thermal Engines Laboratory, which has a $0.3 \times 0.2 \text{ m}^2$ cross section. The air velocity just after the nozzle exit was monitored at the 16.5 m/s value by a Pitot tube. The horseshoe was created in the junction of a bluff body with the bottom 0.3 m wide endwall (Fig. 1b). The bluff body leading edge was formed by a half cylinder with a 0.06 m diameter. The rest was formed by a body with a 0.06 x 0.2 m$^2$ cross section and 0.2 m tall. The injection was implemented through a slot covering the 180° arc of the cylinder - endwall junction with a 3 mm width. The air for the injection was provided by a second small fan, whose supply rate was measured by transversing the 2 cm diameter supply duct by a 0.63 mm total pressure probe and integrating the calculated velocity profile. This mass flux is reported as a velocity ratio $(v_u/u_o)$, where $v_u$ is the average velocity of the injected air (calculated from the slot area and the measured mass flux), while $u_o$ is the mainstream velocity in the nozzle exit.

![Fig. 13 The $u^*$ distribution in the exit plane](https://example.com/fig13.png)
for high pressure turbine stators. Now, there exists no well-defined dimensionalization process for the horseshoe vortex dynamics, but many studies have shown that the boundary layer thickness to cylinder diameter ratio is the most relevant parameter. The endwall boundary layer, as measured by a Hot Wire Anemometer in the absence of the bluff body, produced a typical 2D turbulent boundary layer with a 30 mm thickness in the position of the body leading edge.

The y-z coordinate system employed here has its origin on the body centerline on the endwall surface.

The points employed. The point closest to the endwall was 3 mm away, with a grid spacing of 2 mm near it and 5 mm away from it. The points closest to the bluff body (vertical) surface were 5 mm for the two lower injection ratio values. For the largest injection rate, the strong vortex in the corner was thought that it might lead to

**Fig. 14** The secondary velocity vectors

**II2: RESULTS AND DISCUSSION**

Smoke injection was employed initially to verify the direction taken by the injected air. This showed that the injection creates a streamwise vortex along the endwall-bluff body corner, which for injection ratios $v_i/u_0 > 2$ lifts up, but remains attached to the body surface. This limited the employed injection ratios to values below unity. The reported data, actually, refer to three injection ratio values, i.e. 0.0, 0.37 and 1.07.

The secondary velocity flowfield in the measurements plane is given in figure 14, which also shows the grid of

**Fig. 15** The $E_{ske}$ distribution of the horseshoe leg

**Fig. 16** The vorticity ($\zeta'$) distribution
large errors in the data reduction process (due to the large velocity and static pressure gradients) and no data were taken near the corner. The velocity vectors do verify the presence of a streamwise vortex in the no injection case. This vortex appears much reduced in strength in the low injection rate, but in the strong injection case the situation looks much more complicated.

A more direct picture of the secondary flow is given in figure 15, which presents the corresponding distributions of the E_{sKE}. Apparently, for the low injection rate \( \nu_{i}/u_0 = 0.37 \) the horseshoe vortex is nearly destroyed, although the corner vortex appears somewhat strengthened. In the strong injection case, it appears that both the horseshoe and the corner vortices are strengthened, to levels well above those of the no injection case. The appearance of the strong corner vortex is probably associated with the abrupt ending of the slot. This ending probably created a vortex similar to that observed in jets in crossflows, but further studies are needed in this direction.

The same picture arises from the streamwise vorticity distribution as well (figure 16). For the low injection rate and the no injection one as well, only the horseshoe and the corner vortices appear. In the strong injection case, on the other hand, there appear many vortex structures.

The total pressure loss coefficient \( (C_{p}) \) distribution (figure 17) shows that the main loss mechanism is in the endwall boundary layer for the two cases of no and low injection rates, as observed by Eckerle and Langston (1987) too. For the strong injection case the corner region shows large loss areas.

The nature of the horseshoe vortices can also be studied by observing the streamwise velocity \( (u') \) and transverse velocity \( (w') \) on a line passing through the vortex core, which does not appear to be deflected strongly by the injection. The data in figure 18 were taken from the line at \( z = 0.92 \), since the distributions in figure 16 showed that the horseshoe vortex cores passed through this line. The data show that for the small injection rate the \( u' \) profile (figure 18a) has a much smaller deviation from the one seen in turbulent boundary layers. The other two cases, on the other hand, exhibit significant deviations. The magnitude of the \( w \) velocity component in the measurements plane, for the cases with injection, is somewhat above zero. On the other hand, for the no injection case, the vortex core possesses no \( w \) component. This means that the flow in this case is parallel to the bluff body, while the injection forces a small cross flow, which probably comes from the increasing blockage of the corner vortex. A cross flow below the vortex core exists for all cases (figure 18b), something that supports the cooling requirements, since the injected air moves below the vortex core. This was actually verified by injecting a somewhat hotter air and measuring the resulting temperature field. The \( w \) component, above the vortex core, for the small injection rate case is nearly zero. For the \( \nu_{i}/u_0 = 0.37 \) case, thus, the cross flow here is mostly due to the non-zero transverse velocity of the mainstream at this plane, rather than due to the vortex. In addition, the thickness of the boundary layer in the small injection rate case is nearly half that in the no injection case and equal to that measured in the absence of the bluff body. The no injection case leads to a thickness
nearly double this value, a phenomenon observed by Eckerle and Langston, 1987, too.

Finally, the circulation around the horseshoe vortex was calculated, by employing equation (4). The $\Gamma'$ value was 0.1., for the case without injection. The corresponding $\Gamma$ value is 0.2., which similar to the one measured for the pressure side horseshoe vortex leg in part I.

CONCLUSIONS

The present study reports on the results of two experiments concerning the horseshoe vortex and its appearance in turbine blade channels. The first experiment investigated the contribution of the horseshoe vortices (which were simulated by vortices generated by two delta wing vortex generators) on the total pressure losses and the secondary kinetic energy in the exit plane of a 90°, square cross section bend duct, simulating a turbine blade channel. The results showed that:

(i) The horseshoe vortices increase by about 20% the secondary kinetic energy.

(ii) No visible increase in the mass averaged total pressure losses could be observed.

The second experiment investigated the possibility of controlling the size and strength of the horseshoe vortex by transverse injection, through a thin slot in the blade-endwall junction. The results showed that for very low injection rates this is possible, but as the injection rate increases the losses overshoot the no injection value and the secondary field becomes stronger.

REFERENCES