ABSTRACT

A secondary flow management technique which employs a boundary layer fence on the endwall of a gas turbine passage is evaluated under freestream turbulence conditions that are representative of turbine conditions. A turbulence generator, which was able to reproduce the characteristics of the combustor exit flow, was used. The horseshoe and passage vortices observed in previous tests with low turbulence level remain coherent and strong within the cascade passage when the intensity is elevated to 10 percent. A boundary layer fence on the endwall remains effective in changing the path of the horseshoe vortex and reducing the influence of the vortex on the flow near the suction wall at the high freestream turbulence level. The fence is more effective in reducing the secondary flow for the high turbulence case than for a low TI case, probably because the vortex which has been deflected into the core flow diffuses and dissipates faster in the more turbulent flow. The fence decreases aerodynamic losses for streamlines within the core of the channel flow.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>C</td>
<td>chord (mm)</td>
</tr>
<tr>
<td>Cp</td>
<td>specific heat of the air (kJ/kgK)</td>
</tr>
<tr>
<td>Cps</td>
<td>total pressure coefficient, (\frac{P_t - P_m}{0.5 p U_o^2})</td>
</tr>
<tr>
<td>CsKe</td>
<td>secondary kinetic energy coefficient, (\frac{(v^2 + w^2)}{U_o^2})</td>
</tr>
<tr>
<td>H</td>
<td>height of the fence (mm)</td>
</tr>
<tr>
<td>Hp</td>
<td>pressure side leg of horseshoe vortex</td>
</tr>
<tr>
<td>Hs</td>
<td>suction side leg of horseshoe vortex</td>
</tr>
<tr>
<td>h</td>
<td>heat transfer coefficient (W/m²K)</td>
</tr>
<tr>
<td>PSD</td>
<td>power spectral density (e.g. (u'^2(f, df)/df)), (m^2/s^3)</td>
</tr>
<tr>
<td>Pr</td>
<td>total pressure</td>
</tr>
<tr>
<td>Prt</td>
<td>total pressure in freestream upstream of the cascade</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>ReC</td>
<td>Reynolds number based on the chord length</td>
</tr>
<tr>
<td>Ss</td>
<td>curvilinear distance from stagnation line along suction wall (mm)</td>
</tr>
<tr>
<td>St</td>
<td>Stanton number, (St = \frac{h}{\rho C_p U_o})</td>
</tr>
<tr>
<td>TI</td>
<td>turbulence intensity (%)</td>
</tr>
<tr>
<td>Uo</td>
<td>inlet velocity (m/s)</td>
</tr>
<tr>
<td>v</td>
<td>resolved pitchwise velocity component</td>
</tr>
<tr>
<td>w</td>
<td>resolved spanwise velocity component</td>
</tr>
<tr>
<td>Z</td>
<td>spanwise distance from the endwall</td>
</tr>
<tr>
<td>(\rho)</td>
<td>density (kg/m³)</td>
</tr>
<tr>
<td>(\theta)</td>
<td>momentum thickness (mm)</td>
</tr>
</tbody>
</table>

INTRODUCTION

The general design goals for turbo-engines are contradictory: high cycle efficiency, increased durability and lower operating costs (Yeh and Gladden, 1989). High performance is accompanied by minimum use of cooling air and high turbine inlet temperature. Durability requires minimizing temperatures and temperature gradients. An optimum must be achieved which requires understanding of the complex flow field which influences the heat transfer processes in the turbine passage. Such flow is complicated, containing two legs of a horseshoe vortex, a passage vortex, and endwall crossflow (Langston et al., 1977 and Kawai et al., 1988, Fig. 1). This secondary flow provides an important loss mechanism, creates unwanted heat transfer augmentation on the endwall and suction surfaces (Stieverding, 1985), and makes film cooling of these surfaces difficult.

Film cooling along the blade or the endwall surface, has been effective in reducing overall surface temperatures of turbine components (Goldstein, 1971). However, previous studies showed that the film cooling performance on the blade near the endwall is severely influenced by secondary flow. Goldstein and Chen (1987) and Takeishi et al. (1989) described triangular-shaped regions on the suction surfaces of airfoils where the flow field created by the secondary flow washes film cooling air away from the surface, reducing the film cooling effectiveness to essentially zero. Marston (1991) found that film coolant injected through the endwall has some influence on this region.

Fig. 1 Vortex system in the endwall region of a turbine cascade (from Kawai et al., 1988)

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In the present study, the utility of a boundary layer fence was tested under a high level of freestream turbulence (TI=10%), generated by a device which is able to reproduce the characteristics of the combustor exit flow (Chung, 1992). Turbulence levels at the exit of a combustor are estimated to range from about 8 percent to as high as 25 percent and are highly dependent on combustor geometry (Ames and Moffat, 1990a and Moss and Oldfield, 1991). To conduct the present study, a turbulence generator which has similar features to those of the Ames and Moffat (1990b) combustor simulator was built. The generator produces three main features of a combustor exit flow: (1) large scale recirculation in the primary zone, (2) penetration and mixing of jets in the dilution zone and (3) contraction of the flow in the transition zone.

**APPARATUS**

1. **Test Section**
   
   The experiments are carried out in a blown type, low-velocity wind tunnel shown in Fig. 3. The profile of the test section airfoil is of the CF6-50 shape with chord length and height of 231 mm and 610 mm, respectively. The aspect ratio is 2.64 and the solidity ratio (chord/pitch) is 1.3. The angles of inlet and outlet flows are 44.3° and 62.7°, respectively. The diameter of the leading edge of the blade is 25.4 mm. Lexan sheets of 0.6 mm thickness are used for the pressure and suction walls. These pieces are attached to two plexiglass forms shaped to the blade profile. A top view of this “simulator” test section is shown in Fig. 3. More details of construction and a description of the qualification of the simulator are presented by Chung (1992) or Chung and Simon (1990). It should be noted that the intent of this program is to investigate a curved channel flow with representative secondary flow action. This “simulator” does not allow measurement of stage performance.

2. **Turbulence Generator**

   A turbulence generator with a geometry similar to that of an annular combustor was used to elevate the freestream turbulence level (Fig. 4). Primary air passes through the rectangular slots of panel A to mix with secondary air which passes through the circular holes of panel A, along the nozzle walls and finally through the small holes in side panels B. The generator produces a turbulence intensity level of about 10% and an integral length scale of about 5 cm.
were used to drive the probes.

To characterize the flow from the turbulence generator by Jones (1991). A uniform heat flux boundary condition is applied to measure the velocity in this study. The yaw-pitch calibration must be calibrated with respect to two angles) was used to measure the streamwise component of velocity, checking the uniformities of the mean velocity and turbulence intensity, isotropy of the turbulence and power spectra of the three velocity components at most of the positions. The three velocity components 1.3 cm downstream of the nozzle exit.

The results from the last two items are discussed in the present paper. The composite shows the shear stress directions on the surface.

The purpose of the study was to assess the performance of a fence under elevated freestream turbulence conditions.

5. Flow Visualization Facilities

Various flow visualization techniques were used to observe the secondary flow. The ink-dot-liquid-film technique introduced by Langston and Boyle (1982) was applied on the suction surface of the blade near the endwall. The technique provides patterns of shear stress directions on the surface. A tuft grid of 8 cm by 20.5 cm was utilized to observe the behavior of the vorticity within the passage. The assembly is composed of nylon line patterned into a rectangular grid, with tufts connected, using loops, to each intersection. The tufts, yarn filaments of 2 cm length, are free to point in the direction of the flow. The vortex pattern is recorded by photography. A single tuft probe, a thin rod with a single tuft tied, using a loop, at the end, was used to observe the flow pattern on the endwall, within the saddle point region. A set of arrows was drawn on a grid to match the observed tuft directions at each of the chosen positions. The composite shows the shear stress direction pattern. Application of these techniques is described by Chung (1992) and Chung and Simon (1990).

PROCEDURE

Test conditions for the experiments are listed in Table 1. The momentum and dissipation rates, shape factors and momentum thickness Reynolds numbers of the inlet boundary layers on the endwall were measured by traversing a total pressure tube perpendicular to the endwall at point P of Fig. 3. The last two parameters of this list, \( S_8/C \) and \( S_8/H \), were extrapolated from these measurements to the location of the leading edge of the left-hand side blade (by assuming flat plate, zero pressure gradient, turbulent boundary layer growth).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High TI (present case)</th>
<th>Low TI (comparison case)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( U_e ) (m/s)</td>
<td>15.0</td>
<td>14.0</td>
</tr>
<tr>
<td>( R_e )</td>
<td>2.14 \times 10^6</td>
<td>2.05 \times 10^6</td>
</tr>
<tr>
<td>( T_I ) (%)</td>
<td>~ 10</td>
<td>6.0</td>
</tr>
<tr>
<td>Displacement Thickness(mm)</td>
<td>2.93</td>
<td>0.7</td>
</tr>
<tr>
<td>Shape Factor</td>
<td>1.270</td>
<td>1.479</td>
</tr>
<tr>
<td>( S_8/C )</td>
<td>0.011</td>
<td>0.0067</td>
</tr>
<tr>
<td>( S_8/H )</td>
<td>0.249</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Table 1. Test conditions for the high turbulence case

First, the facility was qualified at a low freestream turbulence level by comparing the pressure profile at the centerspan against data taken in a turbine cascade of the same airfoil geometry and the secondary flow pattern was documented for low-turbulence conditions (see Chung and Simon, 1990). The turbulence generator was installed and the turbulence was documented. Finally, the visualization and measurement program discussed in Chung et al. (1991) was repeated with the high-turbulence flow. The results from the last two items are discussed in the present paper.

RESULTS AND DISCUSSION

1. Qualification of the Turbulence Generator

Qualification of the turbulence generator was made by checking the uniformities of the mean velocity and turbulence intensity, isotropy of the turbulence and power spectra of the three velocity components 1.3 cm downstream of the nozzle exit. The mean velocity was uniform at 20.8 m/s ± 0.5 m/s in the center of the core area. Regions near the top and bottom walls of the nozzle showed peaks in velocity, one as high as 22.1 m/s.

The turbulence intensity was also uniform at 10.2 % ± 1.0 % in the core area. The values within 2.54 cm from the top and bottom walls of the wind tunnel were somewhat lower, at 8.5 % ± 0.5 %.

The spectrum for \( w' \) is reasonably isotropic turbulence was generated. Representative power spectral density distributions for the \( u' \) and \( v' \), fluctuating velocity components are shown in Fig. 5. The spectrum for \( w' \) is

Fig. 4 Turbulence generator installed in the wind tunnel nozzle

3. Instrumentation

Hot Wire Anemometry

Three types of constant-temperature, hot-wire probes were used in the present study. A single straight-wire probe (TSI 1210) and a single boundary layer probe (TSI 1218) were used to measure the streamwise component of velocity, checking the uniformity of the mean and fluctuation level across the inlet plane. A two-wire, boundary layer, X probe (TSI 1243), was used to characterize the flow from the turbulence generator by measuring homogeneity and uniformity of the turbulence. Two-channel, constant-temperature anemometer (TSI 1053A) bridges were used to drive the probes.

Five Hole Probe

A five-hole probe (United Sensor DC-125) was employed in this study to document the secondary flow near the outlet of the passage (Plane A in Fig. 3). The probe has a conical-shaped tip of diameter 3.2 mm. The non-nulling mode (in which neither vector angle is nullled or balanced during a measurement and the probe must be calibrated with respect to two angles) was used to measure the velocity in this study. The yaw-pitch calibration technique of Trenster and Yocum (1979), was employed.

Liquid Crystal Thermometry

Liquid crystals and thermo-foil heaters were mounted on the suction, pressure and endwall surfaces to observe the effects on heat transfer of mixing by the secondary flows. Cholesteric liquid crystals give the temperature distribution map, as described by Jones (1991). A uniform heat flux boundary condition is applied to these surfaces, thus, isotherms correspond to lines of constant heat transfer coefficient.

4. Fence

The main objective of this study is to block and change the track of the pressure-side leg of the horseshoe vortex. To do this, a fence was made of equilateral triangle, cross-sectional shape, 13 mm on a side, and placed in the test section as shown in Fig. 3. More details of the configuration and location of the fence were presented by Chung et al. (1991). The fence is in the path of the pressure side leg of the horseshoe vortex, as sketched in Fig. 2. No attempt was made to optimize the geometry in this study. The
nearly identical to that of \( u' \). They appear to be clean, with no significant peaks.

2. Effects of the freestream turbulence level on the secondary flow

Once the turbulence generator was qualified, the effects of high freestream turbulence level on the secondary flow pattern were documented. A plot of the secondary flow vector pattern at plane A (shown for the high TI case) is compared with that for the low TI case in Fig. 6. The low TI measurements taken from Chung et al. 1991 were made with a two-component LDA. The high TI measurements were made with the five-hole probe. The centers of the vortices, marked with the "+" sign, and their counterclockwise rotation are clear in both cases. Similar to the behavior in the low TI case, the vortex appears to lift up along the suction wall so that its center is near the suction wall and away from the endwall. It can be concluded that the passage vortex is active in the high freestream turbulence flow. Even though the locations of the centers of the vortices and the sense of rotation look the same for both cases, the structures of the secondary flows are somewhat different. In contrast to the intensified and confined vortex shown to the left (low TI), the vortical motion appears to extend into the region very near the endwall, under high freestream turbulence levels. The arrows near the endwall in Fig. 6 show a strong crossflow toward the suction wall. While the tuft grid showed the vortex clearly for the low turbulence case (Fig. 8 of Chung et al., 1991), it did not give good resolution for the high-turbulence case due to the unsteadiness of each tuft position.

Endwall

The shear stress direction pattern on the endwall (shown as Fig. 1 of Chung and Simon 1990, for the low TI flow) is not significantly affected by the freestream turbulence level, though the high-turbulence case showed greater unsteadiness over most of the region. The two are similar because the flow near the endwall is primarily influenced by the pressure gradient and viscous effects. The effects of the turbulence are apparently diminished by near-wall damping of the turbulent eddies.

Suction Wall

Figure 7 is an ink dot visualization of the suction surface shear stress direction distribution under low freestream turbulence level conditions. It shows the track of the passage vortex, marked by a upward skewing of the shear stress in the triangular region shown, as it sweeps up the suction surface (in the vicinity of A). This is consistent with the sketch of Fig. 1. Though beyond the endwall region, the zone of most interest for the present study, one sees a reverse flow in the two-dimensional region (in the vicinity of B). This is a separation zone followed by reattachment. Figure 8, produced by the ink dot visualization technique, shows local shear stress directions on the suction surface for the high TI case. As with Fig. 7, each arrow represents the direction, not the magnitude of the shear stress. The upward skewing is reduced in the high TI case, Fig. 8, both figures show generally the same pattern. A change due to the freestream turbulence level is observed near the two-dimensional zone, however. Figure 8 shows that the separation zone (B in Fig. 7) is completely eliminated in the high TI case.

That the gross secondary flow activity within the endwall region of a turbine is generally unaffected by the level of turbulence is encouraging, for many previous investigations which characterized this flow were done under low turbulence level conditions.
zone. Graziani et al. (1980) also observed relatively high Stanton flow has higher heat transfer coefficients than those measured in the area near the endwall which is influenced by the secondary flow was established, attention was turned to its effect on heat transfer coefficient lines as:

\[ St = \frac{h}{\rho C_p U_o} \]  

(1)

Figures 9 and 10 were made in this manner to show contours of \( St \) number on the suction surface for low and high turbulence intensity cases, respectively. Stanton number values measured by this method hold to approximately 8 % uncertainty. The area near the endwall which is influenced by the secondary flow has higher heat transfer coefficients than those measured in the two-dimensional region. As with the local shear stress distribution on the suction wall (Fig. 7), this region is a triangular zone. Graziani et al. (1980) also observed relatively high Stanton numbers and steep gradients in the three-dimensional flow region on the suction surface near the endwall and noticed that this region is associated with the three-dimensional flow of the passage vortex as it travels off the endwall and onto the suction surface. The high Stanton number region on the lower left corner (A) in Fig. 9 is where the pressure side leg of the horseshoe vortex impinges upon the suction wall. The triangular zone is believed to be established by a combination of the vortex and the continuation of the endwall crossflow. Figure 9 shows the separation and reattachment zone in the two-dimensional region far from the endwall, which was also observed in the shear stress visualization (Fig. 7). In the region of lowest heat transfer coefficient (B), the boundary layer has separated. The region downstream represents a region of reattached boundary layer. Chen and Goldstein (1991) also found, under low-Ti conditions, that the mass transfer distribution on the suction surface is dramatically changed by secondary flows in the endwall region. By contrast, the overall heat transfer coefficient values for the higher Ti case (Fig. 10) are higher than those for the low Ti case, suggesting increased mixing of the near-wall flow. The separation and reattachment zones disappeared from the two-dimensional region due to the high freestream turbulence level. Though the shear stress direction plot showed a triangular zone for both levels of Ti, the Stanton number measurements indicate that the region which is influenced by the secondary flow is confined to very near the endwall, indicating that mixing due to turbulent eddy motion in the channel flow has substantially reduced the influence of the secondary flow on the remainder of the triangular zone. Thus, heat and mass transfer studies should be conducted at elevated Ti levels.

3. Assessment of the performance of a boundary layer fence

The above results show that endwall secondary flow, including the vortices and endwall crossflow, remains coherent and influential as the freestream turbulence level is elevated. The zone of major influence is constrained to nearer the endwall in the high Ti case, however. The effectiveness of a fence on the endwall (Fig. 2) which has been designed to deflect the pressure side of the horseshoe vortex will next be evaluated under elevated turbulence level conditions. The value of the fence under low Ti conditions was discussed by Chung et al., 1991.

Secondary flow vectors in the passage

Figure 11 shows plots of secondary flow vectors measured by a five hole probe at plane A (shown) with and without the fence in place. The center of the vortex in each plot is marked using the "+" sign. The magnitudes of the secondary velocity components are significantly reduced by the fence. The vortex is deflected by the fence so that its center is displaced from the suction wall. The center is also a bit lower with the fence in place. Since the vortex is less near the suction wall, the vortex has less opportunity to climb the wall.

In order to trace the behavior of the horseshoe vortex and the crossflow, the same measurements were taken 11.9 cm upstream of the previous plane. Figure 12 shows plots of secondary flow vectors at plane B (shown) for cases with and without the fence. Without the fence, the horseshoe vortex is against the suction wall. Large vectors near the endwall and the
suction wall show how effective the vortex is at skewing the suction wall flow. The figure helps to explain the elevated heat transfer rates in this region. With the fence, the vortex is deflected up and is carried downstream by the main flow. Vectors at the corner represent a small clockwise vortex which is driven by the horseshoe vortex. This flow may help suppress the endwall crossflow effect on the wall shear in this region (as shown in Fig. 8).

One must recognize that the facility employed is a simulator and not a true cascade. A question may arise, for instance, concerning the effect of the interaction of the channel flow (flow between the two test walls) with flow from outside the passage (see Fig. 3). A careful assessment of this was made by comparing wall pressure profiles in the two-dimensional region and shear stress direction patterns on the suction and endwalls of the simulator and a linear cascade having the same airfoil shape (Chung and Simon, 1990). It was concluded that the interaction with external fluid downstream of the pressure surface has no effect on the pressure-side horseshoe vortex trajectory. Thus, the description of the effect of the fence is accurate. Because this facility is not a cascade, the effect of the fence on the overall stage performance cannot be assessed.

Directions of the Local Shear Stress

The change of the shear stress direction pattern on the endwall due to the presence of the fence is shown in Fig. 13. Multiple arrows indicate higher unsteadiness. Each arrow represents the direction, not the magnitude of the shear stress. It is observed that the flow pattern in the most of the upstream region is not noticeably affected by the fence. The arrows on the lower right-hand corner above the fence (A) show only the crossflow and no signs of a vortex after the pressure side leg of the horseshoe vortex has been deflected by the fence.

The changes in shear stress pattern under high TI conditions due to the presence of the fence are observed by comparing Figs. 8 and 14. The arrows in region A, where the pressure side horseshoe vortex would impinge if there were no fence, show that the vortex was deflected. This is constant with Fig. 12; the boundary layer fence is effective in reducing the influence of the secondary flow near the suction wall, even for the high freestream turbulence level case.

Heat Transfer Measurements

The effect of the fence on heat transfer is determined by comparing Figs. 10 and 15. The crossflow is responsible for some mixing very near the endwall. The region of elevated Stanton numbers is reduced in size by the fence, however.

Aerodynamic Losses

Total pressure loss coefficients were calculated from the five-hole probe measurements taken in Plane A of Fig. 3. The total pressure coefficient, C_p, is defined as the difference between the local total pressure and the total pressure of the flow upstream of the cascade normalized by the velocity head upstream of the cascade:

\[
C_p = \frac{P_{total} - P_{total upstream}}{\frac{1}{2} \rho U^2}
\]
The secondary kinetic energy coefficient, $C_{ske}$, is defined as the summation of the kinetic energies associated with the components of velocities normal to the mainstream:

$$C_{ske} = \frac{1}{2} \rho \left( \frac{v^2 + w^2}{U_0^2} \right)$$

Since the rotational kinetic energy due to the vortex is not converted to mechanical energy within the turbomachine, it must eventually be dissipated. It therefore represents an additional loss.

The total loss is taken to be the sum of the total pressure loss ($C_{p\text{t}}$) and the secondary kinetic energy loss. The effect of the fence on this total loss is shown by comparing Figs. 16 and 17. Note that the plotted domain extends to within 1.0 cm of each wall. The region of higher loss is moved downstream by the fence and the peak loss value is reduced by the fence. Also, the average over the area shown is reduced from 0.159 to 0.132 by the fence.

Kawai et al. (1989) observed that the secondary losses and total losses are reduced by 25% when their optimum fence design was used as a result of local loss reductions near the blade suction wall. The combination of their results and the present results suggest that, within the channel, any additional losses due to the presence of the fence are smaller than the loss reduction due to the decreased secondary flow effect in the passage.

**SUMMARY AND CONCLUSION**

In the present study, a secondary flow management technique which employed a boundary layer fence was tested in a cascade simulator under a high level of freestream turbulence (10%). Conclusions drawn from this study are:

1. The passage vortex remains coherent and active at the high freestream turbulence level ($T_1 = 10\%$).
2. The effects of secondary flow on heat transfer are constrained to nearer the endwall, under high freestream turbulence level conditions.
3. The overall patterns of shear stress direction distribution on the endwall and suction wall near the endwall are not greatly affected by the level of freestream turbulence, up to 10%. The level of unsteadiness is increased when the turbulence level is raised, however.
4. The boundary layer fence is effective in changing the passage of the pressure-side leg of the horseshoe vortex and in reducing the influence of the vortex on the suction wall for high levels of the freestream turbulence ($-10\%$).
5. The strength of the vortical motion is reduced by the presence of the fence.
6. Within the portion of the documented channel, the boundary layer fence, is capable of decreasing the aerodynamic losses associated with the endwall secondary flow even under the high freestream turbulence level conditions.
7. A separation zone, observed in the 2-D region far from the endwall in the low-turbulence case, is eliminated by increasing the turbulence level.
8. Encouraging results suggest that continued work, including optimisation of the fence may be of value. Verification of aerodynamic performance should be made in a true cascade where overall stage performance can be measured.

**ACKNOWLEDGEMENTS**

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