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Vortex Effects Resulting from Transverse Injection in Turbine Cascades, and Attempts at Their Reduction

B. A. ABURWIN

Research Student

N. R. L. MACCALLUM

Senior Lecturer

Dept. of Mechanical Engineering,
University of Glasgow,
Glasgow, Scotland

A preliminary experimental investigation has been made of the effects of vortices in the approach stream on turbine blade row performance. The vortex regime has been simulated by stationary vortex generators. The net pressure losses within the following blade row were reduced by 23 and 12 percent when the vortex generators were placed in line, respectively, with the mid-passages and with the leading edges. Further, the discrete inlet vortices had virtually disappeared at the exit plane. In addition, methods have been tested for reducing the exit vortex, particularly when enhanced by transverse injection. The most effective scheme examined was a fence location on the suction surface near the endwall. However, there is a pressure loss penalty.

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NOMENCLATURE

c = chord

d = distance along blade pitch from one mid-passage line to next, in direction of suction surface

D = measure of strength of exit vortex, defined by $(\Delta\alpha^*)(\Delta y^*/c)$

E = measure of kinetic energy of tangential components in exit vortex, defined by $(\Delta\alpha^*)^2(\Delta y^*/c)^2$

F = measure of angular momentum of exit vortex, defined by $(\Delta\alpha^*)(\Delta y^*/c)^3$

p = pressure

Q = ratio of maximum velocity of injected jet to velocity of main approach flow

s = blade pitch

U = velocity in main flow direction

v = velocity

x = distance in axial direction from leading edge

y = distance from end-wall carrying injection slot

z = distance along pitch direction from leading edge

α = main flow angle, measured from axial direction

ρ = density

Subscripts

o = stagnation

1, 2 = inlet to, outlet from cascade

amb = ambient

ave = average

s = secondary

Superscript

* = range of pitch-integrated exit vortex

INTRODUCTION

When an additional flow is injected transversely into the main flow entering a row of turbine blades, as when disk cooling air in a gas turbine is returned, several significant effects in the main flow are observed (1).[1] One of these effects is the strengthening of the secondary vortex in the flow leaving the blade, or nozzle guide vane row. The influences of injection and cascade variables on the strength of this exit vortex have been studied in straight cascades (2, 3) and in an annular cascade (4).

The present work had two aims. The first

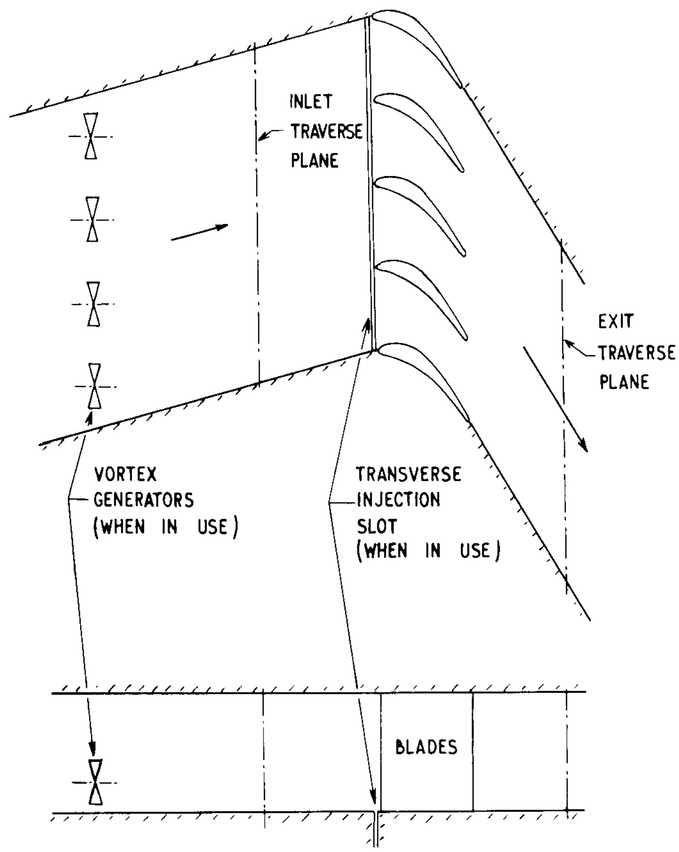

Fig. 1 Test cascade

[1] Underlined numbers in parentheses designate References at end of paper.

Table 1 Coordinates of Blade Profile -- 40-Deg Stagger Angle

pressure surface	x/c	0.0	0.049	0.162	0.285	0.392	0.476	0.544	0.613	0.676	0.749
	z/c	0.0	0.021	0.066	0.132	0.205	0.275	0.342	0.424	0.507	0.630
suction surface	x/c	0.0	.045	0.154	0.272	0.378	0.462	0.534	0.607	0.672	0.748
	z/c	0.0	-0.020	-0.035	-0.016	0.037	0.119	0.226	0.346	0.465	0.615

was to investigate the effect of the exit vortex leaving one row of blades on the performance of the next row. The second aim was to study methods of reducing the strength of the exit vortex. These investigations are discussed in turn in this paper, and the major conclusions are brought together in the final section.

APPARATUS

This consisted of a cascade of five blades (four passages) having a chord of 129 mm (5.07 in.), of aspect ratio 1.0, set at a stagger angle of 40 deg and at a pitch of 88 mm (3.5 in.). The cascade, which had been used in previous related experiments (1-3), is illustrated in Fig. 1, and the coordinates of the blade profile are given in Table 1. The cascade was placed in the suction to a variable speed fan. Typically, the flow velocity at exit from the cascade was 23 m/s (75 ft/s), corresponding to a Reynolds Number, based on the exit velocity and chord, of 2.2×10^5.

The main airflow to the cascade entered through a contraction of area ratio 8.3. Wire grids were placed in this contraction to give a turbulence level, when there were no vortex generators present, of 1.5 percent at inlet to the cascade. The inlet to the cascade was set to give an air angle of 15 deg to the axial direction.

When transverse injection was required, this was made through a slot 3.0 mm wide, running across one end-wall immediately in front of the cascade, as illustrated in Fig. 1. In the present work, the injected air was directed at right angles to the main air flow. The injected flow and the main flow were at the same temperature. When not required, the injection slot was taped over.

Performance of the cascade was established by traversing the flows at inlet and outlet. The inlet traverse plane was at an axial distance of 1.3 axial chord upstream from the blade leading edge, and the downstream plane was at an axial distance of 1.03 axial chord from the trailing edge. The instrument used for measuring the flow velocity, direction and pressure was a five-hole spherical probe of 8-mm dia. This instrument was checked satisfactorily in these flows against a three-hole probe of 2.7-mm dia. Estimated accuracy of the five-hole probe is ± 0.5 m/sec in velocity components and ± 0.5 deg in direction.

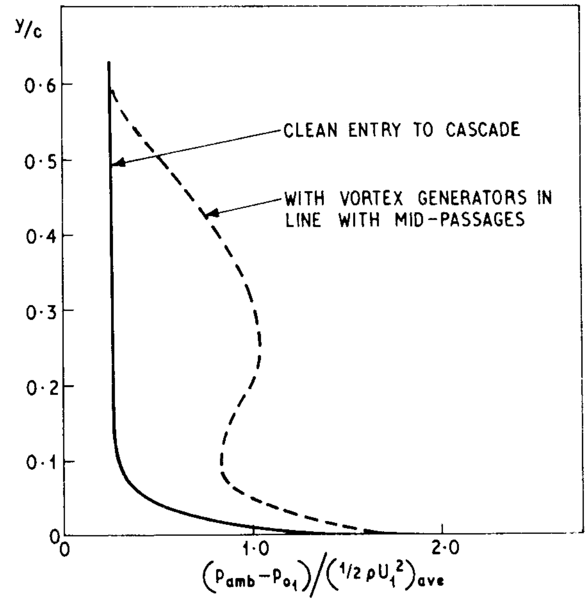

Fig. 2 Inlet pressure loss distributions - without and with vortex generators

The central blade in the cascade was provided with pressure tappings from which the pressure distributions could be observed, over a range of blade heights.

EFFECT OF VORTICES IN FLOW ENTERING A BLADE ROW

As described earlier, there are secondary vortices in the flow leaving a turbine blade row, and these are considerably enhanced if a flow is injected transversely into the main flow entering that blade row. In many turbines, the flow leaving this row of blades then enters a subsequent row.

The aim of the tests reported here was to simulate this series of vortices leaving the first row, and study their effect on the second row. For this work, the second row was represented by the straight cascade described in the previous section, and the vortices in the cascade entry flow were formed by introducing a series of vortex generators. In the real turbine the vortices move periodically across the entry to the passages, from the pressure to the suction surfaces. As time-mean instrumentation was to be used to measure the flow velocity and direction and the pressure at outlet from the

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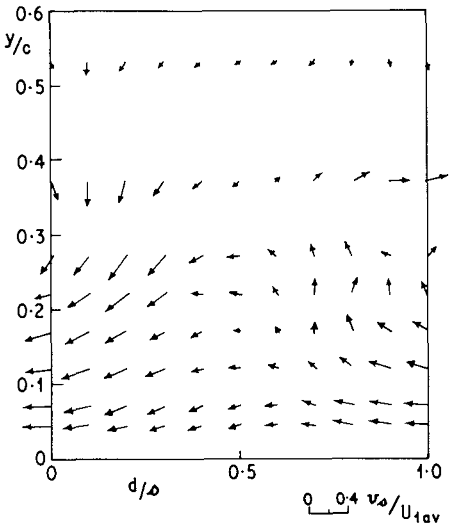

Fig. 3 Secondary velocities at inlet to cascade - vortex generators in line with mid-passages

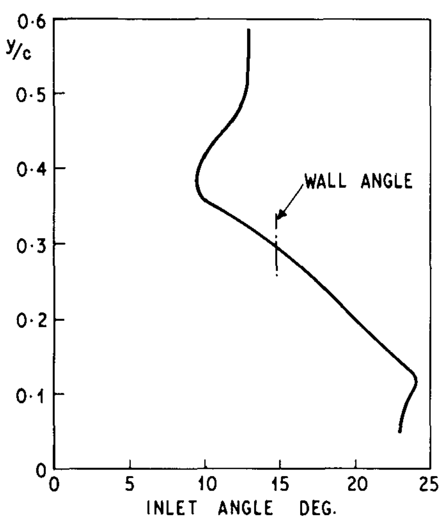

Fig. 4 Integrated inlet angles - vortex generators in line with mid-passages

test cascade, it was decided that for this initial study, the vortex generators should be kept stationary relative to the cascade. Tests would be carried out with generators in different positions relative to the cascade. This use of stationary generators, while not truly representative, should give helpful indications of the effects of these vortices. The design of the entry section to the cascade is greatly simplified by this procedure.

Vortex Generators

The vortex generators were prepared from thin metal disks, 51-mm dia, cut to make eight

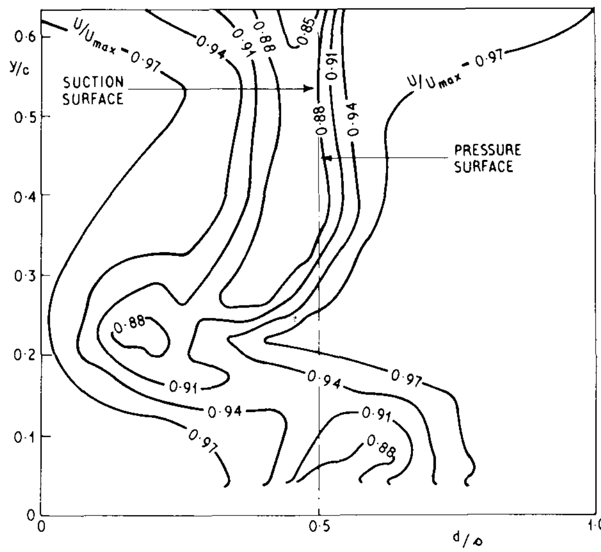

Fig. 5 Velocity contours at outlet traverse plane - clean entry to cascade

vanes, and the vanes twisted to 45 deg to the axis of the disk, the direction of twisting being such as to simulate the exit vortex; i.e., the flow at the side of the vortex nearest the end-wall is twisted toward the suction surface of the passage from which it is leaving. This means that when the vortex enters the next row of blades, the flow at the side of the vortex nearest to the end-wall is twisted toward the pressure surface of this new row.

The vortex generators were mounted, as illustrated in Fig. 1, with their axes at a height of 33 mm (0.26 chord) from one end-wall and at an axial distance of 300 mm (3.1 axial chord) in front of the cascade. The axes of the generators were parallel to the axial flow direction. This positioning of the generators produced vortices which corresponded with the slightly asymmetric exit vortices to be simulated (1).

In the first series of tests using the vortex generators, the generators were placed as illustrated in Fig. 1, in the lines leading to the mid-passage positions. In the second test, the generators were placed in line with the leading edges of the blades. In both cases, therefore, the pitch between the generators was the same as the pitch of the blades in the cascade.

Test Procedure

For these tests, no transverse injection was used and the injection slot was taped over, as was the boundary layer suction slot.

With the entry to the cascade in the

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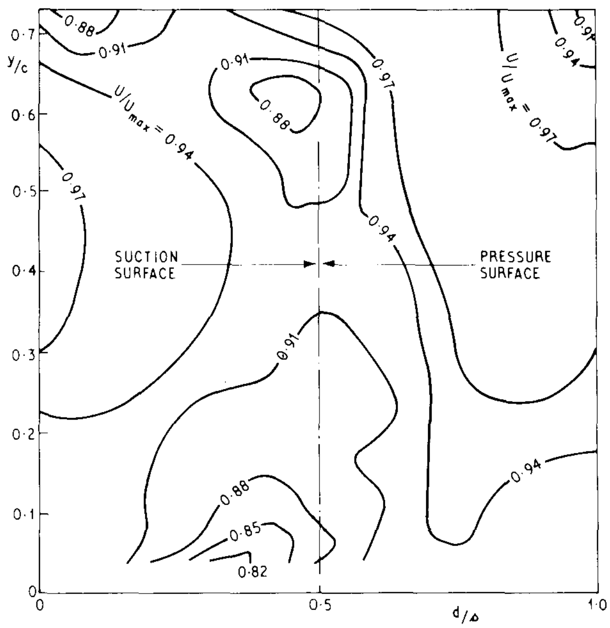

Fig. 6 Velocity contours at outlet traverse plane - vortex generators in entry in line with mid-passages

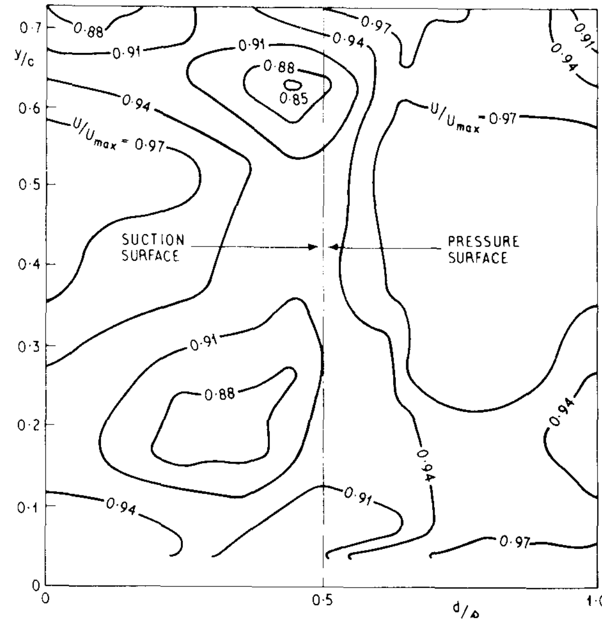

Fig. 7 Velocity contours at outlet traverse plane - vortex generators in entry in line with leading edges

"clean" state, i.e., with no vortex generators introduced, the angles of the exit side-walls were adjusted, relative to the cascade, until there was a symmetric velocity distribution across the exit flow. This occurred when the exit side-walls were at 59.5 deg to the axial direction. The performance of the cascade was then established by traversing the flows at inlet and outlet. Pressure distributions around the blade surfaces were also recorded.

Vortex generators were then introduced, as described in the previous section, and the above series of readings repeated.

Results and Discussion

Inlet Velocity Distributions. The pitch-integrated inlet pressure loss distributions, relative to atmospheric pressure, are shown in Fig. 2, over 60 percent of the blade span, starting from the end-wall on which the vortex generators are mounted.

When there are no vortex generators the losses are very uniform, and small, being due to the inlet system, including turbulence grids.

The introduction of the vortex generators produces, as intended, vortex motion and the secondary flow components are illustrated in Fig. 3; in this case, the generators are situated in line with the mid-passage positions. The blockage of the vortex generator leads to a reduction in forward velocity downstream from the generator, and this is indicated by the pitch-integrated loss distribution shown in Fig. 2. The peak of this pressure loss associated with the vortex occurs at a blade span value of about 0.24 for y/c, which compares with the span position of the generators of 0.26 for y/c. Pitch-integrated inlet angles are shown in Fig. 4.

Strengths of Inlet Vortices. It is necessary to compare the strengths of these vortices produced by the vortex generators with the strengths of the vortices which are introduced into blade passage exit flows as a result of transverse injection. Three simple parameters have been used to quantify the strengths of these exit vortices (2). These parameters, D, E, and F, are proportional to the circulation, to the kinetic energy of the tangential components velocity components in the vortex, and to the angular momentum of the vortex, respectively, if the vortex is assumed to be a rotating solid body bounded in diameter by the positions of maximum pitch-integrated positive and negative deviation. The parameters are given by

$$D = (\Delta\alpha^*)\ (\Delta y^*/c) \quad (1)$$

$$E = (\Delta\alpha^*)^2\ (\Delta y^*/c)^2 \quad (2)$$

$$F = (\Delta\alpha^*)\ (\Delta y^*/c)^3 \quad (3)$$

For a typical case with transverse injection

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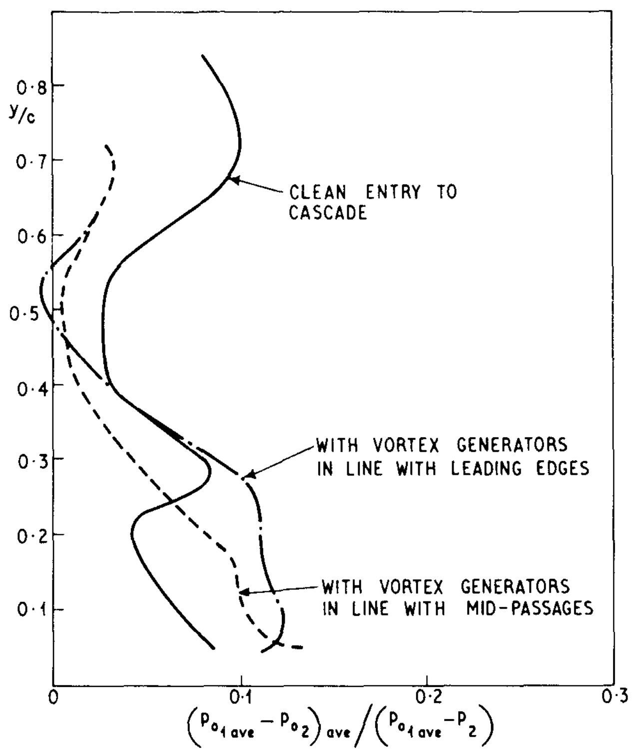

Fig. 8 Integrated stagnation pressure losses across cascade for entry flows without and with vortices

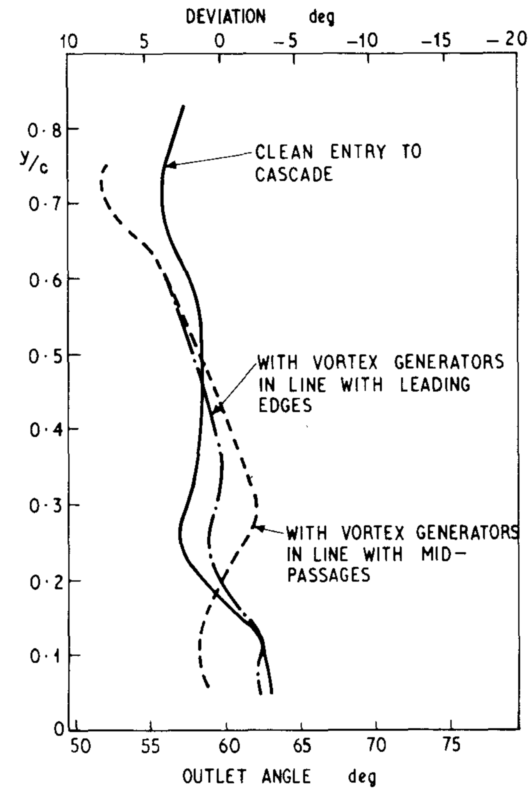

Fig. 9 Integrated outlet angles for entry flows without and with vortices

(3) -- aspect ratio 1.0, stagger angle 45 deg, inlet angle 15 deg, mass injection ratio 0.036 -- the values of the parameters, D, E, and F, for the exit vortices are 1.4, 2.0, and 0.062, respectively. When the flow is considered relative to the next row of blades, these parameters will be somewhat changed due to the change in ($\Delta\alpha^*$) as predicted from the velocity triangles. Typically, the value of ($\Delta\alpha^*$) might be increased by 50 percent; thus, the values of D, E, and F with reference to the next row of blades might become 2.1, 4.5, and 0.093, respectively.

When the same technique is applied to the vortices produced by the generators in the entry section of the present apparatus, the values of the parameters, D, E, and F, are 3.6, 13, and 0.22, respectively.

Thus, the generators being used are creating vortices which are, say, twice as strong as those resulting from the typical transverse injection case referred to (3). As it had been found that the strength of the exit vortex resulting from transverse injection is roughly proportional to the mass injection ratio, it was decided to continue with the present vortex generators, and the results obtained can be scaled linearly to correspond to the appropriate exit vortex strength.

Outlet Velocity Distributions and Losses. Outlet velocity distributions are shown in Figs. 5, 6, and 7 for the cases of "clean" entry to cascade, vortex generators in line with mid-passages and vortex generators in line with blades, respectively.

The major point to note is that, while with the clean entry to the cascade the wake trough drops to about 0.86 of the plateau velocity, when the vortices are introduced in the inlet flow, the blade wake trough is less marked and for a considerable proportion of the span, the velocity in the wake does not drop lower than 0.9 of the maximum velocity. The velocity gradients are, in general, weaker when inlet vortices are present.

The losses in stagnation pressure, relative to the average inlet stagnation pressure, have been integrated across the pitch, and are shown in Fig. 8 as loss coefficients. These coefficients have been based on the average, rather than the maximum inlet stagnation pressure due to the large change introduced by the vortex generators in the inlet stagnation pressure distribution (Fig. 2). The average kinetic energy associated with the rotating motion in the inlet vortices is very small, less than

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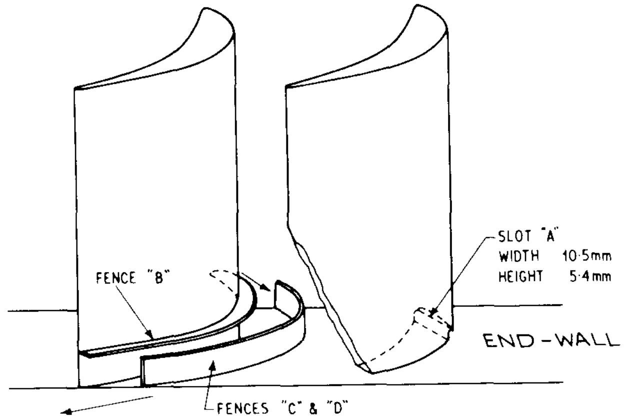

Fig. 10 Schemes for exit vortex reduction

0.1 percent of the kinetic energy of the cascade exit flow, so its contribution as an energy or velocity head input is negligible. Span-wise integration of the loss coefficients, up to a y/c value of 0.75 gives a value for the average loss coefficient of 0.064 for the "clean" inlet condition and values of 0.049 and 0.056 for the cases where there are inlet vortices, in line, respectively, with the mid-passage and with the

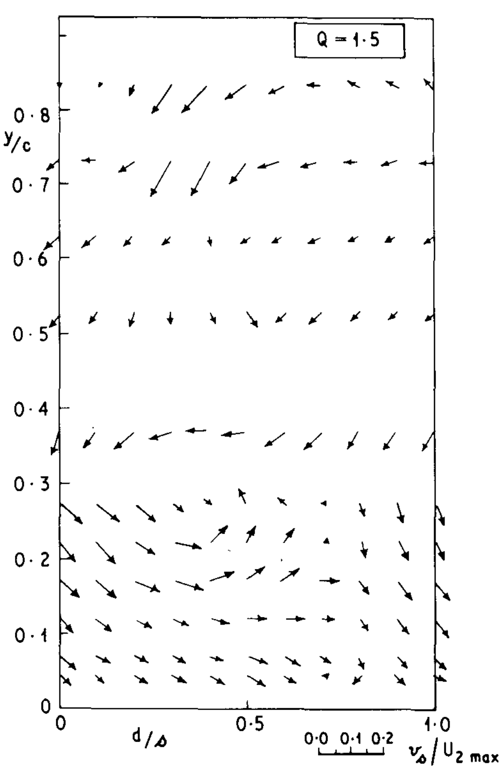

Fig. 11 Secondary velocities at outlet traverse plane - with transverse injection - basic cascade

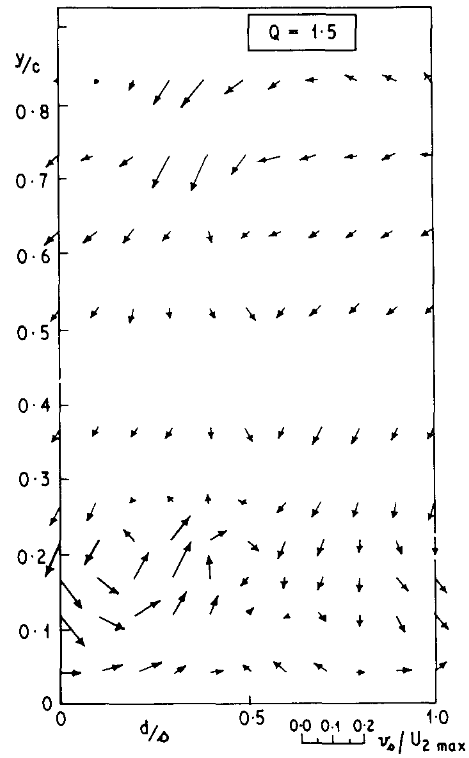

Fig. 12 Secondary velocities at outlet traverse plane - with transverse injection - with thick end-wall fence "C"

blades. At first sight, this reduction in losses when inlet vortices are present is somewhat surprising. However, this finding is consistent with the lower velocity gradients present in the exit flow and, hence, less severe dissipation regions.

On examining the secondary velocity components in the exit flow in the region up to y/c = 0.6, when the inlet flow to the cascade is "clean" the highest local secondary velocity amounts to 12 percent of the maximum main flow velocity. When the vortices are introduced into the inlet flow the highest local secondary velocities are between 9 and 10 percent of the maximum main flow velocity. It is important to note that the pronounced vortex, which had existed in the inlet flow, appears to have been dissipated in passing through the blade channel.

The pressure distributions around the blade showed no discontinuities when vortices were introduced, and the changes which were observed were in line with the altered overall loss of the cascade.

The manner in which the pitch-integrated deviations in the exit flow are influenced by inlet vortices is indicated in Fig. 9. Unfortunately, these pitch-integrated curves con-

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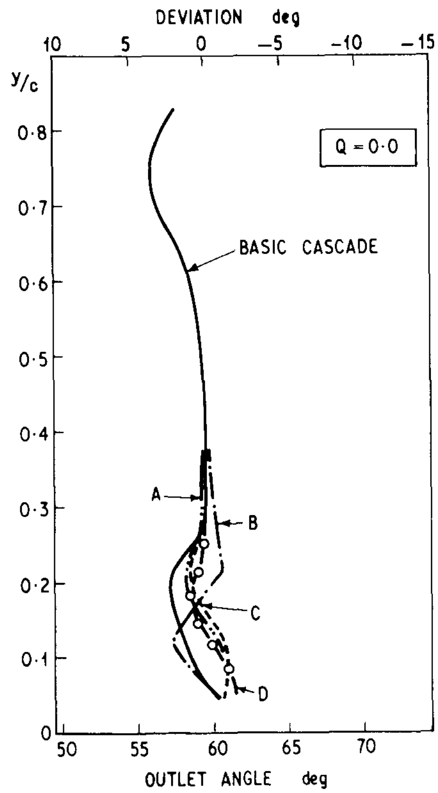

Fig. 13 Integrated outlet angles for various vortex reducing schemes - no transverse injection

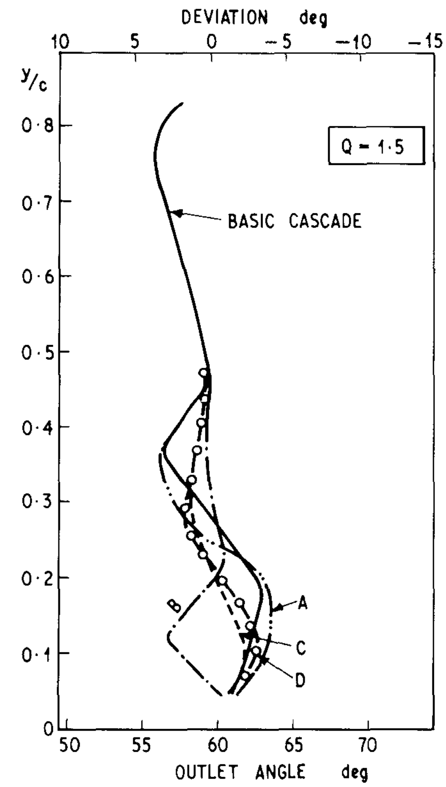

Fig. 14 Integrated outlet angles for various vortex reducing schemes - with transverse injection

ceal the reduction in secondary velocities when vortices are introduced. It should also be noted, however, that when there are vortices in the inlet flow, frequently the highest secondary velocities are in directions which are not parallel to the end-wall, and, therefore, they will not show up in plots of deviations.

The improvement in the secondary flows resulting from the inlet vortices is probably associated with the direction of rotation of the inlet vortex. As stated previously, this direction is such that the side of the vortex nearest to the adjacent end-wall is twisted toward the pressure surface of the blades which the flow is entering. The higher turning angle obtained in the passage in the flow nearest the end-wall brings the end-wall flow out at an angle nearer to the main flow, rather than over-turning it.

REDUCTION OF STRENGTH OF VORTICES RESULTING FROM TRANSVERSE INJECTION

An investigation has been made of several possible methods of reducing the strength of the vortices in the flow leaving a turbine blade row which result from transverse injection in front of that blade row.

Devices Examined

Two different techniques have been considered. The first was an attempt to counter the motion from the pressure to the suction surface which had been observed within the separation bubble on the end-wall immediately downstream of the slot from which the transverse jet emerged (1). It appeared that the exit vortex originated from near the suction surface end of this separation bubble. If the mass flow, and hence momentum, within the bubble toward the suction surface could be reduced, then the exit vortex might be weakened. The method used was to cut a slot through the blade adjacent to the end-wall, as illustrated (Scheme A) in Fig. 10. The slot runs from a position of high pressure on the pressure surface side to a position of lower pressure on the suction side. It will, therefore, carry fluid into the separation bubble with a momentum to oppose the previously observed flow within the bubble. The dimensions of the slot are given in Fig. 10.

The second technique was to employ boundary layer fences, as described by Prumper (5), on the suction surface of the blades near the end-wall from which the transverse jet is injected

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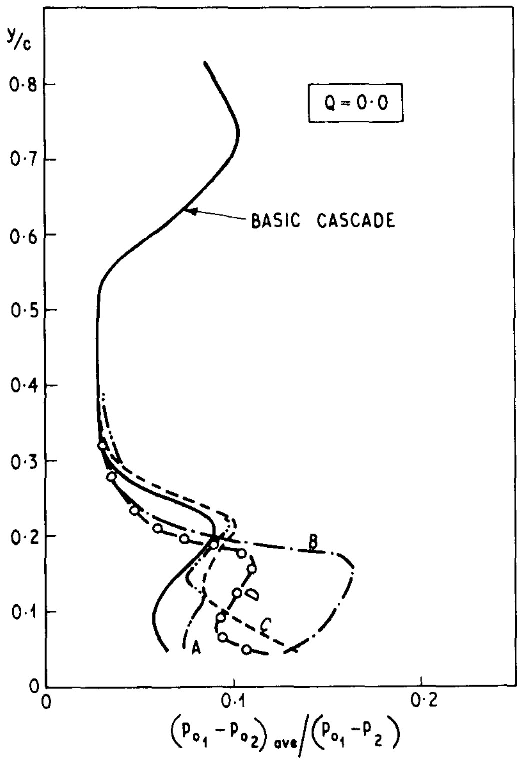

Fig. 15 Integrated stagnation pressure losses for various vortex reducing schemes - no transverse injection

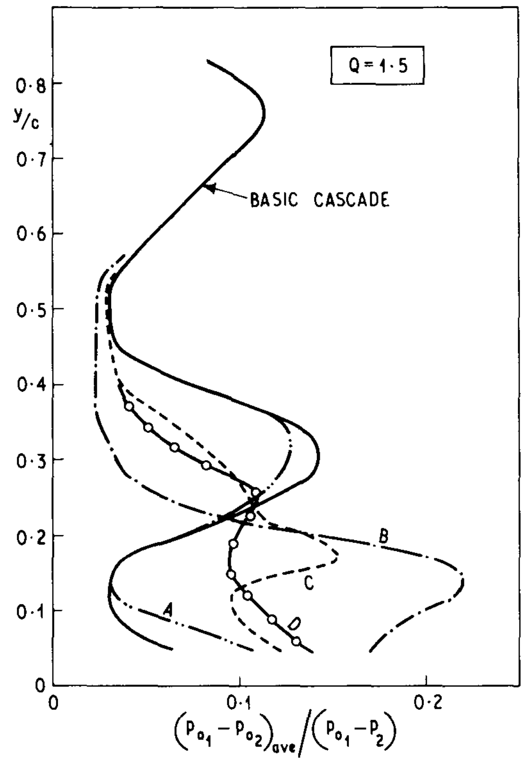

Fig. 16 Integrated stagnation pressure losses for various vortex reducing schemes - with transverse injection

(Scheme B), and on the end-wall itself parallel to the suction surfaces (Schemes C and D). Fence B runs the full length of the suction surface at a distance of 15.9 mm above the end-wall and extends 7 mm out from the suction surface. The thickness of the fence is 0.33 mm. Fences C and D stand 13.5 mm out from the end-wall, have the same profile as the suction surface, and are positioned throughout their lengths at 0.33 blade pitch from the suction surface. Fence C is 1.6 mm thick (the "thick" fence) while Fence D is 0.46 mm thick (the "thin" fence).

Test Procedure

The turbine cascade employed was the same as that used for the investigation described in the earlier part of this paper on the effect of vortices in the flow entering a cascade, i.e., the leading particulars were: stagger angle, 40 deg; inlet angle, 15 deg; aspect ratio, 1.0. When transverse injection was introduced, the velocity of the jet was 1.5 times, the velocity of the main approach flow and the injection slot width was such that the ratio of injected mass flow to main mass flow was 0.036. When no transverse flow was required, the injection slot was taped over. The boundary layer on the end-wall carrying the injection slot was sucked away 180 mm in front of the slot.

Results and Discussion

As the primary aim of the various devices was to reduce the exit vortex resulting from transverse injection, the exit velocity patterns under conditions of transverse injection are first considered, particularly with reference to the secondary velocity components.

With the basic cascade, transverse injection led to the significant vortex in the exit flow illustrated in Fig. 11. The introduction of Scheme A (slot through blade) made little difference to this pattern. The fences on the end-wall (Schemes C and D) led to a slightly reduced vortex closer to the end-wall, and a smaller vortex alongside, in counter rotation. This is illustrated in Fig. 12. The device which was most successful in reducing the exit vortex was the fence on the blade suction surface (Scheme B). In order to give a numerical comparison between the flows with the various Schemes, the extremes of local deviations immediately above and below the apparent eye of the vortex have been examined. With the basic cascade, the range of local deviations is just over 10 deg, while with Scheme B, it is about 5 deg. Schemes A, C, and D indicate correspond-

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Table 2 Pressure Loss Coefficients for Various "Vortex Reducing" Schemes

Geometry	$(p_{o1} - p_{o2})_{ave}/(p_{o1} - p_2)$	
	No transverse injection	Injection mass ratio = 0.036
Basic Cascade	0.061	0.075
Scheme A - slot through blade	0.068	0.076
Scheme B - fence on suction surface	0.077	0.085
Scheme C - thick end-wall fence	0.080	0.083
Scheme D - thin end-wall fence	0.068	0.079

ing deviation ranges of about 11, 9, and 6.5 deg, respectively.

Pitch-integrated deviations are shown in Figs. 13 and 14 for cases without and with transverse injection. Due to the creation by the fences of other, smaller vortices, it is not meaningful to apply equations (1) to (3) to these pitch-integrated deviations. However, the curves do give some indication of the variation of directions in the exit flow. On this basis, Scheme B (fence on suction surface) is seen to be about the best of the alternatives, when transverse injection is taking place.

However, the changes in pressure loss coefficients resulting from using the various devices must also be examined. The pitch-integrated loss coefficients are shown in Figs. 15 and 16 for the situations without and with transverse injection. To assist in the comparison of the loss coefficients, the pitch-integrated coefficients have been averaged over the blade span up to $y/c = 0.8$. The results are given in Table 2. For the cases without transverse injection, all Schemes adopted lead to higher pressure losses, the greatest increase being with Scheme C (thick fence on end-wall) while the smallest increase is with Scheme A (slot through blade). When transverse injection is present, all Schemes except Scheme A lead to increased losses, when compared to the basic cascade, Scheme B being the worst. With Scheme A, the losses are virtually unchanged. Thus, in no case has there been a reduction in losses in the present work, although Fences of types B, C, and D have been reported as giving reduced losses elsewhere (5). The explanation for this

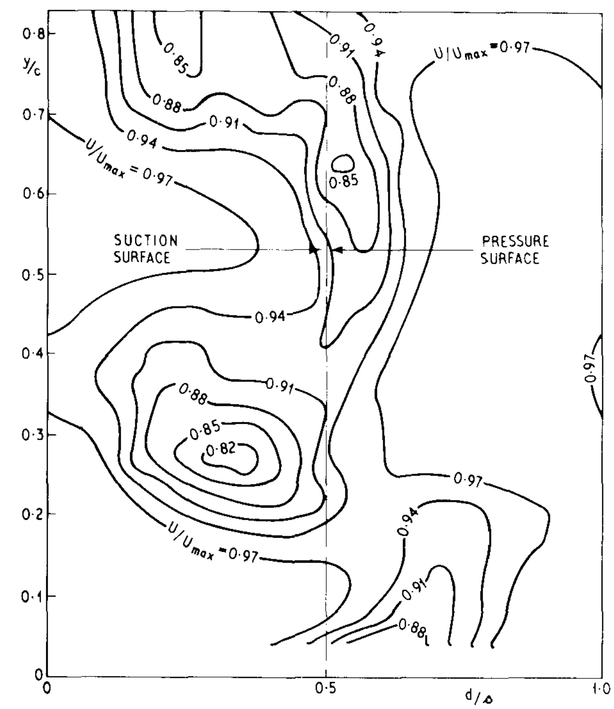

Fig. 17 Velocity contours at outlet traverse plane - with transverse injection - basic cascade

discrepancy may lie in the very low aspect ratio (0.25) used in Reference (5), which causes the two end-wall secondary flows to interact.

Further insight into the effect of the various Schemes on pressure losses can be gained by looking at the exit main flow velocity distributions. Only two of these velocity distributions are presented here -- that for the basic cascade in Fig. 17 and that with Scheme D (thin fence on end-wall) in Fig. 18. In both cases, transverse injection is taking place. The pronounced trough associated with the exit vortex from the basic cascade is considerably diminished by the fence.

CONCLUSIONS

When there are vortices adjacent to an end-wall in the flow approaching a cascade of turbine blades, the vortices having the direction of rotation toward the pressure surface for the fluid on the side of the vortex nearest the end-wall -- as results from transverse injection in front of the previous row of blades -- then, from these initial studies, there appears to be a reduction in the pressure loss in the row of blades being considered. The vortices themselves virtually disappear as the flow passes through the blade channels. These findings require further testing to provide confirma-

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tion, particularly as in this simulation the vortex generators were stationary relative to the cascade that the flow was entering.

The vortex which results from transverse injection can be reduced. Of the devices tested for achieving this, the most effective was a boundary layer fence on the suction surface of the blade, near to the end-wall. However, a significant penalty in pressure loss is incurred. Devices which have lower pressure loss penalties are less effective in vortex reduction. In view of the conclusion given in the preceding paragraph, it may not be desirable to reduce the vortex which results from transverse injection.

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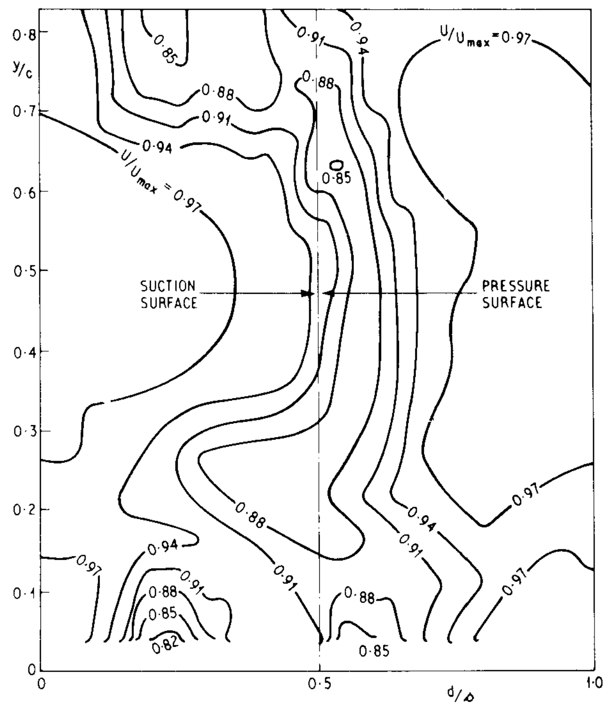

Fig. 18 Velocity contours at outlet traverse plane - with transverse injection - with thin end-wall fence "D"

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