

# Effect of boundary layer fences on turbine blade losses

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Secondary flow remains a challenging task for both the researchers who pursue diligently their efforts to develop an improved understanding of the mechanisms of loss production and for the designers who endeavor to minimize the impact of losses on turbine performance by controlling secondary flow and by reducing their interference with the main flow. As an extension to control secondary flows and reduce losses in turbine blading in earlier work by the author, an experimental investigation was carried out to establish the effect of boundary layer fences on a turbine blade losses. Circular fences configuration were used and positioned to the blade suction side and the endwalls in a straight blade cascade. Tests were conducted at a passage aspect ratio of 1.0 and pitch to chord ratio 0.7, for exit Mach number ranging from 0.3 - 0.5. The measured loss coefficient is plotted in contours of blade loss along the blade pitch for four tested cases: Turbine blades without fences ( $N_1$ ), with fences attached to the suction side ( $N_2$ ), with fences attached to the endwalls ( $N_3$ ) and with fences attached to the suction side and the endwalls ( $N_4$ ) of a turbine blade cascade. The loss coefficient, the total and secondary losses for different cases are presented in order to show the fence effects. A flow visualizations using oil flow were carried out in a fixed turbine blade cascade with and without boundary layer fences at exit Mach number 0.3. The characteristics of the proposed boundary layer fences diminish the thickness of the endwall vorticity and loss regions and leads to decreasing the secondary losses.

يتناول البحث دراسته معمليه على ريش التربينات الثابته بهدف العمل على تقليل المفاقيد و خاصة المفاقيد الثانويه و ذلك باستخدام فواصل مثبتة على جانب السحب للريش و على بعد معين من حائط الكاسكيد ثم فواصل مثبتة على جدار الكاسكيد و موازيه لخط المنصف للريش ثم فواصل مثبتة على جانب السحب و على جدار الكاسكيد و مقارنتها بالريش في حالة عدم وجود فواصل ، تم تصميم جهاز معملى و اجريت التجارب مع تغيير سرعة الخروج لرقم ماخ في حدود 0.3 إلى 0.5 و تم قياس معامل الفقد الكلى للضغط و مفاقيد البروفيل و المفاقيد الكليه و الثانويه . كذلك تم تصوير السريان و ذلك في حالة عدم وجود عوائق و في حالة وجود عوائق مما كان له أثر كبير في بيان توزيع السريان داخل قناة الريش بينت النتائج العمليه أن وجود الفواصل المثبتة على جانب السحب و الفواصل المثبتة على جدار الكاسكيد قد عمل على تقليل المفاقيد الثانويه. كذلك بينت النتائج العمليه أن وجود الفواصل المثبتة على جانب السحب و على جدار الكاسكيد تعمل على خفض المفاقيد الثانويه بنسبه أكبر . من النتائج المستخلصة تعتبر هذه الطريقه إحدى طرق التحكم في المفاقيد الثانويه مما يعمل على زيادة الكفاءه.

**Keywords:** Turbine blade cascade, Boundary layer fences, Secondary flow, Flow visualization, Turbine blade losses.

## 1. Introduction

Turbine efficiency can be significantly improved by reducing blading losses. The secondary flow losses, which are associated with the stream vorticity in the exit flow from turbine blades, are often a very significant fraction of the total losses. In fact, secondary flows in a blade passage are caused due to the combined effect of blade curvature and

boundary layers on the annulus walls. The trailing vortices which are located principally at the two ends of the blade lead to an increase in the flow energy loss. Control or minimization of these losses is a very important fact in the design of turbomachines. A clear understanding of this is necessary for a design engineer to assess the performance of a blade configuration and to optimize the blade profile so as to minimize losses.

Numerous aerodynamic studies of the complicated nature of turbine passage secondary flows are available in the literature [1-5]. A comprehensive review of known cascade secondary flow behavior and its effect on cascade losses is given by Sieverding [6]. Included in that review are the secondary flow loss studies of Dunham [7], as well as the work of Game[8] who obtained inlet and exit plane total pressure surveys of a large scale cascade with varying inlet boundary layer thickness and incidence. Aerodynamic investigations are the effect of leading edge shape on the overall loss in a large-scale linear cascade of turbine blades [9] and the work of Chen and Dixon [10], which concerns a program of experimental work carried out to determine the effect of flow mixing processes and varying inlet boundary layer thickness on the total pressure losses developed by low-speed flow through a high - deflection turbine blade cascade. The Three-dimensional nature of the flow field in a large scale rectilinear turbine cascade was investigated in [11].

Several researchers have attempted to diminish the loss by modifying the tip endwall contour [12] and installing boundary layer fences [13, 14]. The results of net loss coefficient were as follows: In the case of normal blades was 0.078, in the case of installing fences on the suction blade surface was 0.070, in the case of installing fences on the endwall was 0.070 and in the case of combined fences was 0.066. In these references the experiments were carried out on turbine rotor blades with aspect ratio of 1.41 but as we know, the effect of secondary flow becomes more and more pronounced on total energy loss as the blade aspect ratio is decreased. In this case, the secondary flows mix with the main flow. Therefore, our main expectation is that the effect of these fences on the secondary flows will exist, for the case of short blades and in the case of fixed blade also. Cooling air injection into secondary flow zone [15] are also attempted. Another attempt [16] used multiple smoke wires to investigate the secondary flow near the endwall of a plane

cascade with blade shapes as used in high performance turbine shapes. The present author made an attempt to control secondary losses using bump blades [17]. Also another technique has been made which deals with a program of experimental work carried out to determine the effect of fences fitted to the suction side [18] and the effect of endwall fences on a turbine blade losses [19]. The effects of unsteady inflow on the stagnation quantities at exit from a turbomachine blade row were investigated by Hodson and Dawes [20]. Some of these attempts were successful though the resulting loss diminution were obtained.

A review of the literature has thus shown that there exists a need to provide the detailed aerodynamic characteristics data necessary for an accurate evaluation of proposed experimental techniques, and for understanding the complex flow field resulting from the turbine blade passage. In an effort to improve the aero-dynamic characteristics of a turbine blade cascade and reducing the blade losses, circular boundary layer fences were attached to the blade suction surfaces and the endwalls of a turbine blade cascade. The new cascade has been designed taking into account the effects of the secondary flow on turbine blade cascade. The successful development of efficient turbomachines requires an understanding of flow conditions which are exceedingly complex, so a flow visualization was carried out with and without boundary layer fences. The results of the experimental study in turbine blade cascade on the blade losses are reported in this paper for four different cases : Firstly for normal blades ( blades without fences,  $N$  ); Secondly blades with fences positioned to the suction side (  $N_1$  ) Fig. 1. Thirdly blades with fences located at the endwalls (  $N_2$  ) Fig. 2 and finally blades with fences attached to the suction side and the endwalls (  $N_3$  ) Fig. 3. Experiments were carried out for different exit conditions.

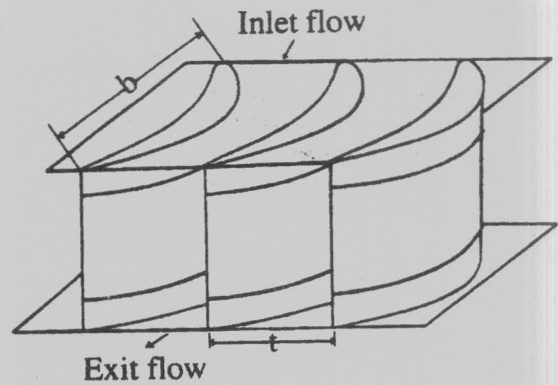
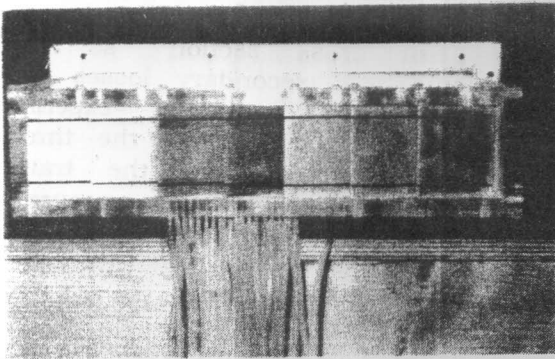


Fig. 1 Installation of boundary layer fences.

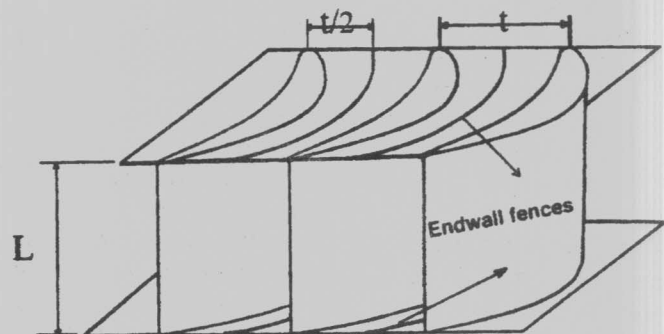
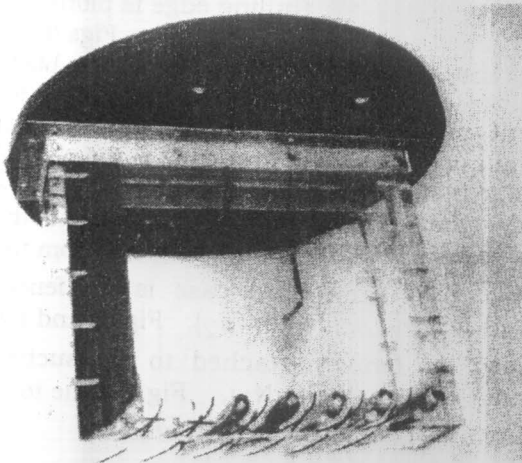


Fig. 2. Location of endwall boundary layer fences

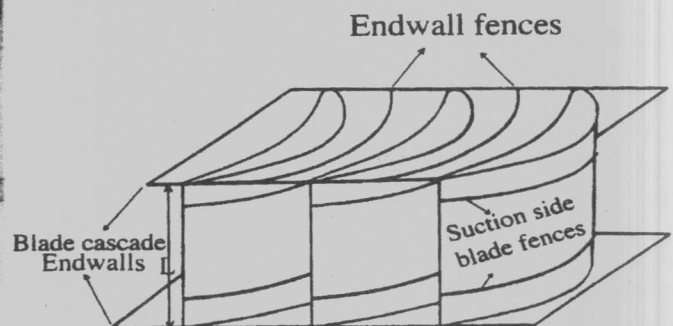
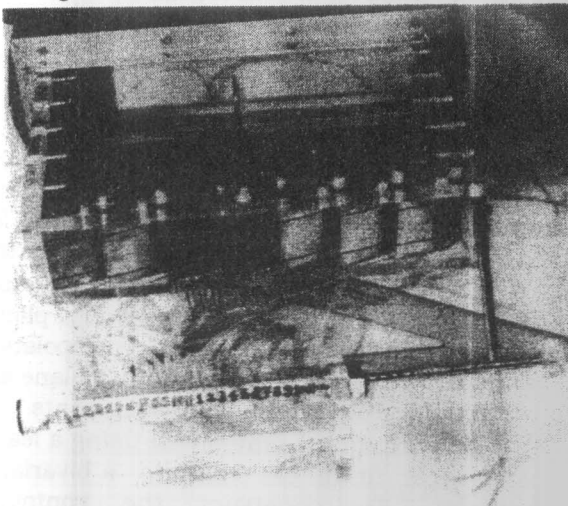


Fig. 3. Boundary layer fences attached to the suction side and the endwall.

## 2. Experimental apparatus

The experiment was conducted in an open circuit cascade wind tunnel, Fig. 4. The facility has been previously described in the aerodynamic investigations [21].

The profile under investigation is taken from [22]. The normal profile has a chord of 50 mm, aspect ratio 1, pitch to chord ratio 0.7, inlet flow angle  $\alpha_1 = 90^\circ$  and exit flow angle  $\alpha_2 = 15^\circ$  and the blade setting angle  $\alpha_y = 45^\circ$ . The arrangement of the combined fences is shown in Fig. 3. The endwall fences were attached to the endwalls, parallel to the camber line of the blades at the center of the blade pitch. The blade fences were additionally attached to the suction surfaces of the blades and located at  $\bar{X} = 0.1$  and  $0.9$  from the endwall.

Seven blades were die-molded using aluminum alloy material. The free-stream total and static pressures were measured using a pitot static tube. The flow field at the cascade exit is measured by a traversing three-hole pressure probe, Fig. 5. To control and adjust the position of the three-hole probe along the test section, a three dimensional traverse mechanism was used, see Fig. 4. Surface oil flow is an experimental flow visualization technique that depicts the surface flow pattern at the endwall of tested blade cascade. The flow visualization using oil flow technique generates streamlines around the turbine blade and in the blade channel. The oil flow method was used for visualizing limiting streamlines on the endwall. The oil was a mixture of paraffin and a small amount of oleic acid with suspended white titanium dioxide. Viscosity of the oil was locally varied, depending on the local shear stress on the endwall.

In an attempt to reduce the secondary losses in the fixed turbine blade cascade, a circular configuration of boundary layer fence with a diameter of 1.005 mm was attached to the blade suction surfaces and located at  $\bar{X} = 0.1$  and  $0.9$  from the endwall. At the same time another circular configuration of boundary layer fences with a diameter of 1.24 mm was attached to the endwall parallel to the camber line of the blades at the center of the blade pitch as shown in Fig. 3.

Sufficient measurements have been made along the blade height and across the blade pitch to define the secondary flow over the entire exit cross section so the loss coefficients and secondary losses can be evaluated. The estimated experimental uncertainties associated with the three hole probe, manometers and the traversing mechanism are as follows: for pressure  $\pm 0.5\%$  and for the linear position  $\pm 0.5$  mm.

## 3. Results and discussion

In the present work an experimental study of boundary layer fences behavior in a turbine blade cascade was conducted. The measured loss coefficient at the trailing edge is plotted in contours of total local blade loss in Figs (6-9), across the blade pitch and along the blade height at exit Mach number 0.3 and for different tested cases at 5 mm downstream of the trailing edge: The first case is for normal blades (blades without fences (N)), Fig. 6; the second case is for fences attached to the suction side ( $N_1$ ) at  $\bar{X} = 0.1$  and  $0.9$  from the endwall, Fig. 7; the third case is for fences attached to the endwall ( $N_2$ ), Fig. 8, and the last case for fences attached to the suction side and the endwall ( $N_3$ ), Fig. 9. The total pressure loss coefficient is defined as:

$$C_{Pt} = (P_{01} - P_{02}) / 0.5 \rho U_o^2.$$

Where;  $P_{01}$  upstream total pressure,  $P_{02}$  downstream total pressure, and  $U_o$  the upstream freestream velocity.

The graphical presentation of experimentally generated data sets frequently involves the construction of contour plots. A general computer algorithm has been developed for the construction of contour plots. The algorithm accepts as input data values at a set of points irregularly distributed over a plane. The algorithm is based on an interpolation scheme in which the points in the plane are connected by straight line segments. In general, the data is smoothed using a least-squares-error fit of the data to a bivariable polynomial. To construct the contours, interpolation along the edges of triangles is performed, using the bivariable polynomial if

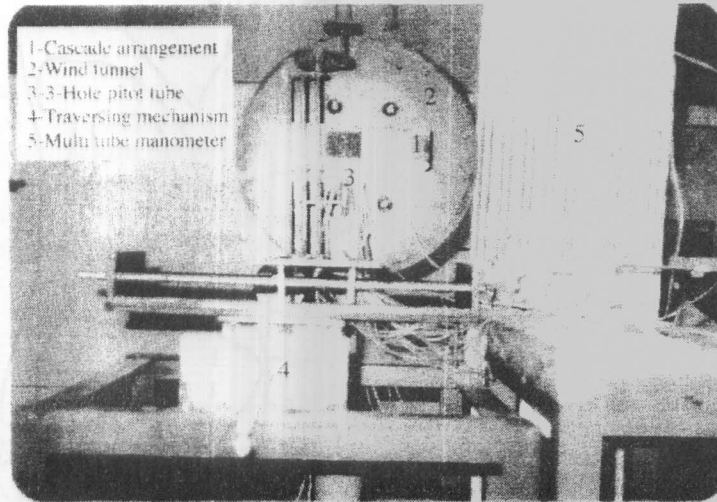


Fig. 4. Experimental apparatus.

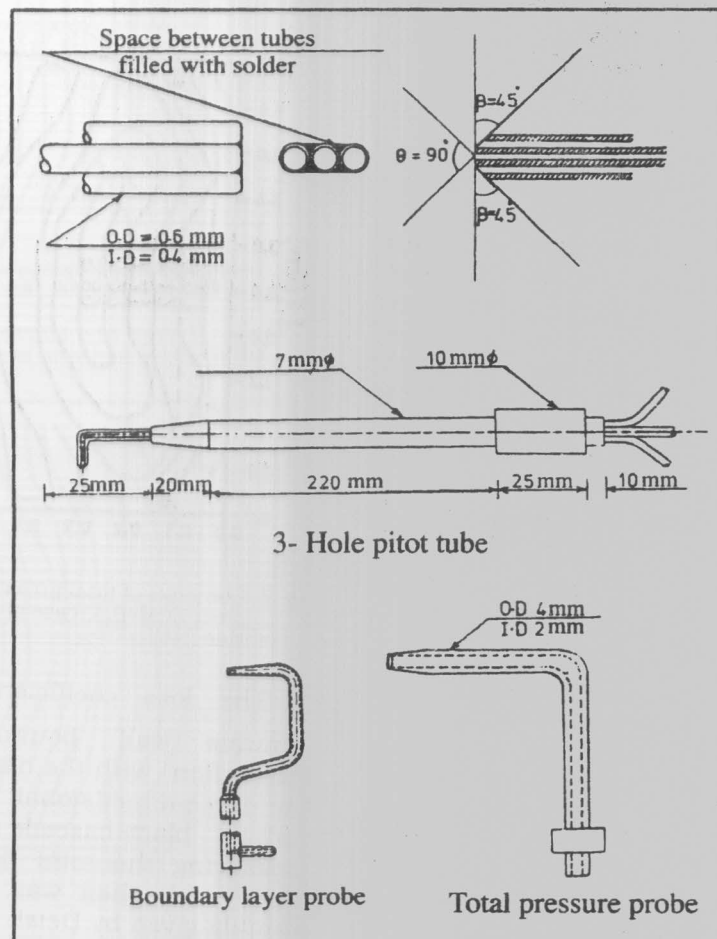


Fig. 5. Dimensions of the pitot tube.

data smoothing was performed. Once the contour points have been located, the contour may be drawn.

The procedure for plotting the contours of the total pressure loss coefficient is obtained as follows: measure the pressure distributions in the downstream region (5mm from the trailing edge), calculate the pressure loss coefficient, chose the constant values of pressure loss coefficient and then determine the coordinates of each value of  $C_p$ , after that drawe the contours for constant  $C_p$ .

From these figures it is noticed that the value of total pressure loss in the region between the mid blade pitch region and near the blade surfaces region changes as the fences are located (N1, N2 and N3). In addition to this, the passage vortex occurs near the suction surface due to transverse fluid motion from pressure side to the suction side along the endwall and the value of the total pressure losses in the core of this flow changes between  $C_{pt} = 6.34\%$  in case of N to  $C_{pt} = 5.02\%$  in case of N<sub>3</sub>. Fluid with total pressure losses in the passage vortex is convicted toward the middle of the passage. The underturning vortex decays faster toward the midspan in the combined fence case than in the normal blading case. The fast decay of underturning with the combined fences may be explained by the velocities induced by the fence vortex. The fence-vortex induced velocities are added to the passage-vortex induced underturning velocities on the endwall side of the fence vortex center.

The flow with high loss region near the pressure side of the blade has a peak value of  $C_{pt} = 12.3\%$ . While this peak value reduces in the case of N1 to  $8.20\%$  and to  $8.12\%$  in the case of N<sub>2</sub> and to  $7.33\%$  in the case of N<sub>3</sub>.

The high losses obtained for normal blades can be explained as the passage vortex in the blade and its eventual mixing and dissipation give rise to additional losses. The mixing is the exchange of momentum and energy between the blade and the free stream. This transfer of energy results in the decay of the boundary layer. The high level of losses is connected with the complex structure of flow in the cascade of blades without fences.

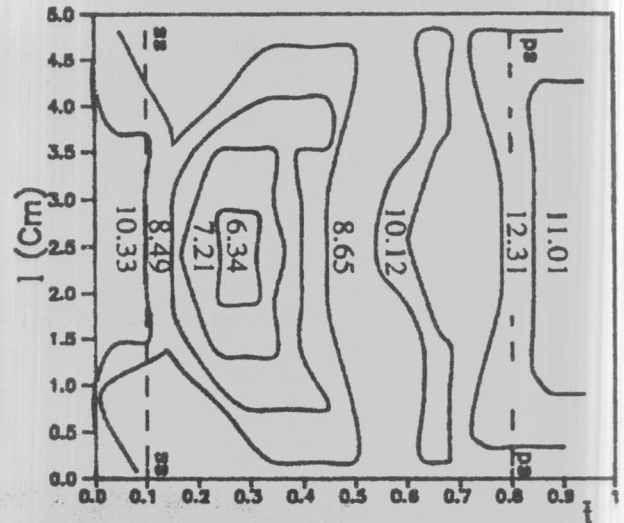


Fig. 6. Contours of total pressure loss along the blade pitch at  $M=0.3$ , case of normal blade (N) blade without fences.

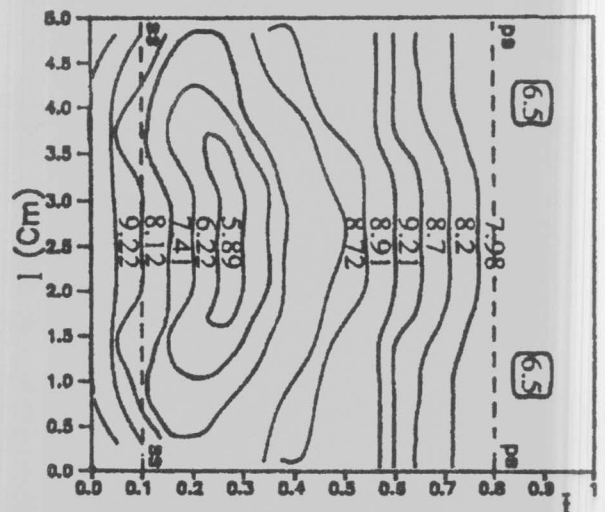


Fig. 7. Contours of total pressure loss along the blade pitch at  $M=0.3$ , case of attached fence the suction side (N1).

The loss coefficient ( $\tau_p$ ) is due to the annulus wall boundary layer and their interaction with the blade row and also due to the three-dimensional flow phenomena in the turbine blade cascade and was determined by measuring the total pressure along the blade pitch and then was calculated using the formula given by Deish [22].

$$\tau_r = \varepsilon^{(k-1)} \frac{1 - [1 - (\Delta p_i / \Delta p_o)(1 - \varepsilon)]^{(k-1)/k}}{(1 - \varepsilon^{(k-1)/k})[1 - (\Delta p_i / \Delta p_o)(1 - \varepsilon)]^{(k-1)/k}}$$

The cascade passage averaged loss coefficient is obtained by integrating the average loss coefficient along the blade height. The secondary losses ( $\tau_s$ ) were determined by subtracting the measured midspan averaged loss coefficient ( $\tau_{pr}$ ) from the passage averaged loss coefficient ( $\tau_t$ ).

$$\tau_s = \tau_t - \tau_{pr}$$

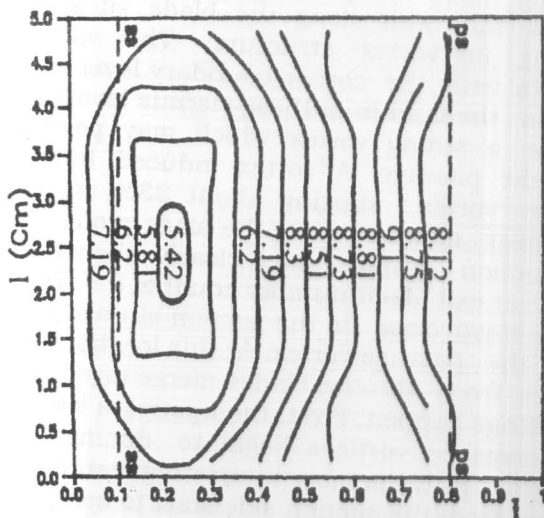


Fig. 8. Contours of total pressure loss along the blade pitch at  $M=0.3$ , case of attached fence on the endwall ( $N_2$ ).

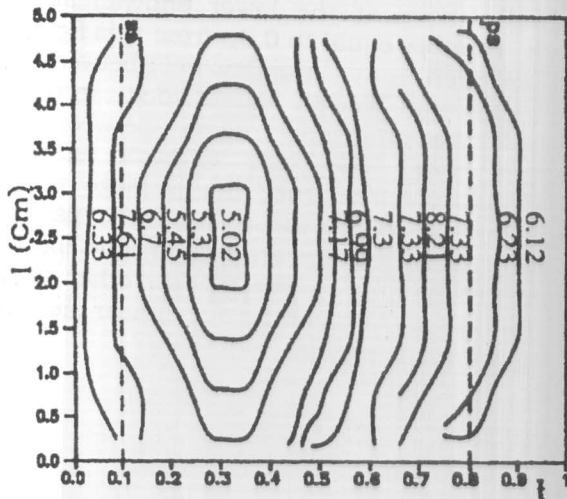


Fig. 9. Contours of total pressure loss along the blade pitch at  $M=0.3$ , case of attached fence on the suction side endwall ( $N_2$ ).

The results of loss coefficient along the blade height at exit Mach numbers ranging from 0.3 to 0.5 are presented in Fig. 10 for different tested cases ( $N$ ,  $N_1$ ,  $N_2$  and  $N_3$ ).

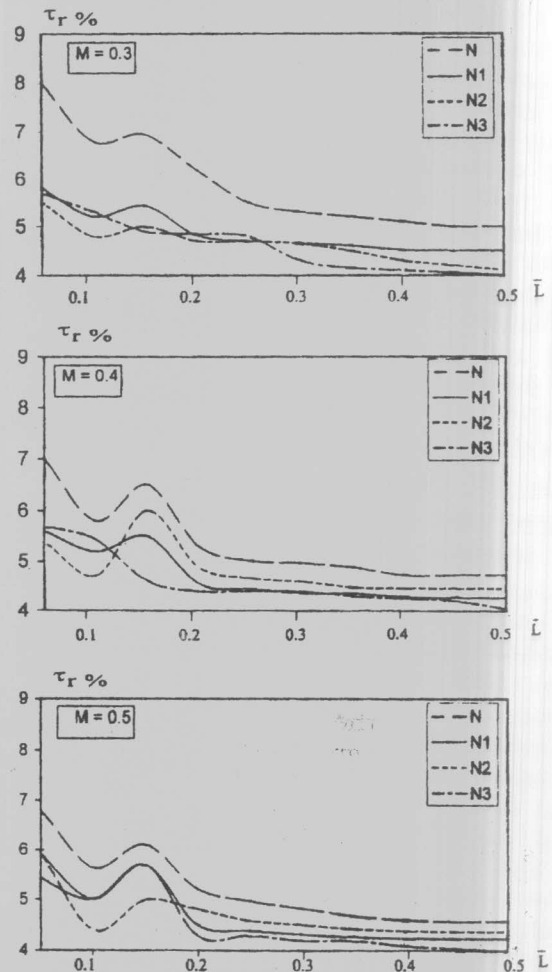


Fig. 10. Loss coefficient for different tested cases along the blade height for different exit Mach number

It can be seen from this figures that, the loss coefficient is decreased for the case of  $N_1$ ,  $N_2$  and  $N_3$  than that for the case of  $N$  where the blades are without fences. In the case of  $N_1$  the loss coefficient at exit  $M = 0.3$  is lower by about 12.5 % at than in the case of  $N$ , where as the loss coefficient in case of  $N_2$  at the same conditions is lower by about 8.5 % than  $N$ . However, the loss coefficient in case of  $N_3$  (also at the same conditions) is decreased by about 14.5 % than  $N$ . The higher

value of loss coefficient in unfenced blade cascade (  $N$  ) is due to the interference of the endwall boundary layer with the suction side boundary layers. Also there exists a high loss core away from the suction surface, close to the center of the passage vortex. The region at midspan near the suction surface also exhibits high losses. The change of the loss coefficient is due to the position of fences on the turbine blade cascade. This can be explained as the flow field has a strong dependence on the existing of boundary layer fences and its effects on the characteristics of oncoming boundary layer flow.

Figures 11 and 12 illustrate the effect of total and secondary losses for the tested cases for different exit Mach numbers. It is observed from these figures that the value of  $\tau_t$  and  $\tau_s$  is higher in the case of unfenced blade ( $N$ ) than  $N_1$ ,  $N_2$  and  $N_3$ . Also it is noticed that as the Mach number increased the secondary losses decreased and  $N_3$  has a lower value of losses. This can be explained as near the suction surface, there are strong secondary flows towards midspan. This is associated with a three dimensional flow separation so the secondary flow and the wall boundary layer growth are responsible for this increase. The secondary flows on the pressure side of the passage is comparatively smaller, this is confirmed by flow visualization in Figs. 13 and 14.

Flow visualization is an effective tool of understanding different flow phenomena inside the blade passage. It can make visible the very different cases that can not be measured by any other methods. The method using oil technique for flow visualization in turbine blade cascade. This method has been used successfully to make visible. The effect of boundary layer fence and its effect on the flow through turbine blade passage is obtained through the surface oil flow visualization on the investigated case of normal blades and with fences on the endwall.

In order to confirm the above results a flow visualization was made at the lower endwall at exit Mach number equal to 0.3 in the case of normal blade cascade ( blades without fences), Fig. 13 and in the case of existing endwall boundary layer fences, Fig. 14. From these figures it can be observed that, when the boundary layer fluid approaches the blade leading edge, it is subjected to an adverse pressure gradient and starts to roll up to form a horseshoe vortex. Also the curvature of streamline upstream of the leading edge introduces pitchwise motions oriented away from the blade along with spanwise motion towards the wall along the blade surfaces resulting in vortex structure. This vortex interacts with the corner boundary layer and entrains the fluid from these viscous layers to produce a strong vortex which may persist along the passage. A vortex induced by the passage vortex, starting about 33% of the curvilinear distance along the blade profile on the suction surface was clearly shown in Fig.13 at exit Mach number equal to 0.3. This vortex stays close to the suction surface and above the passage vortex. At this location the vortices from the two blades merge together, two things happen. First, the upstream legs of the horseshoe vortices begin to diminish in strength. But, the more interesting feature, is the legs from the suction side start to move up the blade surface, away from the endwall. Fig. 14 presents visualization for the case of endwall fences at the lower endwall at exit Mach number equal to 0.3, from this figure it can be seen that, the flow field between the two adjacent blades, is divided into two distinct regions, the region between the suction side and the endwall fence is approximately free from the passage vortex. The leading edge vortex and the passage vortex which are generated from the endwall fence are mixing to produce the other region starting about 22% of the curvilinear distance along the blade profile.

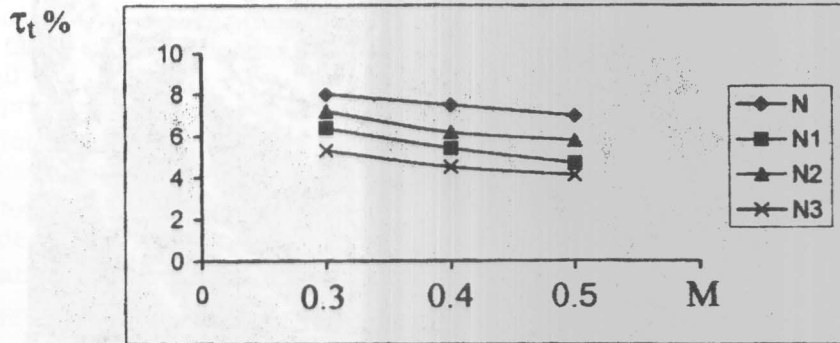
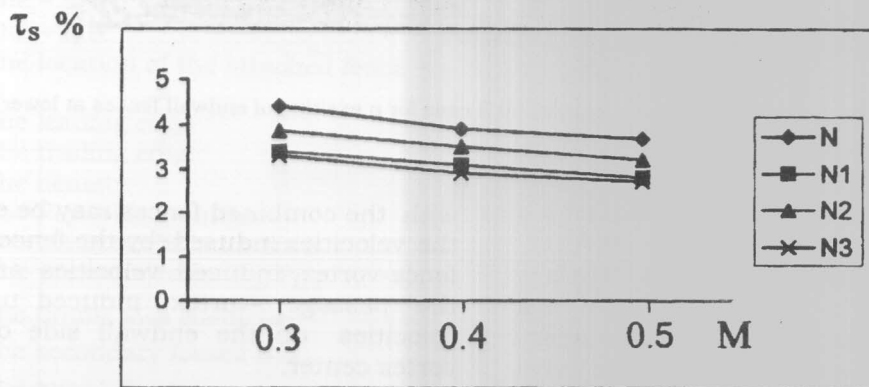


Fig. 11. Effect of Mach number on the total losses.



M

Fig. 12. Effect of Mach number on the secondary losses.

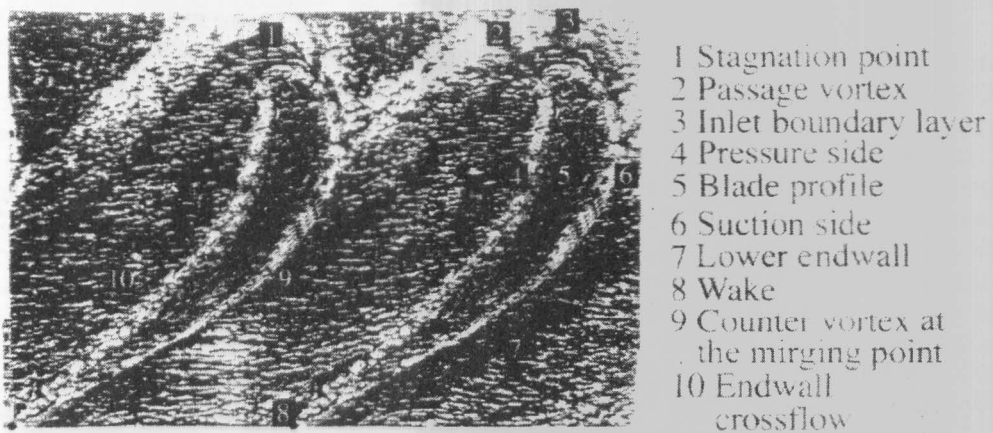


Fig. 13. Flow visualization for a turbine blade at  $M_\infty = 0.3$  case for normal blade (blade without fences).

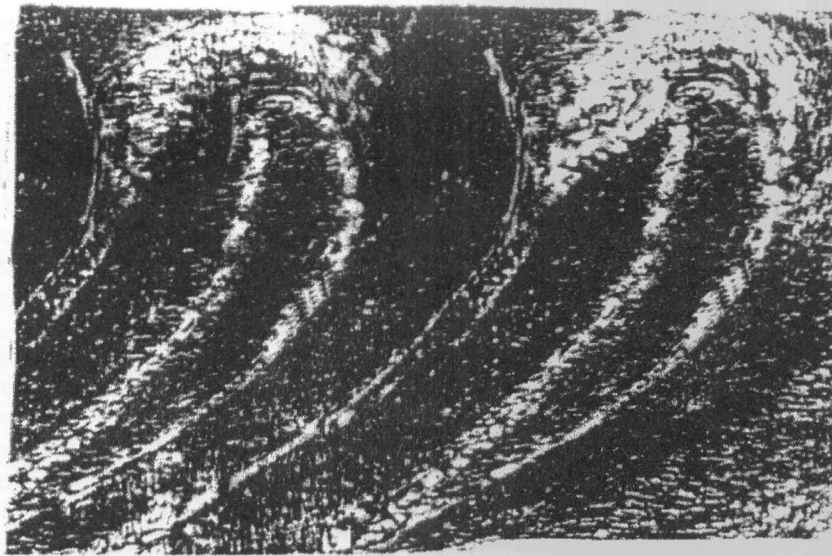


Fig. 14. Flow visualization for a turbine blade at  $M_\infty = 0.3$  case for  $n$  exiting of endwall fences at lower endwall.

#### 4. Conclusion

The boundary layer on a blade surface leaves the blade as a wake. The wake is a velocity defect generated by the boundary layers of the blade surfaces, it would move downstream while decaying slowly. The higher value of loss coefficient in unfenced blade cascade (  $N$  ) is due to the interference of the endwall boundary layer with the suction side boundary layers. The secondary flow is directed from the pressure side to the suction side of the blade near the wall and in the opposite direction in the middle of the channel. The flow field has a strong dependence on the existing of boundary layer fences and its effects on the characteristics of oncoming boundary layer flow. The existence of fences in a turbine blade cascade is weakened the secondary flow by trapping the pressure side legs of the horseshoe vortices. The suction side leg of the horseshoe vortex is dissipated within the blade passage. Existence of boundary layer fences to the suction side and endwall surface is an example in the secondary flow limit, dominated by the decay of passage vortices and the dissipation of secondary kinetic energy. The fast decay of underturning vortex

with the combined fences may be explained by the velocities induced by the fence vortex. The fence-vortex induced velocities are added to the passage -vortex induced underturning velocities on the endwall side of the fence vortex center.

The proposed boundary layer fences diminish the momentum thickness of the endwall vorticity and lead to decreasing the losses and is suggested as one of the methods for controlling the development of secondary flows.

#### Nomenclature

B	is the blade chord
B	is the axial chord
B.L	is the boundary layer
$C_{pt}$	is the $= (P_{01} - P_{02}) / 0.5 \rho U_\infty^2$
D	is the diameter
K	is the ratio of specific heats
L	is the blade height
M	is the Mach number
N	is the normal blade (blade without fences)
N1	is the blade with fences attached to the suction side
N2	is the blade with fences attached to the endwall

N3	is the blade with fences attached to the blade suction side and the endwall
P	is the pressure on blade sides
P <sub>01</sub>	is the total pressure before the blade cascade
P <sub>02</sub>	is the total pressure after the blade Cascade
P <sub>2</sub>	is the atmospheric pressure
p <sub>s</sub>	is the pressure surface
Δp <sub>o</sub>	is the = P <sub>01</sub> - P <sub>2</sub>
Δp <sub>i</sub>	is the = P <sub>01</sub> - P <sub>02</sub>
ss	is the suction surface
t	is the blade pitch
$\bar{s}$	is the = s/b
$\bar{t}$	is the = t/b
$\bar{x}$	is the location of the attached fence = x/b
L.E	is the leading edge
T.E	is the trailing edge
ρ	is the density
R	is the Reynolds number
s	is the blade surface distance
ε	is the pressure ratio P <sub>2</sub> /P <sub>01</sub>
τ <sub>pr</sub>	is the profile loss coefficient
τ <sub>s</sub>	is the secondary losses
τ <sub>t</sub>	is the total losses
τ <sub>r</sub>	is the loss coefficient
ν	is the Kinematic viscosity
α <sub>1</sub>	is the inlet flow angle
α <sub>2</sub>	is the exit flow angle
α <sub>y</sub>	is the blade setting angle
L	is the aspect ratio = L/b

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