Eighth Australasian Fluid Mechanics
Conference, University of Newcastle,
N.S.W., 28 November/2 December 1983.

INVESTIGATIONS INTO SECONDARY LOSSES OF A TURBINE NOZZLE CASCADE

M. GOVARDHAN, N. VENKATRAYULU AND D. PRITHVI RAJ

DEPARTMENT OF MECHANICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY, MADRAS 600 036 INDIA

SUMMARY The results of investigations on the effects of aspect ratio, space-chord ratio, entry boundary layer thickness on secondary losses in a two dimensional nozzle blade cascade are presented in this paper. The pitch-wise mass averaged exit static pressure, exit flow angle, local loss coefficient are presented along the span of the blade, also presented here are the results of total, profile, and secondary loss coefficient obtained for each case of investigation. Results obtained here clearly show the dependence of secondary losses on aspect ratio. The important result that the secondary losses vary inversely proportional to the aspect ratio is confirmed. The optimum space-chord ratio is found to be around 0.65. The optimum space-chord ratio based on total loss minimisation is found to be different from that based on profile loss considerations. The test results confirm the existance of critical boundary layer thickness beyond which there is no further increase in secondary losses.

NOTATION

AR	Aspect ratio	h/ch
ch	blade chord	mm
h	blade height	mm
p	static pressure	mm of WG
Re	Reynold's number	
s	blade spacing	mm
Y	loss coefficient	
z	distance from wall in spanwise direction	mm
α	absolute flow angle measured with respect to axial direction	degrees
δ	boundary layer thickness	mm
	Subscripts:	
1	blade inlet	
2	blade outlet	
p	profile loss	
s	secondary loss	
Local	local loss	
t	total loss	

1 INTRODUCTION

It has long been known that the energy losses occuring in an axial compressor or turbine cannot be fully accounted for by the skin friction losses on the blades and annulus wall losses. The difference, usually termed as the secondary loss, is attributed to miscellaneous secondary flows which take in the blade row. These flows both cause losses in themselves and modify the operating conditions of the individual blade section to the detriment of overall performance.

A study of literature reveals clearly the importance of secondary loss problem and the need to reduce it. Many investigators have worked on a basic understanding of secondary losses. Though the flow pattern associated with the secondary loss is adequately understood the magnitude of the loss has not been understood by any one to any degree of accuracy. Secondary losses depend on blade inlet and outlet angles, profile shape, space-chord ratio, incidence, flare, Mach number and Reynold's number. Together these parameters are known as 'Aerodynamic Loading'. Although some investigators have varied, perhaps, one of the parameters systematically there is, in general, insufficient evidence to identify the influence of any individual parameter. Wolf (1961), Scholz (1954), New (1940), Boulter (1962) and Bauemeister (1963) varied one or two parameters of aerodynamic loading.

But in no experiments has the blade pitch been varied systematically, so that the effect of altering space-chord ratio from its optimum value based on profile loss considerations is not known. So it was decided to test a set of turbine nozzle blades in cascade to investigate the effect of space-chord ratio on secondary losses. Apart from aerodynamic loading other parameters which affect secondary losses are aspect ratio and upstream boundary layer. Krafts (1949) and Scholz (1954) show strong influence of aspect ratio. But on analysing the Krafts results, Ainley and Mathieson (1951) conclude that increase in loss is due to change in δ_1/h and s/h Boulter (1962), New (1940) also confirm the linear increase of secondary losses with decrease in aspect ratio. But all these investigators varied blade height only to obtain different aspect ratios, so it was difficult to say whether effect was due to change in δ_1/h and s/h or change in aspect ratio. Hence it was decided to vary aspect ratio. in both ways namely (i) by varying chord and keeping blade height constant (ii) by varying blade height and keeping chord constant. Armstrong (1955) Turner (1951), Senoo (1958) varied upstream boundary layer and found higher losses as δ_1/ch increases. Experiments were conducted for various entry boundary layer thicknesses and effect of this parameter on secondary losses was also studied.

2 EXPERIMENTAL APPARATUS & EXPERIMENTAL PROCEDURE

All the experiments described in this paper were conducted in a low speed two dimensional cascade tunnel using a turbine nozzle profile having a deflection of 76.5°, blade height of 400 mm, stagger angle of 37.5°. A centrifugal blower supplied air to the tunnel at the rate of 3.5 m^3/sec, and at a pressure of 520 mm WG and was driven by 24 KW dc motor. The schematic diagram of test set up is shown in Fig.1. The different aspect ratios were obtained in two different ways, namely (i) by varying blade height, keeping the chord constant and (ii) by varying the blade chord with a constant blade height. The first set of experiments were carried out using nozzles blades of 100 mm chord and different blade heights. Different blade heights were obtained by using two movable side plates to get aspect ratios 0.5, 1.0, 2.0 & 3.0. Second set of experiments were carried out with same nozzle blade profile but having different chord lengths namely 200 mm, 142.8 mm, 125 mm, 100 mm, so as to obtain aspect ratios 2.0, 2.8, 3.2 and 4.0.

Experiments were also conducted on a set of blades of 100 mm chord and 400 mm height for space-chord ratios 0.47, 0.54, 0.63, 0.70. Entry boundary layer thicknesses of 30 mm, 50 mm, 70 mm, 85 mm and 95 mm respectively were maintained in order to determine the effect of boundary layer on secondary flows on the same nozzle profile having 100 mm chord and 400 mm height. Inlet pressures were measured by using boundary layer probe and exit pressures were recorded with a three hole wedge probe. The results were processed by

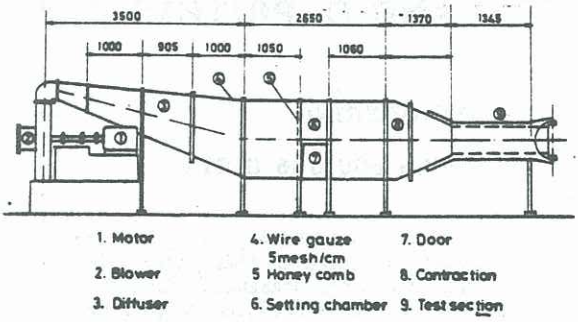

Fig.1 Schematic diagram of two dimensional cascade tunnel

IBM 370/155 and flow quantities were mass weighted averaged. In this paper exit static pressures, exit flow angle and local loss coefficient are circumferentially mass averaged and presented along the blade span. Total, profile and secondary loss coefficients are also presented against aspect ratio, space-chord ratio and entry boundary layer thickness.

3 RESULTS AND DISCUSSIONS

It is seen from Fig.2, that for different aspect ratios obtained by keeping the chord constant and varying the blade height, the loss is constant over a major portion

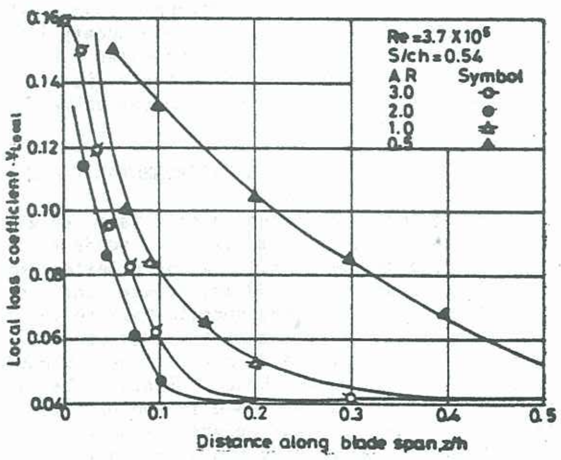

Fig.2 Variation of local loss coefficient with aspect ratio (obtained by keeping chord constant)

of the span, and equals to the profile loss and as we go closer to the wall, the loss coefficient increases sharply and uniformly. Experiments by other investigators have shown that the low energy fluid making up the inlet boundary layer is swept across the passage, upon to the convex surface of the blades, a little away from the wall, in the form of concentrated vortex core. This forms part of the secondary losses. A new boundary layer is developed on the blade surfaces, which is comprised of fluid which was originally in the mainstream. This also gives rise to part of the secondary losses hence higher losses near the wall. A very steep rise in losses very near the wall may have resulted from separation. The variation of mean exit angle along the span is plotted in Fig.3. The angle is also constant over a substantial portion of the span. Increased deflection indicating over turning

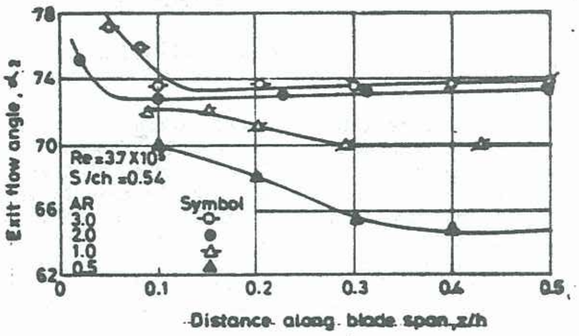

Fig.3 Variation of absolute flow angle with aspect ratio (obtained by keeping chord constant)

is observed near the wall. The exit flow angle is decreased when the aspect ratio is decreased. Deviation is more pronounced when the aspect ratio is .5. This may be due to increased losses.

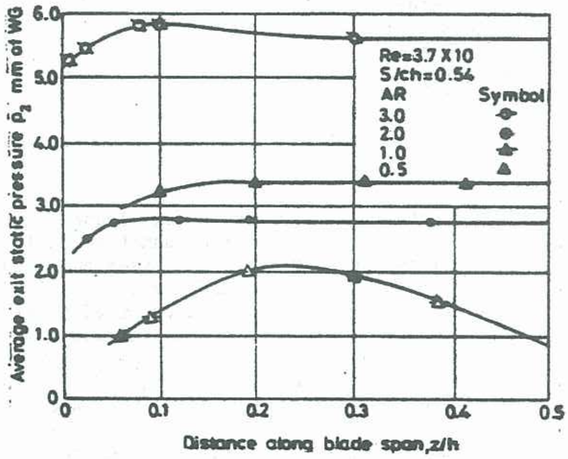

Fig.4 Variation of exit static pressure with aspect ratio (obtained by keeping chord constant)

As shown in Fig.4, the average static pressure decreases as the distance from the wall is decreased. The variation of locall loss coefficient, exit flow angle and static pressure are presented in Fig.5, for various space-chord ratios.

The trend of locall loss coefficient variation remains more or less same as described earlier. The mean exit flow angles are less than that of a centre section at a small distance from the wall, this may be due to the circulatory nature of the secondary flow. The static pressure is found to increase above atmospheric as one proceeds towards the wall, even though one would expect it to remain constant for a two dimensional flow. This is due to the improper functioning of the blade at sections near the wall due to secondary flows. The decrease in the static pressure very

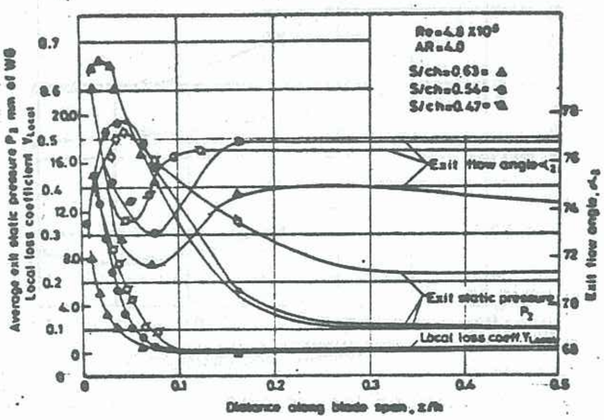

Fig.5 Variation of local loss coefficient, flow angle, static pressure with space-chord ratio.

close to wall from the maximum is due to the presence of stagnant atmospheric fluid around the cascade where end walls are not present. Variations of the locall loss coefficient, flow angle, static pressures are shown in Figs.6, 7, 8 for various entry boundary layer thicknesses. The trend of the parameters is same as explained earlier.

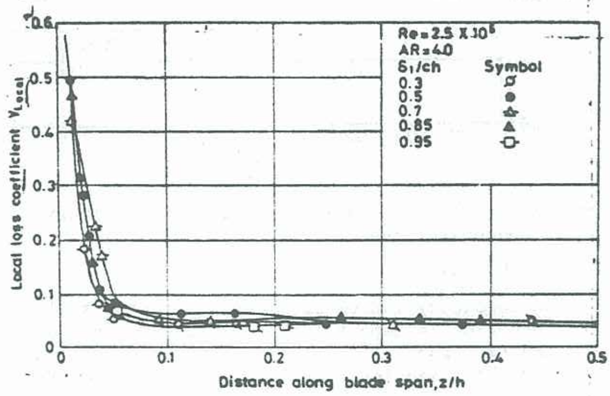

Fig.6 Variation of local loss coefficient with entry boundary layer

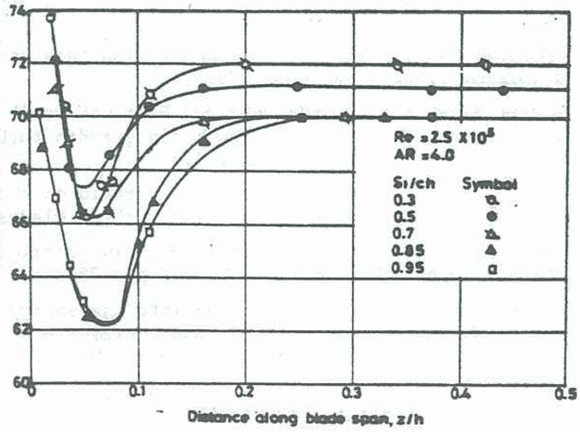

Fig.7 Variation of exit flow angle with entry boundary layer

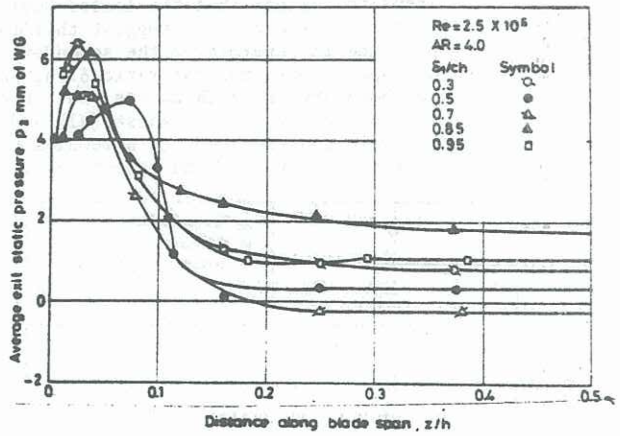

Fig.8 Variation of exit static pressure with entry boundary layer

At all the aspect ratios 3.0, 2.0, 1.0, 0.5 which are obtained by keeping chord constant and varying blade height, the secondary loss varies inversely proportional to aspect ratio as seen from Fig.9.

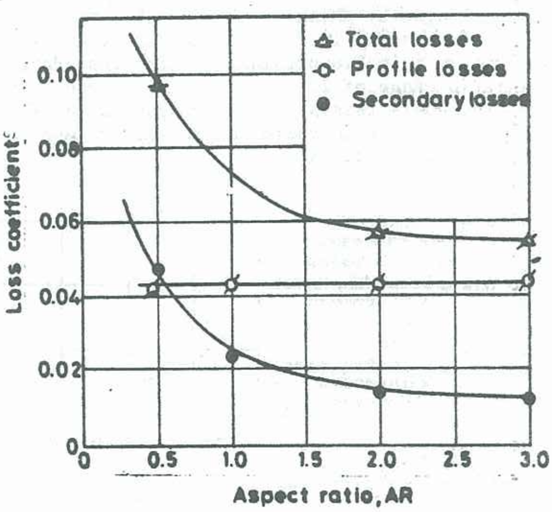

Fig.9 Variation of loss coefficients with aspect ratio (obtained by keeping chord constant)

At low aspect ratios, secondary loss amounts to almost 50% of total loss, it is because major portion of the blade is effected by the boundary layer growth on the walls. Fig.10 shows the variation of losses with aspect ratio where height of the blade was kept constant and chord varied.

It is found that centre section loss remains constant when the aspect ratio is changed over the range tested. This is to be expected because the aspect ratios tested were not too small for the secondary loss zones at the blade ends to extend to the blade centre. The secondary loss is found to vary linearly in a range whereupon it shows a sudden increase for the aspect ratios below 2.8. Due to constant values of profile loss in this range, the total losses are also found to vary in a manner identical to the variation of secondary losses.

The linear variation of secondary losses with aspect ratio is a result which has been widely confirmed by many previous investigators. But one difference is that all these investigators varied the height keeping the chord constant. Here the inverse linear dependence of secondary losses on aspect ratio seem to be a natural outcome of averaging over the blade height. However, if aspect ratio is varied keeping the height constant the discussion by Ainley and Mathieson (1951) of Kraft's (1949) results seems to suggest that the losses would remain constant. This has led them to suggest that the parameters of importance in determining the secondary losses is not the aspect ratio but the ratio $\delta 1/h$, where $\delta 1$ refers to inlet boundary layer thickness. But in the present case inlet boundary layer thickness ($\delta 1$) and blade height (h) remain constant thus $\delta 1/h$ remains same, but the losses vary inversely with the aspect ratio.

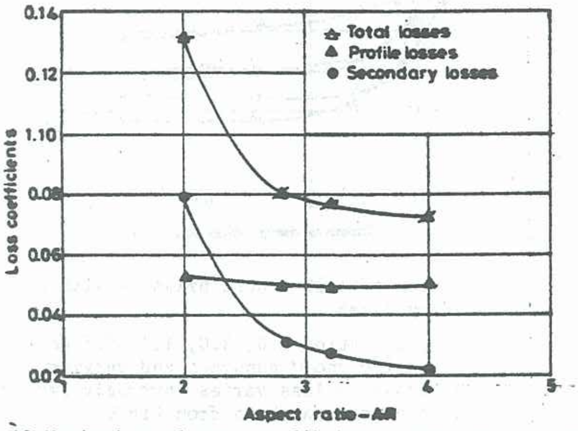

Fig.10 Variation of loss coefficients with aspect ratio (obtained by keeping blade height constant)

The secondary losses are slightly more when the aspect ratio is changed by changing chord rather than by changing height as shown in Fig.11. The same trend was observed by Kraft in his original cascade test data in the aspect ratio range of 2.5 to 5. The discrepancy of increased secondary losses may be because in the former case $\delta 1/ch$ varied with chord and in latter case $\delta 1/ch$ is same in all the cases.

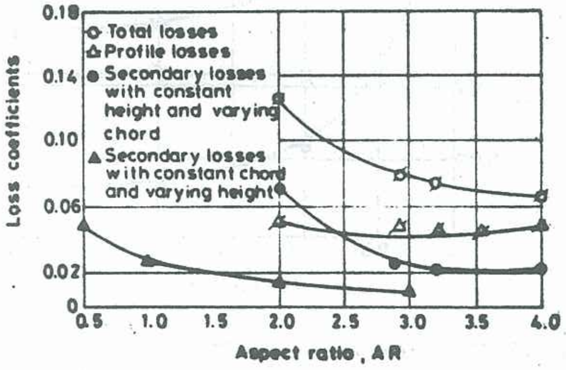

Fig.11 Variation of loss coefficients with aspect ratio.

It is seen from Fig.12 that the total and profile losses both show a tendency to decrease with increase in space-chord ratio . The secondary loss curve shows a minimum when space-chord ratio is about 0.65 and increase again. The optimum space-chord ratio based on total loss minimisation will be around 0.67, but whereas space-chord ratio based upon profile loss minimisation will be around 0.7.

Soundaranayagam (1963) analysis predicted an increase in the strength of the shed vortex with increase in space-chord ratio. This might suggest that secondary losses should increase with space-chord ratio. But the results obtained show that the secondary losses first decrease in a given range and then begin to increase again as space-chord ratio is increased. The variation of total and secondary losses in Fig.13. suggest that losses increase as $\delta 1/ch$ is increased upto a value of 0.5 and then remains constant for further increase of $\delta 1/ch$. This clearly shows that there is a critical value of $\delta 1/ch$ beyond which secondary losses remain unaffected. This is in agreement with the results obtained by Wolf (1961) and strongly support the existance of the critical boundary layer thickness.

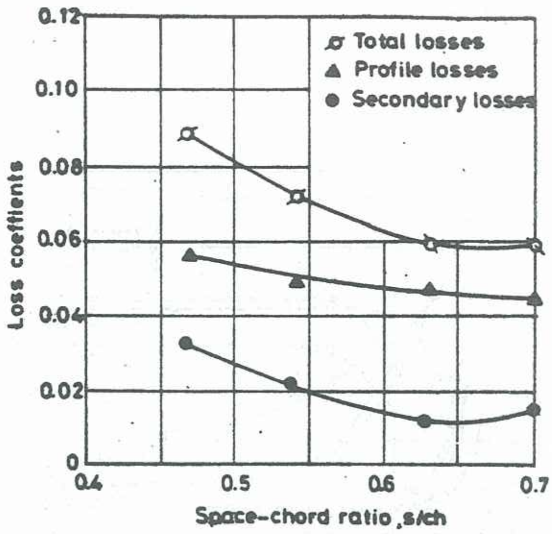

Fig. 12 Variation of loss coefficients with space-chord ratio.

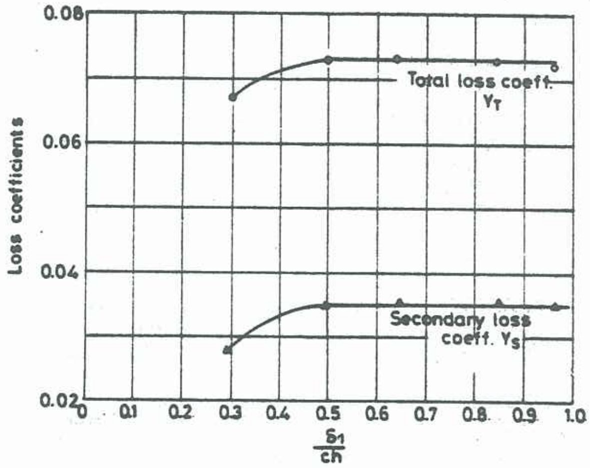

Fig. 13 Variation of loss coefficients with entry boundary layer

4 CONCLUSIONS

(i) The secondary losses are found to increase linearly with reduction in aspect ratio upto about a value of 2.8.
(ii) The existance of a critical entry boundary layer thickness has been indicated, beyond which secondary losses tend to get levelled up.

5 REFERENCES

AINLEY, D.G. and MATHIESON, G.C.R. (1951) A method of performance estimation of axial flow turbines, ARC, R & M 2974

ARMSTRONG, W.D. (1955) The secondary flow in a cascades of turbine blades, ARC R&M 2979.

BAUERMEISTER, K.J. (1963) Uber den Einfluss der Schaufelbelastung auf die Sekundarstromung in geraden turbinenund verdichtergitten. VDI Forschhft 496

BOULTER, R.A. (1962) Effect of aspect ratio on the secondary losses in a cascade of impulse turbine blades.

KRAFT, H. (1949) Reaction tests of turbine nozzles for subsonic velocities, Trans.ASME, 71, pp. 781.

NEW, W.R. (1940) An investigation into the energy losses in a steam turbine elements by impact traverse static test at sub-acoustic velocities. Trans.ASME, 62, pp.489.

SCHOLZ, N. (1954) A secondary flow losses in turbine cascades, J. Aero.Sci. 21, pp. 707.

WOLF, H. (1961) Die Randverluste in geraden Schaufelgi Hern. Wiss.z. Tech. Hochsch. Dresden, 10