Some Practical Aspects of Cascade Testing at High Reynolds Number

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1.Introduction

As part of the Company's development programme for its range of fixed blades used in the low reaction stages of large steam turbines, an extensive cascade test series has been undertaken. The objective was to model the conditions in the high pressure and intermediate pressure (HP/IP) cylinders of large steam turbines. Thus the Reynolds number (Re) was varied to the maximum achievable in the test facility, and a turbulence grid was used to generate turbulence in the inlet flow. It was not possible to achieve the Reynolds numbers of the HP/IP cylinders which are of the order of $Re = 10^7$, but it was possible to produce Reynolds numbers up to 10^6, which were large enough to produce naturally turbulent blade boundary layers. Using a high Reynolds number and a moderate amount of inlet turbulence meant avoiding the need to trip the boundary layers on the blade surfaces. Downstream traversing was performed using a traditional time averaging pneumatic probe. The probe was aligned with the flow at each measuring position.

During the testing two main problems were encountered. One was achieving periodic flow in the cascades and the other was the design of the downstream probe. This paper first of all briefly describes the test facility and test techniques. Then it outlines the techniques employed to produce periodic cascades, followed by a discussion of the problems encountered with various probe designs. It concludes with a comparison of losses for two different blade profiles, and recommendations for cascade testing.

2. Test Facility and Measurement Technique

2.1 Test Facility

Figure 1 shows an outline of the test facility,

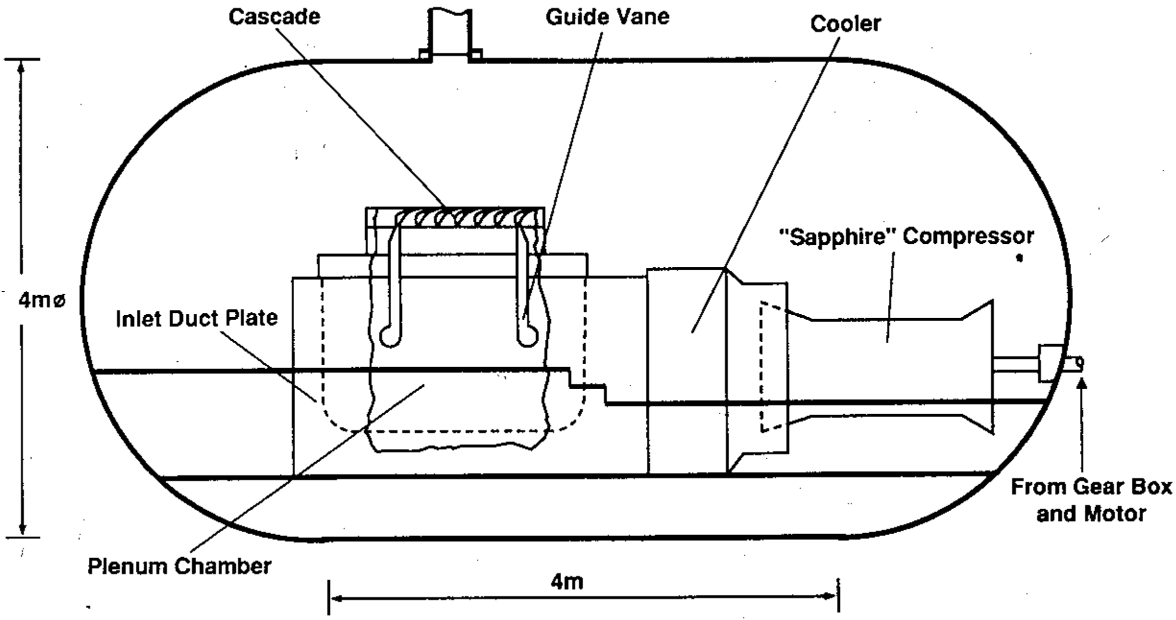

Fig 1. *General Arrangement of Test Facility*

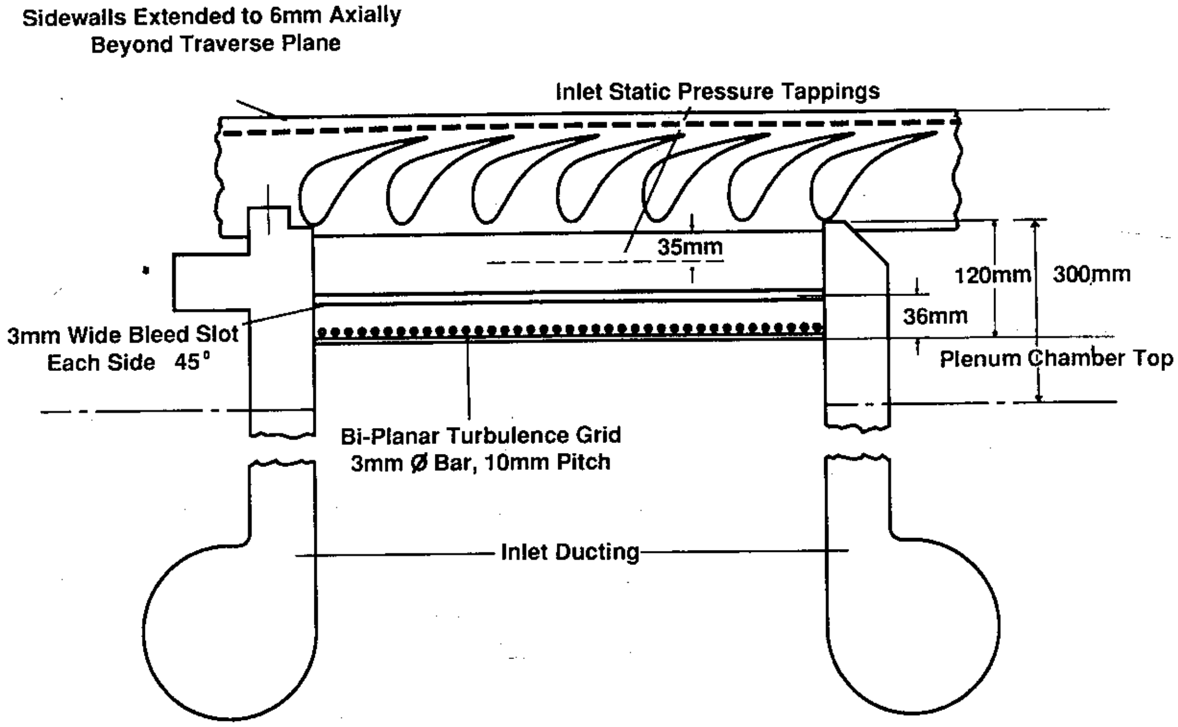

Fig 2. *Detail of the Cascade*

which has been fully described in Reference 1. It is a closed loop variable density facility, capable of being operated with dry air or a mixture of gases. The test series described here used dry air. The shell is a 4m diameter cylinder, 4m long, with hemispherical ends. Power comes from a 2MW variable speed electric motor. The air is compressed by a multi-stage axial flow compressor situated within the shell. Discharge air from the compressor passes through a cooler to a plenum chamber before entering the 1m long cascade inlet duct. The cascade discharges air into the test shell, which is then drawn back to the compressor.

Figure 2 gives more detail of the cascade inlet. Approximately 120mm upstream of the cascade inlet plane is a bi-planar turbulence grid, consisting of 3mm diameter bars on a 10mm pitching. This generates around 6·5% homogeneous turbulence at the inlet plane. This is representative of the background turbulence levels, but does not model wake passing. On each side of the inlet duct is a forward facing bleed slot, 3mm wide, set at 45°, to remove the inlet sidewall boundary layer. This helps to produce 2-dimensional flow over a high proportion of the blade and assists in studying secondary flow losses. Just upstream of the inlet plane are static pressure tappings. These are used to provide a mass flow continuity check on the measured discharge angle, (i.e. to check the axial velocity density ratio). The Laboratory practice with downstream traverses is to traverse at a distance of 75% blade chord, in the streamwise direction ($\sin^{-1}$ (throat/pitch)). The cascade side walls continue 6mm axially beyond the traverse plane, as this has been found to prevent side wall entrainment effects at the traverse plane, without adversely affecting the static pressure distribution. Data logging and probe positioning are computer controlled.

In all of the tests referred to here, the cascade height (span) was 205mm, with a chord of 135mm giving an aspect ratio of 1·5. Each of the cascades had 7 blades, including the end blades. This was a compromise between achieving the maximum Reynolds number, and having sufficient blades to enable periodic flow to be achieved in the cascades.

2.2 Blade Geometry

A range of stator blade and passage geometries, covering those encountered in HP/IP cylinders was tested. Figure 3 gives an outline of a typical blade profile, and the range of pitches over which it was tested

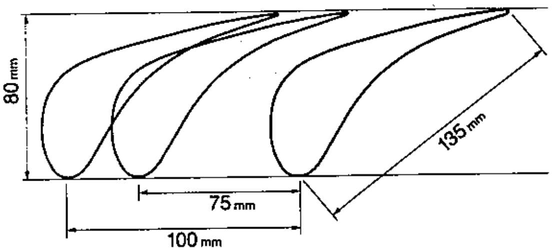

Fig 3. *Outline of Blade and Passage Geometry*

2.3 Facility Operating Range

The main advantage of the variable density facility is that the Mach number and Reynolds number can be varied independently, by varying the pressure in the discharge shell. Figure 4 shows a typical test operating range. The Mach number is the actual discharge Mach number and following Company practice the Reynolds number is based on exit velocity and discharge throat. In the test series the pressure in the shell (the discharge pressure) was varied from ·15 bar to 3·7 bar (2psia to 55psia). At a Mach number of ·5 the Reynolds number was varied by a factor of 20 from $\cdot 5*10^5$ to $1*10^6$. At a Reynolds number of $\cdot 5*10^6$ the maximum Mach number achievable was approximately ·8, and in order to achieve Mach 1·0, the Reynolds number had to be reduced to $\cdot 3*10^6$.

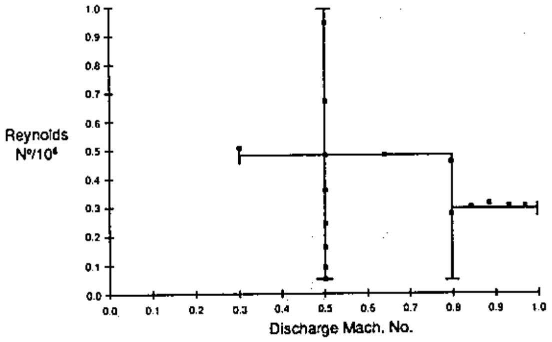

Fig 4. *Operating Range*

2.4 Choice of Traverse Distance

The usual practice is to traverse at a distance of 75% chord streamwise downstream of the trailing edge. This is a compromise between probe size and strength, velocity gradient effects, probe resolution, response time, and capturing the mixing losses. Figure 5 shows the variation in wake profile across one pitch obtained by traversing the same blade at 25% and 75% chord downstream. Efficiency, $\varnothing^2$, is defined as

$$\varnothing^2 = \left(\frac{\text{actual velocity}}{\text{isentropic velocity}}\right)^2$$

Also shown is the effect of measuring the local static pressure or assuming it to be uniform and equal to the discharge pressure.

Analysis of the traverses yielded the pitch averaged mixed out efficiency to be greater at 25% chord than at 75% chord by around 1% point. It is believed that this was predominantly an effect of the pitot probe being too large for the velocity gradients. It indicated a pressure which was nearer to the maximum pressure seen across the probe nose, than to the pressure at probe nose centre.

The effect of using a measured static pressure at the traverse plane, or assuming it to be equal to the discharge pressure is less dramatic, giving a change of ·1% in pitch averaged efficiency.

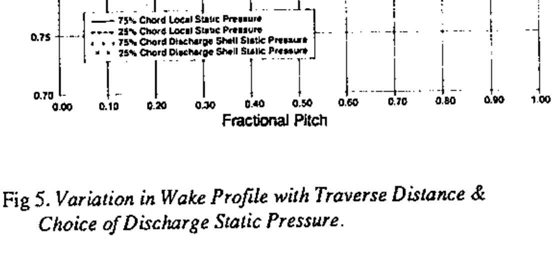

Fig 5. *Variation in Wake Profile with Traverse Distance & Choice of Discharge Static Pressure.*

3. Periodicity

In low reaction steam turbines, small changes in flow angles can result in large changes in the turbines' swallowing capacity. Thus it is very important to measure the flow angle accurately, and consequently the cascade must be periodic.

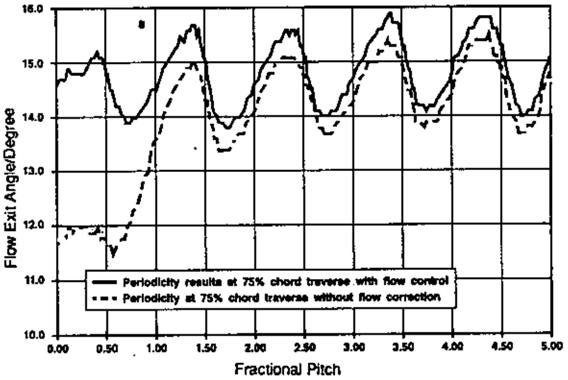

Fig 6. *Periodicity With and Without Downstream Flow Control*

3.1 Effect of Flow Control

With only 7 blades in the cascade, entrainment effects at both ends of the cascade gave poor periodicity in the centre unless some form of downstream flow control was introduced. Figure 6 shows the type of result achieved. Traverses were carried out with the wake centred at mid pitch, and in Figure 6, the wake of the centre blade is at a fractional pitch of 2·5. It shows the variation in angle over the central 5 blades, with and without downstream flow control. Though the central blade shows very little change in angle at the pitch ends without flow control, the outer blades do show significant variation. Thus there is uncertainty that the central blade is correctly modelling the flow. By introducing downstream flow control, periodicity as shown was achieved. It is worth noting that introducing the flow control has not only improved periodicity, but changed the pitch averaged angle as well. It was found that there was only one setting of the flow controls which produced periodicity for a given cascade. Mass flow continuity checks confirmed the pitch averaged angle to be correct within ± ·1° with the flow control correctly set.

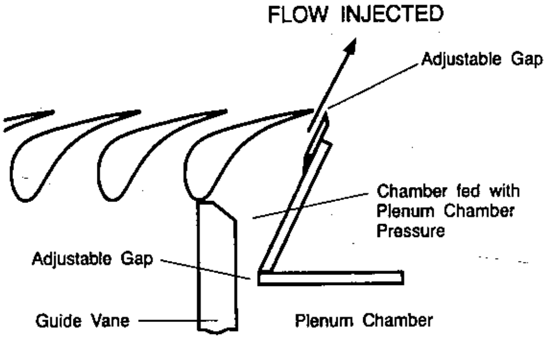

Fig 7. *End Injection*

3.2 End Injection

The first technique used to control the flow was end injection, Figure 7. In this technique, air from the plenum chamber was injected into the discharge flow at the trailing edge of one end blade, as shown. Note, flow was not taken from the inlet duct end walls. The amount of air injected was controlled by adjusting the two gaps, and the height of the knife edge. It is believed the injected flow had two effects. First, was to actually force the cascade discharge flow to a different discharge angle, and second was to feed the entrainment vortex between the discharge flow and plenum chamber top. This technique was very effective and easy to adjust but did not give sufficient control at the largest pitches tested, where there was less 'control' within the cascade.

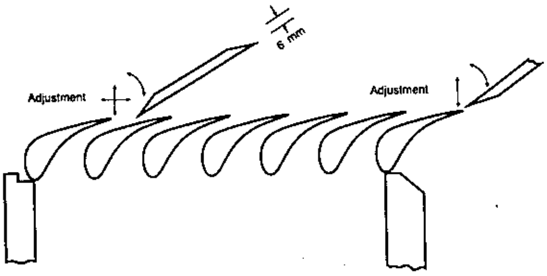

Fig 8. *Tailboards*

3.3 Tailboards

For the larger pitched cascades tailboards were introduced at both ends, Figure 8. At one end, the tailboard was axially aligned with the trailing edge, having angular and axial adjustment as shown. At the other end, the tailboard was also adjustable along the pitch. The flow could be extremely sensitive to this board and considerable patience was required to give good periodicity.

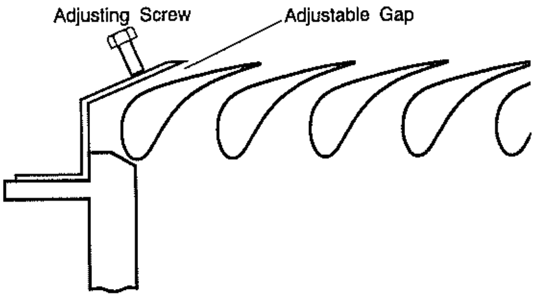

Fig 9. *Bleed and Feed*

3.4 Bleed & Feed

The third technique used was developed for blades with high turning and consequently high passage contraction. This produced a lower inlet Mach number for a given exit Mach number, resulting in larger inlet end wall boundary layers. Initially neither end wall had a boundary layer bleed slot. The increased boundary layer thickness caused a poor distribution of inlet total pressure, which showed up as a severe fall off in exit total pressure towards the end blade. Several methods of correcting the discharge flow were tried, but success was only achieved by bleeding off some of the inlet end wall boundary layer. The bled flow was fed back to the discharge flow via an adjustable gap, Figure 9.

4. Probe Design

Initially a single probe combined pitot-yaw meter was used for downstream traversing. This probe however gave poor repeatability over the Reynolds number range which could have been caused by a transition flow phenomenon around the complicated tip geometry. Thus it was necessary to develop an alternative probe.

The start point was a Neptune probe (3 prong), previously used for transonic work. This probe had a rigid stem, to reduce bending under relatively high aerodynamic loadings. However, the wedge shaped stem of this probe caused considerable lift, partially lifting the probe out of the wake and giving higher than true pitch averaged efficiencies. The lift was reduced by fitting a relatively large circular nose to the wedge, and then further reduced by fitting small deflectors to the circular nose. Though the lift on the probe was considerably reduced, there was still noticeable deflexion, because the mounting arrangement on the traverse gear was too flexible. Therefore, the mounting arrangement was redesigned, and a new probe incorporating the main features from the old Neptune probe was designed. The new probe is shown in Figure 10.

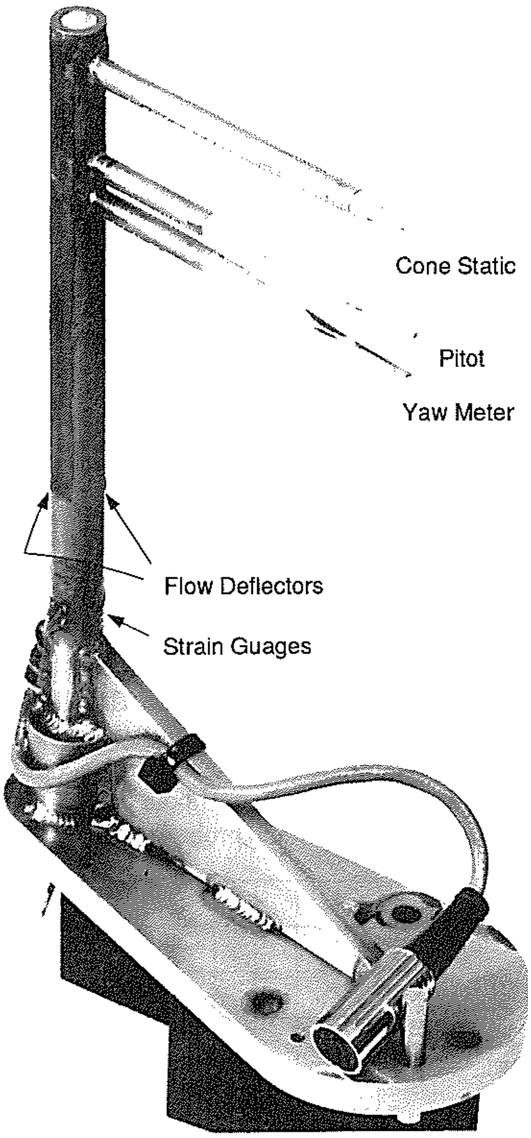

Fig 10. *New Neptune Probe*

The main features are separate pitot and yaw (angle) meters, with a calibrated cone for measuring static pressure. The stem is circular, with strain gauges and deflector strips fitted at right angles to the 3 prongs. Calibration of the strain gauges at known deflexions allows monitoring of the probe deflexion, which did not exceed ·05mm during testing. The probe stem is approximately

15mm diameter, and the prongs around 100mm long.

The new Neptune probe was calibrated in a uniform jet. The yaw meter did not show any Mach number or Reynolds number dependency over the test range of conditions. Similarly, the static pressure cone produced a characteristic which agreed with theory (up to Mach 1·2) except for a small deviation around transonic conditions. The pitot probe read true total in the Mach number range presented here.

5. Results

Figure 11 shows a profile loss vs Reynolds number curve for two different profiles. Loss is defined as $(1-\varnothing^2)$. In Figure 11 the loss is shown relative to the loss of the more efficient blade at the maximum Reynolds number. The difference in loss of 0·2% at the maximum Reynolds number is quite significant in a steam turbine, but may not have been identified without due care being paid to periodicity and probe design.

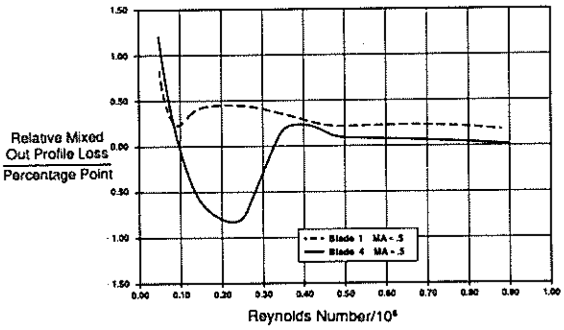

Fig 11. *Loss vs Reynolds Number for 2 Different Blade Profiles*

Figure 11 also shows the natural transition of the more efficient blade, around a Reynolds number of ·1 to ·4*10^6. Had the blade boundary layers been artificially tripped then this feature would have been lost.

6. Conclusions

Experience has resulted in downstream traverses being carried out at 75% chord in the streamwise direction. At this distance the probe can be large enough to meet strength and deflexion considerations, yet small enough to resolve the flow detail. Using a local static pressure measurement is preferable to assuming a uniform pressure equal to the discharge shell pressure. By operating at a high Reynolds number and using a turbulence grid at the cascade inlet a good model of the conditions in HP/IP turbines was produced. It is necessary to pay considerable attention to both periodicity and probe design to help to ensure accurate measurements. Adjustable tailboards and end flow injection can be used to give periodic flow, and probe designs should be as rigid as practicable.

7. References

1. Development of experimental turbine facilities for testing scaled models in air or freon. Forster, V.T., Archer, B.V. & Unsworth, R.G. I.Mech.E. Conference on Heat and Fluid Flow in Steam and Gas Turbine Plant, April 1973.