L.P. Turbine Tip Section in Wet Steam Flow

by

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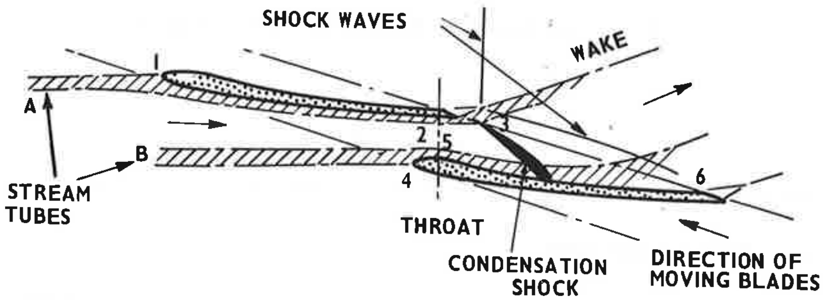
1. INTRODUCTION

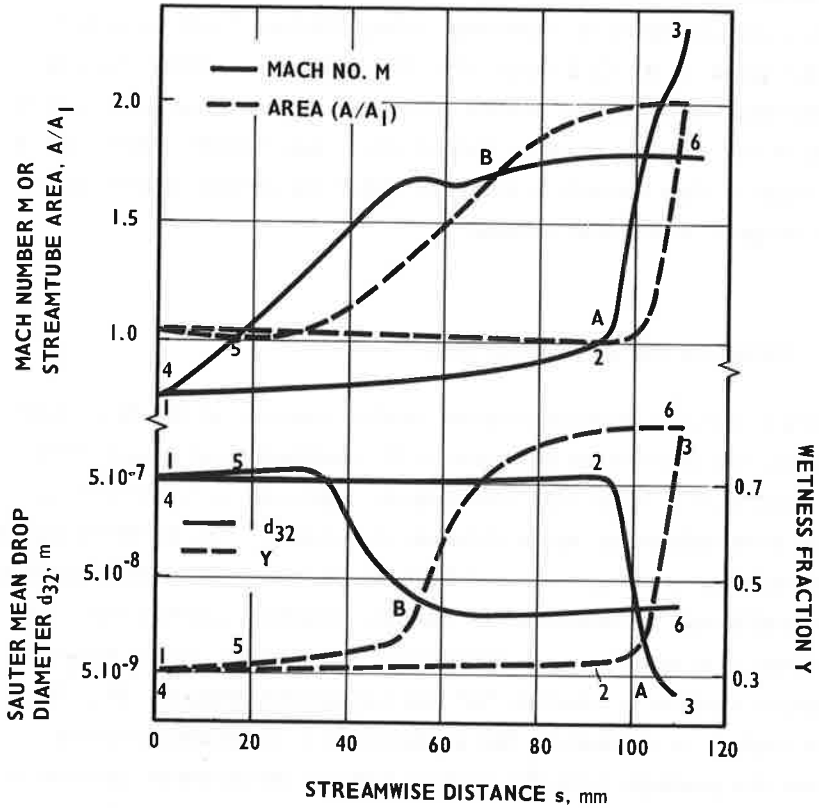
Theoretical studies of wet steam flows through turbine blading have shown that interesting phenomena can occur, including the possibility "condensation shocks" occurring in the blade passages. This paper gives some examples of calculated nonequilibrium flows, followed by a description of the C.E.R.L. Wet Steam Tunnel in which various fundamental experimental studies have been made. Finally, details are given of the cascade working section which has recently been built for the study of flow through a transonic rotor tip section typical of the final stage of a 500 MW turbine.

2. RESULTS OF CALCULATIONS

Figure 1 shows a modern reverse camber cascade of the type which is going into service in the latest L.P. turbines. The curves show the results of a "quasi-non-equilibrium" approach in which stream-tubes were defined by an equilibrium calculation. The boundary stream-tubes at suction and pressure surfaces were then used in onedimensional non-equilibrium calculations, so that the results represent the first iteration of a complete non-equilibrium computation. In the figure the pressure surface is labelled "A" and the suction surface "B". The main feature to be seen is the existence of a condensation shock across the passage from the trailing edge of the pressure surface to the neighbourhood of half chord along the suction surface. The "condensation shock" is the name given to the ramp of increasing pressure



(a) EXAMPLE OF TIP SECTION OF A FINAL STAGE L.P. ROTOR BLADE



(b) CALCULATED CONDENSATION IN STREAMTUBES

Fig. 1 Non-equilibrium flow through a modern L.P. tip section cascade

produced by the release of latent heat of condensation as the supersaturation, built up during the expansion through the passage, collapses with the nucleation of large numbers of very small droplets.

The variations of the specified streamtube area ratios are shown, together with the resulting streamwise distributions of Mach number, M, wetness fraction, Y, and Sauter mean diameter of the droplets, d_{32}. Note that the calculation indicated that the droplets formed in this secondary nucleation were extremely small, incorporating only a few molecules. The validity of this result is not known at present, although preliminary observations with laser illumination show nucleation at this position in an experimental cascade.

The results of a fully two-dimensional calculation for an impulse cascade are shown in figure 2. The conditions are based on an experiment reported by Filippov (1970). Here, nucleation was reported at an earlier stage than predicted by calculations based on a mean streamline through the turbine. The possibility existed that the more extreme expansion occurring along the suction surface might promote earlier nucleation and the calculation did indeed indicate this. The inlet pressure was 0.40 bar with 13K subcooling. Nucleation occurred at 25K subcooling, although the quantity of moisture produced was small and the drops relatively large. More details of this calculation were given by MOORE et al (1973).

A further example (MOORE and SIEVERDING, 1976) is the case of an aerodynamic shock, behind which there may be long relaxation zones. Figure 3 shows an oblique shock in wet steam, with the variation of vapour and droplet velocities and pressure behind the shock, together with the temperature difference between vapour and droplets. It can be seen that there are separate inertial (δ_I) and thermal (δ_T) relaxation distances behind the shock, but both are long, of the order of tens of mm. The upstream conditions here were pressure, 0.072 bar, wetness, 0.10 and droplet diameter 2.0 µm.

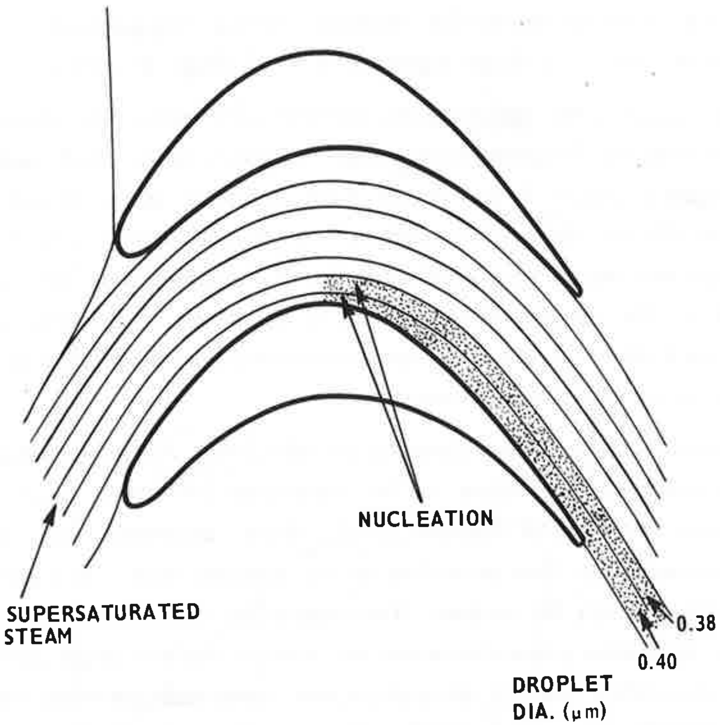


Fig. 2 Two dimensional non-equilibrium flow through an impulse cascade

In addition to these calculations, pressure and flow angle measurements have been made in a number of 500 MW turbines. The results have been incorporated into a streamline curvature throughflow program TURBETA (WOOD, unpublished) which calculates stage and blade efficiencies. The results obtained have indicated some possible effects of wetness on performance.

Thus, wet steam cascades offer some interesting new fluid dynamic loss mechanisms in addition to the traditional losses anticipated from the transport of water through the turbine.

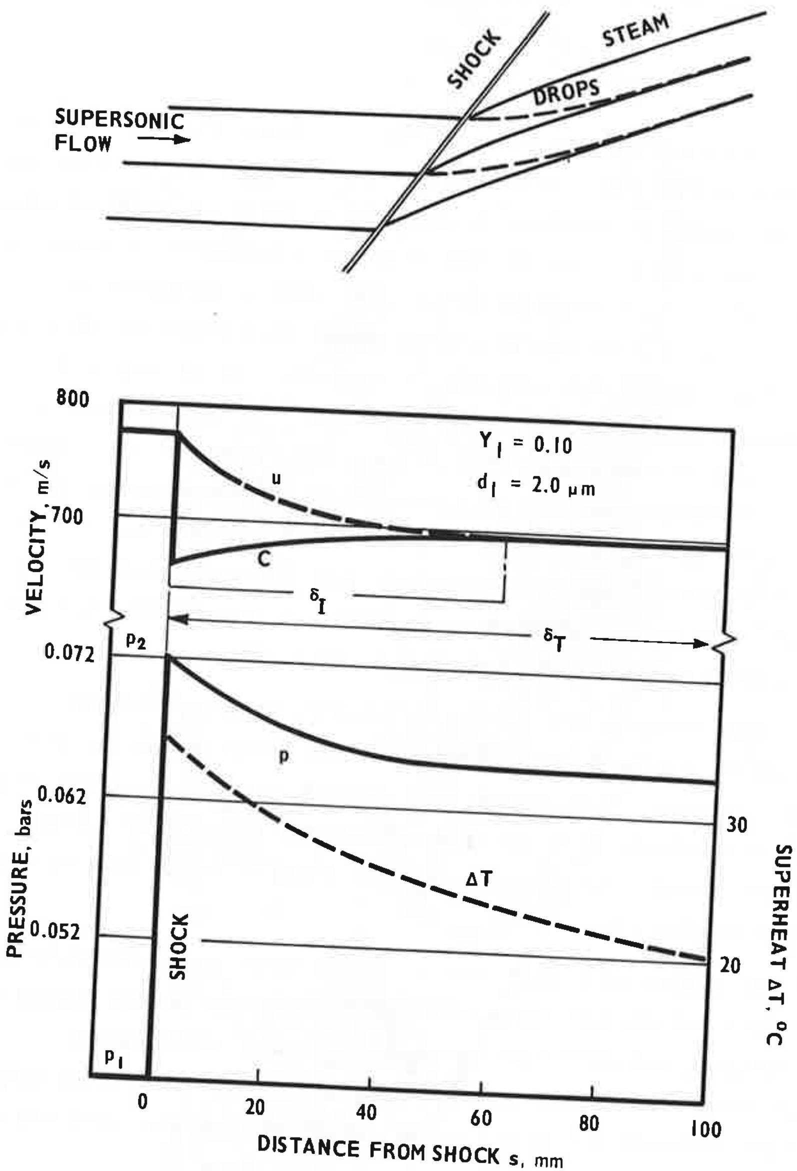


Fig. 3 Wet steam flow through an oblique shock wave

3. EXPERIMENTAL PROGRAMME

3.1 Steam tunnel

Cascade tests are planned for the CERL Wet Steam Tunnel, which is illustrated in figure 4. The tunnel is continuous with a closed circuit. Steam at saturation conditions is produced by the 2 x 1.5 MW oil-fired boilers, and passes to the 120 kW electrical superheater. A turbine is used to extract work from the steam. The work is measured at a brake and can be regulated to provide either superheated or wet steam which flows into the approach duct at mass flows up to 1 kg/s at pressures typical of L.P. turbine wet stages. The contraction runs into the test section, which may be parallel for subsonic measurements, or convergent-divergent for supersonic flows. The test section has been used in the past for studies on erosion, for fundamental studies, including boundary layers and deposition, and non-equilibrium flow in nozzles. Calibrations of measuring probes are carried out regularly and cascade measurements are about to begin.

At the exit from the test section is a simple divergent diffuser followed by a curved adjustable exhaust duct which guides the flow to the condenser. The exhaust duct contains removable sections which enable the diffuser to be tilted downwards for variation of cascade exit flow angles. The condenser cooling water is cooled in a forced-draught cooling tower.

The test section inlet state may be varied between approximately $10^{\circ}C$ superheat and 5% wet. Drop sizes produced by the turbine depend on the wetness, and cannot be varied independently. Nevertheless, experiments can be carried out on non-equilibrium flows using droplets of mean diameter 0.2 to 2.0 µm by varying the turbine speed and hence wetness.

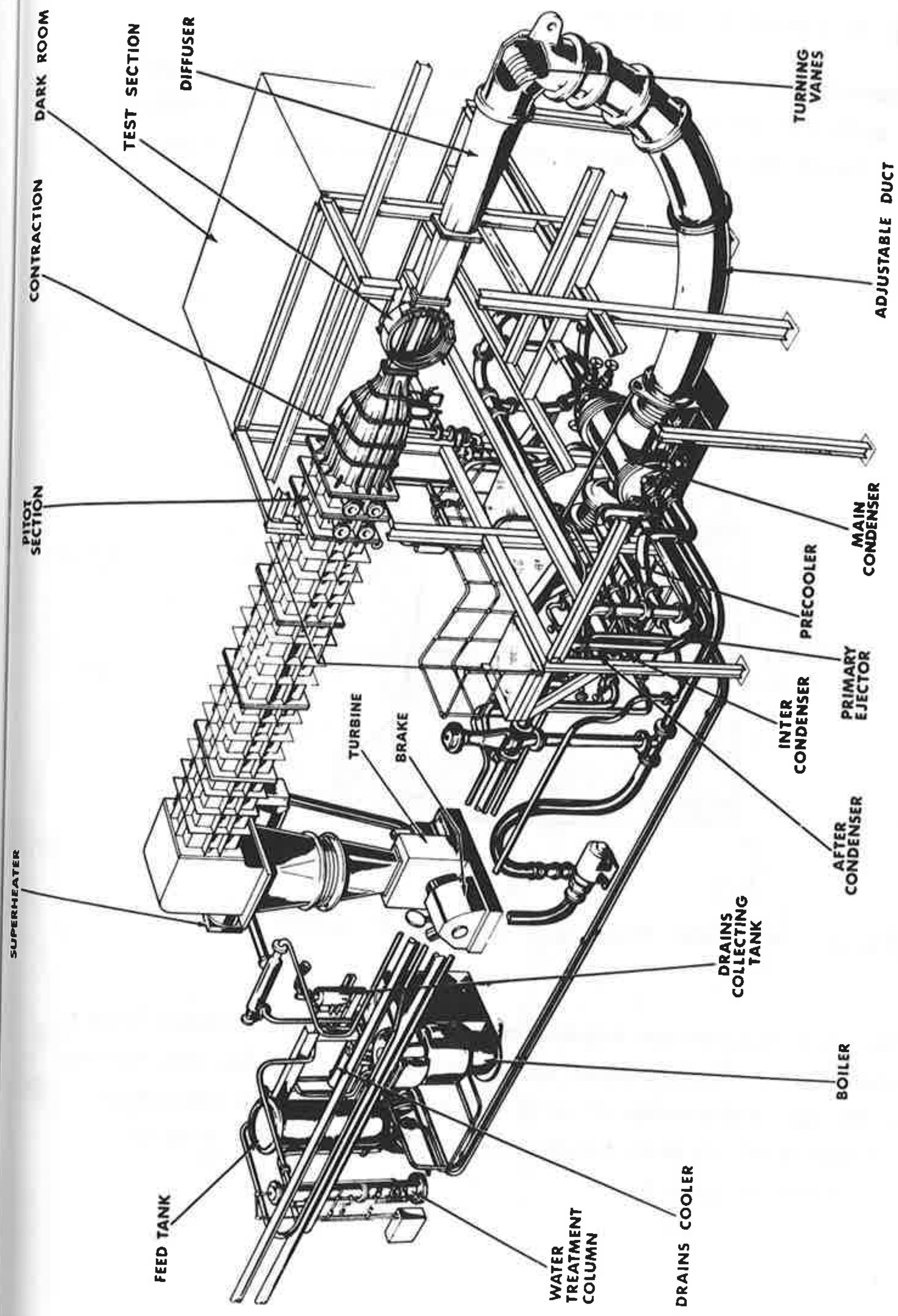


Fig. 4 C.E.R.L. Wet steam tunnel

3.2 Transonic cascade

A cascade has been designed and built to represent the final stage tip section of an L. P. turbine moving blade. The final three stages of a typical large low pressure steam turbine are shown in figure 5.

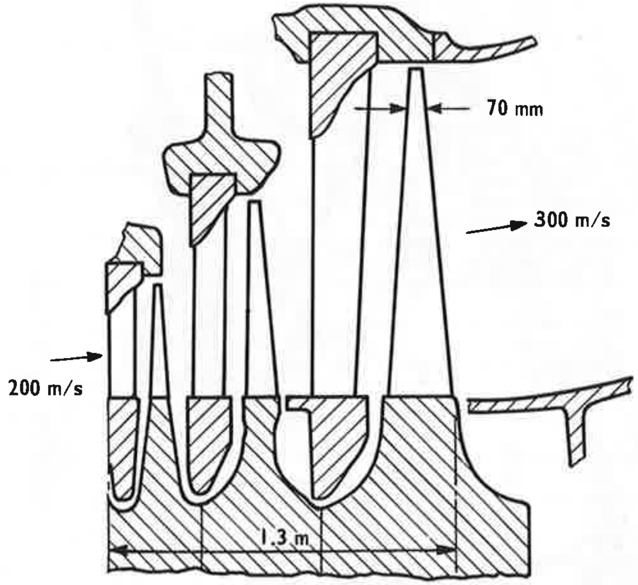


Fig. 5 Wet steam stages of a typical L. P. turbine

The main features are low hub/tip ratio, with a highly twisted rotor blade having a near-impulse section at the root and some 70% reaction at the tip. The cascade which is the subject of the first experiment represents 87.5% blade height from a 500 MW machine. This is illustrated in figure 6.

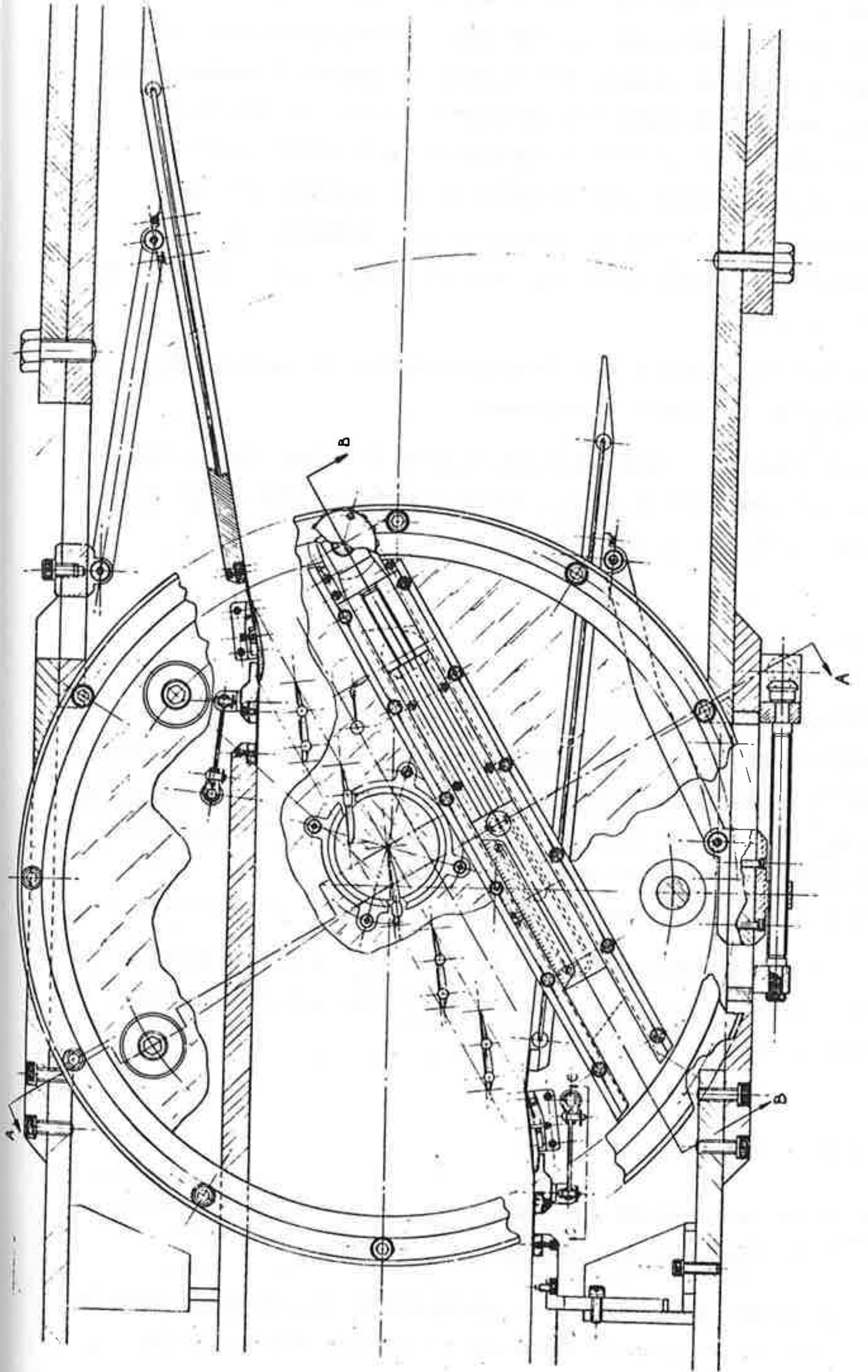


Fig. 6 L.P. tip section cascade in CERL wet steam tunnel

The test section is 200 mm high by 150 mm wide. There are 6 passages and the half-scale cascade has a pitch / chord ratio of 1.17 with a chord of 64 mm. The blades are pegged in perspex side windows. A different fixing has been provided for the two central blades to allow glass schlieren windows to be inserted, covering the inlet of one passage and the outlet of the adjacent one. The whole perspex window can be rotated to vary incidence. There are independently adjustable tailboards and a traverse slide built into one rotatable window.

No boundary layer bleeds have been provided in the initial build, but they can be incorporated as necessary.

The inlet pressure covers the range 0.06 to 0.30 bar and the lower limit on exit pressure is approximately 0.025 bar. The design Mach numbers are 0.5 at inlet and 1.4 at exit.

3.3 Similarity

Dimensional analysis of wet steam flow produces the following non-dimensional groups: Reynolds number (Re), Mach number (M), ratio of specific heats (γ), Prantl number (Pr), enthalpy ratio (CpT_{sat}/h_{fg}) where h_{fg} is the latent heat of vaporisation, ratio of surface tension to the product of pressure and a reference length (σ/pL), non-dimensional droplet diameter (d/L) and geometrical similarity (x/L).

Some of these parameters (M, γ, Pr, CpT/h_{fg}, x/L) can be modelled to a high degree of accuracy, whilst Re, σ/pL and d/L can be modelled to within a factor of two.

3.4 Instrumentation

Schlieren or shadowgraph are, of course, a basic requirement in tests of this kind, and are possible in wet steam.

Pressure probes tend to fill with condensed steam, so these must be purged with air to keep the lines clear. Purging may either be

intermittent, with the measurements taken with purge off, or continuous, in which case the pressure measurements must be calibrated against purging rate. The pressure measurements planned are sidewall static, simple pitot and the M.E.L. static pressure disc (CURTIS et al, 1973).

For outlet angle measurement, methods available include the momentum method, the visual technique of observing the wake from a wire on the schlieren, the M.E.L. single-hole cylinder (CURTIS et al, 1973) and the laser velocimeter.

The inlet wetness will be measured by an optical light extinction method (WALTERS, 1973). Elsewhere the wetness may be obtained from thermodynamic relations and spot optical checks.

The laser velocimeter is of considerable interest to us in this context. Laser doppler measurements have been made in the steam tunnel at velocities up to 200 m/s (CRANE and MELLING, 1975) but the background noise level became too high at higher velocities. For higher velocities the Laser 2 Focus method of SCHODL (1975) looks promising.

Hot wire measurements of turbulence levels are possible in wet steam (WOOD, 1973, 1975) but the measurement techniques are difficult and the analysis is time consuming. Laser methods ought to be superior if they can be made to work in the dense wet steam fog.

4. CONCLUSION

The CERL wet steam tunnel and cascade facility has been described, and the instrumentation required for wet steam measurements have been discussed.

Acknowledgements

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Comparison of 2-D-Cascade Tests Done in the VKI and AVA Cascade Wind Tunnels

by

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The charakteristic data of a high turning gas turbine cascade, described in Ref. [1], were measured in the wind tunnels for straight cascades and for rotating (annular) cascades of the AVA-DFVLR-Göttingen. The exit flow conditions were changed from subsonic up to supersonic velocities. The turning and the losses obtained in the two facilities are compared to those measurements done in the VKI-cascade wind tunnel. The surface pressure distribution measured in the straight cascade wind tunnels of VKI and AVA were also compared.

The results of these comparisons can be summarized as follows:
The pressure distribution measurements of VKI and AVA are in a good agreement except of a small region at the end of the suction side of the blade. These deviations are certainly due to differences of the Reynoldsnumbers in both facilities. The turning measured in all three facilities is in agreement in the sub- and supersonic flow regime; only in the case of transonic flow there are derivations up to 1.5 degrees.

The losses are - within a certain scatter of 1% -point - in a good agreement up to that Machnumber, where the losses increase rapidly, i.e. in this case up to Machnumber of $M_2 \approx 1.1$. It is interesting to note that the wind tunnel for rotating cascades gives the same results as the wind tunnels for straight cascases up to the downstream Machnumber of $M_2 \approx 1.1$.

A detailed description of the above mentioned comparison of experimental results is given in Ref. [2], including results obtained by theoretical methods.