through unconventional design features. Clearances between the stationary and rotating parts, surface finish, thickness of blades, scaling and casing treatment were among the topics covered in the papers. The session on performance evaluation was mainly user orientated. It dealt with such aspects as optimisation of compressor vane and bleed settings, comprehensive study of guide vanes of an axial flow compressor, prototype variable geometry industrial turbines, data handling systems etc.

Unsteady flows in turbomachinery also received considerable attention and 15 papers were presented. The topics covered included measurements of self excited flow oscillations and rotating stall in centrifugal compressors, development of a generalised method for bluff body and stalling aerofoil flows, three dimensional aerodynamic characteristics of oscillating supersonic and transonic annular cascades, interactions of unsteady flow distortions with high Mach number cascades, distorted flow fields, computation of unsteady blade forces by means of potential flow theory and viscous wakes, laminar-turbulent boundary layers disturbed by wakes etc.

The session on blade boundary layers and wakes included papers on wakes from compressor cascades, trailing edge ejection and base pressure in transonic turbine cascade, prediction of blade wakes, turbulent boundary layers, base pressure on a blunt base in transonic flows, and visual studies of boundary layers. Five very interesting papers reported the results of investigations on the end wall and secondary flow phenomena in axial flow turbines and compressors. The session on turbulence effects included four papers which dealt with such topics as coherent structure of the turbulent boundary layers at low and high velocities, influence of free stream turbulence on boundary layer transition, and three dimensional flow field in the tip region of a compressor rotor passage.

The Conference and Exhibition attracted over three thousand visitors; technical sessions were attended by about eleven hundred delegates.

F. S. Bhinder
Mechanical Engineering Dept,
Hatfield Polytechnic, UK

Viscous flow effects in axial compressors and turbines

D. G. Gregory-Smith*

In the design of axial flow turbomachinery, information about the viscous flow effects is very important. Such information, whether experimentally or theoretically derived, may be used directly or in conjunction with throughflow calculation techniques. Viscous flow information allows the designer not only to avoid gross flow distortions due to boundary layer separations, but also to estimate the aerodynamic losses, and hence the efficiency and power of the machine.

Due to the complexity and importance of viscous flows, a substantial proportion of the papers on axial flow turbomachinery aerodynamics presented at the conference dealt with these flows. With 84 sessions spread over 4 days with up to 12 parallel sessions at any time, inevitable clashes occurred even for one with fairly limited interests. This review, however, attempts to highlight the main points of interest on viscous flows.

The effects of viscous flows may be divided into blade boundary layers distant from the end walls and flows near the end walls including secondary flows, end wall boundary layers and tip clearance effects. This division is not wholly satisfactory, since there are mutual interactions as some of the papers showed. The blade boundary layers give rise to wakes which decay and also affect the following blade rows, and several papers dealt with these aspects. Similarly the effects downstream near the end walls are important, although very complex.

Since the early days of overall empirical correlations, such as those of Howell for compressors and Ainley and Mathieson for turbines, there has been a steady progress towards a more detailed physical understanding of turbomachinery flows. Over the past few years this progress has been accelerated due mainly to the advent of fast computers, of large storage. These have allowed the acquisition, analysis and numerical or graphical presentation of large amounts of data from experiments. Improvements have also been made in instrumentation and flow visualisation techniques. Thus it is not surprising that the majority of papers presented at the conference were reporting mainly experimental work.

Progress in the difficult task of relating the physical understanding to improved theoretical models is slow, although some papers attempted to do this. There were also a few papers dealing with calculation methods for viscous flows in blade passages.

Blade boundary layers

Although boundary layers on blades are considerably less complex than those on the end-walls, they are still subjected to a number of 'unusual' effects, such as large streamwise pressure gradients, radial pressure gradients, unsteady flows and high curvature. Profile losses for reasonably high aspect ratio turbine blades may be predicted with some confidence. Problems arise, however, at low aspect ratios, and for compressor blades, and when details such as transition and local skin friction are considered. The work presented at the conference illustrated these points.

The papers may be subdivided into fundamental studies of boundary layers, and studies of boundary layers on compressor and turbine blades. Among the former were two papers on laminar-

* Department of Engineering, University of Durham, Science Laboratories, South Road, Durham, UK, DH1 3LE

turbulent transition. Pfeil, Herbst and Schroder[1] investigated the effect of the wakes from a rotating cage of cylinders on transition of a boundary layer on a flat plate. This simulated the wakes from an upstream blade row. Blair[2] reported the effect of free stream turbulence on transition in the presence of a favourable pressure gradient, with application to pressure surface boundary layers.

Coherent structures in turbulent boundary layers were studied by Barra and Zakkay[3], and by Han and Cox[4]. The latter used flow visualisation on a turbine blade pressure surface and showed the existence of longitudinal Görtler vortices. These interacted with the Karman vortices shed at the trailing edge to form a complex vortex pattern in the blade wake.

Sharma and Graziani[5] presented an analysis of the suction surface boundary layer on a low aspect ratio turbine blade. They showed that the end wall flows may significantly affect the development of the boundary layer at mid-span and predicted reductions in skin friction and Stanton number compared with calculations for a two-dimensional boundary layer. Walker[6] looked at the boundary layer on a compressor stator blade, and showed significant departure from logarithmic wall similarity and conventional skin friction correlations. Equilibrium calculation methods proved unsatisfactory, and he recommended a lag-entrainment method for predicting the blade boundary layers.

Blade wakes

Understanding the development of blade wakes is important because of their effects on subsequent blade rows, the diffusion of loss from the wake into the main stream and the displacement effect which may be used in potential flow calculations.

Hobbs, Wagner, Dannenhoffer and Dring[7] measured the wake downstream of a compressor cascade. They developed velocity profile parameters with the object of producing a wake model for use in an inviscid potential flow calculation method. Kool and Hirsch[8] presented a prediction method for the decay of the wake in a streamwise pressure gradient. They included the separation bubble at the trailing edge, and compared the predictions with experimental results. Measurements of the wake from a transonic turbine blade were made by Bryanston-Cross and Camus[9]. They developed an optical technique, sampling points in the image plane of a Schlieren system and correlating them digitally. They showed strong vortex shedding from the trailing edge, and obtained information on the wake velocity.

Two other papers on transonic turbine blades were on the effects of bleed air on the base pressure at the trailing edge. Sieverding[10] carried out tests on a large scale model of the trailing edge region for detailed measurements, and then tested a cascade of nozzle blades. Motallebi, Edwards and Norbury[11] tested a symmetrical blunt nosed aerofoil with a square cut trailing edge. Both papers showed the effect of bleed air at different Mach numbers, with implications for the design of cooled turbine blades.

Two papers were presented on the unsteady and interaction effects of blade rows. Both reported work on the United Technologies Research Center large scale rotating rig. Joslyn, Dring and Sharma[12] studied a nozzle row followed by a rotor row and a second stator row. They measured the flow after each row using phase locked sampling to obtain mean and unsteady flow quantities. They showed strong radial flows in the blade wakes and the effects of relative rotor and stator blade positions. Dring, Joslyn, Hardin and Wagner[13] used only the nozzle row and rotor row, and measured fluctuating blade surface pressures and heat transfer with nozzle-rotor gaps of 15% and 65% of axial chord. The effect of the wake on the downstream blade row and the mutual interaction of the two potential flows could be seen.

End wall flows

A number of papers dealt with the complex flows near the ends of blades where a number of factors are present. These include the secondary flows generated by turning the upstream wall boundary layer, the tip clearance leakage, and skew effects due to the relative motion of blade and end wall. The differences between turbines and compressors are very marked. In compressors the end wall boundary layer maintains some identity across a blade row, with perturbations due to the effects mentioned above. However, in turbines the secondary flows produced by the high turning are such as to sweep the upstream boundary layer off the end wall and allow a new boundary layer to form on the end wall. Most of the papers dealt with compressors, and this may partly reflect the more critical nature of the boundary layers in the rising pressure field across the blade row.

Compressor end wall flows

One paper, that by Leboeuf, Barlo, Boris and Papailiou[14], dealt with transonic flow in a compressor. They measured the secondary flows between the blade rows of a transonic stage, consisting of inlet guide vanes, rotor and stator. A secondary flow model was used with an inviscid through flow type calculation to predict the flow, which compared well with the measured flow.

Five papers report work on large scale low speed compressors, chosen so that detailed measurements of the flow near the end wall could be made. Hunter and Cumpsty[15] studied the flow through an isolated rotor row with varying tip clearance. Measurements of the mean flow were made using pressure probes, and the blade to blade structure of the flow was investigated using phase locked sampling by a hot-wire probe. They were able to show how the increasing tip clearance degraded the compressor performance.

Three papers from the Pennsylvania State University reported detailed studies within the blade passage region of the rotor on their low speed compressor facility. Pandya and Lakshminarayana[16] investigated the flow in the tip clearance region by traversing a two sensor hot-wire probe inwards from the casing and using phase locked ensemble averaging. Traversing was at ten axial stations, four of which were within the blade row, where, of course, the radial extent of the traverse was limited by the value of tip clearance. They presented mean velocity and angle data, and showed strong interaction of the leakage flow with the casing wall boundary layer. Lakshminarayana, Pouagare and Davino[17,18] presented two papers, Parts I and II of an investigation of the flow near the tip of the rotor using a triaxial hot-wire probe rotating with the rotor. These complemented the previous paper[16] by extending the radial positions to within the blades. Part I[17] presented the mean flow velocities and angles. They observed the leakage flow rolling up away from the suction surface, with substantial radial velocities present, unlike observations in stationary cascades. Part II[18] presented the turbulence properties. They found high values of turbulent stresses in the leakage flow mixing region, with the radial component of stress much higher than the streamwise components. They also observed the decay of the inlet guide vane wake. Some of the conclusions in the three papers were a little tentative, due to the relatively few traverse positions. Even so, the amount of data collected was very large, only made possible through use of computerised acquisition and analysis systems.

Bettner and Elrod[19] investigated the influence of tip clearance, stage loading and wall roughness on a highly loaded compressor stage. The roughness variation was achieved by placing roughness elements into a small depression in the casing in the region of the rotor tip. Using both pressure and hot-wire probes to traverse the flow at rotor inlet and exit and at stator exit, they showed how the above effects influenced the casing boundary layer and performance of the compressor.

Turbine end wall flows

Binder and Romey[20] presented work on a turbine nozzle row of 0.756 hub to tip ratio and low aspect ratio, 0.56. They investigated the secondary flows and blade wakes as they developed downstream of the stator row, using pressure probes. The variation of mixing loss with axial position and Mach number was shown, as was the persistence of strong vortices and radial flows in the wake region. Gregory-Smith[21] presented a modelling procedure for the estimation of losses and secondary flows for a turbine cascade, based on a variety of previously published work. In attempting to model the physical processes, he identified three elements of the loss: the upstream boundary layer which is shed downstream as a loss core, the new highly skewed boundary layer on the end wall, and the effect of the passage secondary vortex.

Calculation methods

Considerable advances have been made in the calculation of three-dimensional flows, some of which include viscous effects. Even with modern high speed computers, however, they tend to suffer from excessive computation times and poor definition of the flow when considering the rapid spatial variations near an end wall. Thus work continues in this area, and three papers were presented on the calculation methods for blade passages.

Lacor and Hirsch[22] presented an inviscid, finite element method, separating the flow into a potential part and a rotational part. Agreement with experimental results for a 90° elbow was initially quite good but deteriorated downstream as viscous effects become more important. Abdallah and Hamed[23] presented a novel method for inviscid flow by calculating on three orthogonal surfaces. On each surface the flow field was represented by a source sink distribution, and information was exchanged between the three surfaces. The method was very efficient in computer time, and the results agreed satisfactorily with data from a curved duct.

Sheoran and Tabakoff[24] presented a viscous, incompressible flow calculation method on three sets of arbitrary orthogonal surfaces, using momentum and vorticity transport equations. The method dealt with laminar viscous flows, and they presented results for a stationary and a rotating duct.

Lastly, mention must be made of a paper that might be termed a posthumous tribute to Professor R. Hetherington, lately of Cranfield Institute of Technology. The paper by Wang, Hetherington and Goulas[25] presented a calculation method for estimating the deviation angle in subsonic compressor cascades. The method calculated the flow on the blade-to-blade S1 surface using a viscous turbulent model near the blade surfaces and a finite element numerical technique. The results showed good agreement with Carter's correlations and NASA data.

Comments

The range and quality of the work presented at the conference was impressive, and a major contribution of such a conference is the bringing together of a wide range of workers and ideas. Clearly there is the need for continuing work on viscous flows, both experimental to give a better understanding of the physical processes, and theoretical to produce improved models for calculation of the flow. The incorporation of the research work into the analysis and design procedures for turbomachinery is a further difficult task. However it is an important one since, apart from the general scientific interest, the engineering aim must be to produce better turbomachines.

References

The reference number of each paper is given here; some papers will appear in the ASME Journal of Engineering for Power.

1. **Pfeil H., Herbst R. and Schroder T.** Investigation of the laminar turbulent transition of boundary layers disturbed by wakes. *A.S.M.E.Paper No. 82-GT-124*
2. **Blair M. F.** Influence of free-stream turbulence on boundary layer transition in favourable pressure gradient. *A.S.M.E. Paper No. 82-GT-4*
3. **Barra V. and Zakkay V.** Coherent structure of the turbulent boundary layer at low and high velocities. *A.S.M.E. Paper No. 82-GT-78*

4. **Han L. S. and Cox R. W.** A visual study of turbine blade pressure-side boundary layers. *A.S.M.E. Paper No. 82-GT-47*

5. **Sharma O. P. and Graziani R. A.** Influence of endwall flow on airfoil suction surface mid-height boundary layer development in a turbine cascade. *A.S.M.E. Paper No. 82-GT-127*

6. **Walker G. J.** The turbulent boundary layer on an axial compressor blade. *A.S.M.E. Paper No. 82-GT-52*

7. **Hobbs D. E., Wagner J. H., Dannenhoffer J. F. and Dring R. P.** Experimental investigation of compressor cascade wakes. *A.S.M.E. Paper No. 82-GT-299*

8. **Kool P. and Hirsch Ch.** A prediction scheme for the decay of a turbomachine blade wake. *A.S.M.E. Paper No. 82-GT-273*

9. **Bryanston-Cross P. J. and Camus J. J.** Auto and cross correlation measurements in a turbine cascade using a digital correlator. *A.S.M.E. Paper No. 82-GT-132*

10. **Sieverding C. H.** The influence of trailing edge ejection on the base pressure in transonic turbine cascades. *A.S.M.E. Paper No. 82-GT-50*

11. **Motallebi F., Edwards S. J. and Norbury J. F.** Base pressure on a blunt base in transonic flow—some effects of base geometry and bleed air. *A.S.M.E. Paper No. 82-GT-317*

12. **Joslyn H. D., Dring R. P. and Sharma O. P.** Unsteady three-dimensional turbine aerodynamics. *A.S.M.E. Paper No. 82-GT-161*

13. **Dring R. P., Joslyn H. D., Hardin L. W. and Wagner J. H.** Turbine rotor-stator interaction. *A.S.M.E. Paper No. 82-GT-3*

14. **Leboeuf F., Bario F., Boris G. and Papailiou K. D.** Experimental study and theoretical prediction of secondary flows in a transonic axial flow compressor. *A.S.M.E. Paper No. 82-GT-14*

15. **Hunter I. H. and Cumpsty N. A.** Casing wall boundary layer development through an isolated compressor rotor. *A.S.M.E. Paper No. 82-GT-18*

16. **Pandya A. and Lakshminarayana B.** Investigation of the tip clearance flow inside and at exit of a compressor rotor passage. Part I: Mean velocity field. *A.S.M.E. Paper No. 82-GT-12*

17. **Lakshminarayana B., Pouagare M. and Davino R.** Three-dimensional flow field in the tip region of a compressor rotor passage, Part I: mean velocity profiles and annulus wall boundary layers. *A.S.M.E. Paper No. 82-GT-11*

18. **Lakshminarayana B., Pouagare M. and Davino R.** Three-dimensional flow field in the tip region of a compressor rotor passage, Part II: Turbulence properties. *A.S.M.E. Paper No. 82-GT-234*

19. **Bettner J. L. and Elrod C.** The influence of tip clearance, stage loading and wall roughness on compressor casing boundary layer development. *A.S.M.E. Paper No. 82-GT-153*

20. **Binder A. and Romey R.** Secondary flow effects and mixing of the wake behind a turbine stator. *A.S.M.E. Paper No. 82-GT-46*

21. **Gregory-Smith D. G.** Secondary flows and losses in axial flow turbines. *A.S.M.E. Paper No. 82-GT-19*

22. **Lacor C. and Hirsch Ch.** Rotational flow calculation in three-dimensional blade passages. *A.S.M.E. Paper No. 82-GT-316*

23. **Abdallah S. and Hamed A.** The elliptic solution of the secondary flow problem. *A.S.M.E. Paper No. 82-GT-242*

24. **Sheoran Y. and Tabakoff W.** A study of viscous flow in stator and rotor passages. *A.S.M.E. Paper No. 82-GT-248*

25. **Wang L. C., Hetherington R. and Goulas A.** The calculation of deviation angle in axial flow compressor cascades. *A.S.M.E. Paper No. 82-GT-230*

Heat transfer sessions

A. Brown*

In reviewing the four heat transfer sessions it is convenient to take the first two together and then treat the last two separately. Thus this report has three subdivisions: external blade heat transfer; film and transpiration cooling; and blade internal cooling.

Regardless of the continuing improvements made in the structural capabilities of high temperature alloys used in gas turbine components, many gas turbines operate at turbine entry temperatures where component cooling is necessary. Cooling is usually achieved by systems using relatively cold bled compressor air. The aim is to design the cooling system for minimum coolant flows compatible with the maximum stresses experienced during cyclic operation and an acceptable component stress rupture and creep operating life. Also excessive cooling is detrimental to engine efficiency as the use of compressor bled air for cooling partially offsets performance improvements obtained by higher turbine entry temperature. Thus turbine component cooling design engineers have to meet the dual challenge of minimising cooling air consumption and assuring that component temperatures are low enough to meet life requirements. Knowledge of the fluid mechanics of flows within and over turbine components and the consequent heat transfer between gases and components is essential. This knowledge is continually being improved upon by basic research and is being adapted in the design of modern high temperature gas turbines.

* Department of Mechanical Engineering and Engineering Production, University of Wales Institute of Science and Technology, Cathays Park, Cardiff, UK, CF1 3NU

External blade heat transfer

Measurements of heat transfer on both suction and pressure surfaces of rotor and stator blades in cascades for a range of flow conditions were reported in six papers[1,3,4,6,9,10]. Of these six papers, five used transient techniques to measure heat transfer, the exception being the measurements of Krishnamoorthy[4]. Krishnamoorthy measured the heat transfer coefficient distribution over a blade profile at constant heat flux boundary conditions. The heat transfer test blade was made of low thermal conductivity