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A NEW EXPERIMENTAL TECHNIQUE FOR MEASUREMENT OF THE STEADY-STATE METAL TEMPERATURE DISTRIBUTIONS OF FILM-COOLED NGVs

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ABSTRACT

A new experimental technique for the measurement of steady-state metal temperature distributions of film cooled nozzle guide vanes has been developed. It is advantageous in that engine representative flow conditions can be established using a relatively low mass flow rate of air. This is made possible by using an annular sector of test vanes in place of a full annular cascade. A new technique for establishing pressure boundary conditions in annular sector cascade experiments has been developed (Povey et al., 2004), and has been demonstrated to offer significant improvements over previous methods in terms of the degree of passage-to-passage flow periodicity achieved. Using the technique, pressure boundary conditions very similar to those that develop in an annular cascade can be established using only a small number of vanes.

The power of the annular sector technique is that actual engine components can be used without the need for scaling – as in the case of a linear cascade. For film-cooled components, the correct momentum flux ratio and blowing rate ratio may be established by using heated foreign gas of a higher density than air, or by using liquid-nitrogen cooled air. Using these techniques, order of magnitude savings in both time and cost – over conventional experimental techniques – can be realized.

The new technique employs deswirl vanes downstream of the annular sector of test vanes. The design of the deswirl vanes is such that the radial pressure gradient established in the swirling flow downstream of the test vanes is not disturbed. The deswirl vane exit-flow – which is axial – can be exhausted without unsteadiness, and without the risk of separation, into a plenum at constant pressure. The test vane pressure ratio is tuned by adjusting the throat area at the exit of the deswirl vane passage.

The Oxford deswirl vane technology has previously been used to set pressure boundary conditions in fully annular cascades, both small-scale and engine-scale (the Isentropic Light Piston Facility in Farnborough; see: Povey et al., 2001; Povey et al., 2003). The deswirl vane is particularly suited to the control of highly whirling transonic flows.

It has been demonstrated by direct comparison of aerodynamic measurements from fully annular and annular sector experiments that periodic flow – with the desired radial pressure gradient – can be established in a five-passage annular sector. This novel use of the deswirl vane technology for flow conditioning in the annular sector environment offers a means for solving the annular sector boundary condition problem, and allows approximately engine-representative flow to be established in such a cascade. Experiments results in support of this are presented.

A new annular sector heat transfer research facility has been developed in Oxford for the measurement of the steady-state surface temperature distributions of modern highly film-cooled nozzle guide vanes. A five-passage sector of test vanes (engine parts) will be tested. The mass flow rate requirement of the facility is therefore relatively low (2.5 kg/s), and, because run times are correspondingly long, a steady-state temperature field can be attained in a conventional blow-down type facility of moderate size. A run time of 100 s can be achieved in the Oxford blow-down facility. The design of the new facility is described.

It is expected that the technique will enable cascade designers to exploit the obvious advantages of annular sector cascade testing: the reduced cost of both facility manufacture and facility operation, and the use of engine parts in place of two-dimensional counterparts.

NOMENCLATURE

Romans and Greeks

a, acoustic velocity, m/s
c_p, specific heat at constant pressure, J kg^{-1} K^{-1}
c_v, specific heat at constant volume, J kg^{-1} K^{-1}
L, length scale, m
v, velocity, m s^{-1}
ρ, density, kg m^{-3}
μ, dynamic viscosity, N s m^{-2}

Non-dimensional groups

B, Blowing rate ratio, $\rho_c v_c / \rho_m v_m$
I, Momentum flux ratio, $\rho_c v_c^2 / \rho_m v_m^2$
M, Mach number, v/a
Pr, Prandtl number, $c_p \mu / k$
Re, Reynolds number, $\rho v L / \mu$
γ, Ratio of specific heats, c_p / c_v

Subscripts

m, mainstream flow
c, coolant flow

INTRODUCTION

In the annular cascade experiment, the nature of secondary flow development depends upon both inlet and exit-flow conditions. Where a nozzle guide vane row is tested in isolation – in a stationary cascade – engine-representative pressure boundary conditions are often difficult to achieve. Radial pressure gradients, established in regions of swirling flow, affect the growth of secondary flows and, indeed, the span-wise velocity distribution at the vane exit-plane. Several methods have been developed to establish the correct radial pressure gradient at the exit of annular cascade facilities, although many are in some way unsatisfactory – a common problem is that of unsteady flow separation downstream of the test vane.

An alternative to annular cascade testing, is the use of a fixed linear cascade of vanes, a technique that is attractive because testing is possible at lower mass flow rates – a smaller number of test vanes can be used at the same chord size. In the linear cascade, radial pressure gradients are not established, and secondary flows do not develop as they would in a working engine. This means that radial distributions of total pressure loss and whirl angle are un-representative of engine conditions. In addition, surface heat-transfer rate distributions, which are strongly influenced by the secondary flow structure, are non-representative of engine conditions. An additional shortcoming is that only geometrically simplified (usually two-dimensional) designs can be tested, whereas in annular cascade experiments the exact three-dimensional vane profiles, even engine parts, can be used. Another difficulty is that of establishing truly periodic inlet and exit-flow conditions, which, being established automatically in the annular facility, can be achieved in a linear cascade only when a very large number of vanes is used.

The sidewalls of the inflow and exit ducts of a linear cascade exert a strong influence on the streamline pattern within the cascade, and techniques such as variable wall-suction and flexible sidewalls have been employed to *tune* the inlet and exit-flow conditions. Achieving even approximately periodic conditions is generally problematic however. A very comprehensive review of advanced techniques applicable to both linear and annular cascade testing has been published by AGARD (Hirsch, 1993).

Annular sector cascade testing is a technique that can combines the advantages of both the annular and linear cascade testing methods. Actual engine components can be tested, and the radial pressure gradients established in regions of swirling flow ensure secondary flows develop as they would in an operating engine. Model and testing costs for annular sector cascades can therefore be considerably lower than for their fully annular equivalents. Annular sector cascade testing is, however, relatively uncommon. This must in part be because the designer is faced with the dual challenges of establishing vane-to-vane periodicity, and of maintaining the radial pressure gradient in the sector cascade exit-flow. These problems are difficult to resolve, and, consequently, the potential advantages of annular sector testing have so far not been fully enjoyed.

ANNULAR SECTOR FACILITIES

Because the annular sector technique is little used, there is very little literature concerning methods for design or operation of such facilities. Over the years, however, a few annular sector facilities have been developed, primarily for studies of cooling flow effectiveness and for measurements of vane surface heat transfer coefficient. An early example is the NASA Lewis Research Centre Hot Section Facility (Gladden and Gauntner, 1975), a 23° annular sector cascade in which engine components were used.

More recently, a high-pressure high-temperature annular sector facility was commissioned at ABB STAL – Sweden (Radeklint and Hjalmarsson, 1998). The initial configuration was a four-passage, 40°, annular sector of high-pressure nozzle guide vanes operated without film cooling. A large compressor unit was used, capable of delivering 10 kg s^{-1} at a pressure of 20 bar and a temperature of 200ºC. The mainstream flow was heated in a combustion chamber – oil-fired burner – to temperatures of up to 800ºC. The designers took considerable care in establishing engine-representative inlet boundary conditions, and, by introducing cooler air though the hub and the case platforms upstream of the test vanes, the radial temperature gradients that are present at the exit of a combustor were modelled. By using the technique of hot-wire anemometry, the freestream turbulence intensity was characterised (4 to 5 per cent). The test vanes were instrumented with thermocouples. An infrared camera was also used to conduct temperature measurements. By operating the experiment in several different *modes*, it was possible to calculate the cooling effectiveness, and the internal and external heat transfer coefficients. A short exit-duct with an abrupt expansion was used downstream of the test vanes.

A detailed annular sector study was conducted by Wiers and Fransson (1998; 2000), who investigated the influence on cross-sector periodicity of various tailboard and diffuser geometries. The facility that was used for the study was a five-passage annular sector, with two – smaller – bypass channels. The facility could operate continuously, with air supplied by 1 MW compressor at up to 4.7 kg s^{-1} at a pressure of 4 bar. The inlet temperature could be varied between 30ºC and 180ºC. An adjustable valve was used to set the downstream pressure. Very detailed measurements were conducted of the distributions of vane surface pressure, and end-wall pressure. To quantify the degree to which periodicity had been achieved across the sector, measurements of the circumferential pressure distribution were conducted on the hub and case walls at axial distances from the trailing edge equal to 9 per cent and 35 per cent of the vane axial chord respectively. Measurements were conducted across only the centre two passages of the cascade, however. Tests were conducted with a diffuser with a 12° flare angle, with an abrupt expansion, and with various combinations of right hand and left hand tailboards. The diffusers were in both cases situated at axial distances equal to 190 per cent of the axial chord downstream of the test vanes.

Interestingly, after extensive experimentation, the authors found that the best periodicity was obtained when the flow was allowed to exhaust as a free jet into the downstream plenum, with no flow conditioning whatsoever. For the two passages for which measurements were taken, the peak isentropic Mach numbers at hub were 0.87 and 0.84. The corresponding Mach numbers at the case were 0.81 and 0.80. The experiments demonstrate that reasonably periodic flow can be obtained across at least a limited part of an annular sector, by using the free-jet approach. The Wiers and Fransson (1998; 2000) investigation is probably the most comprehensive aerodynamic survey in an annular sector to date.

A novel annular sector facility has been developed for the study of aeroelastic behaviour of low-pressure rotor blades when subject to forcing (Vogt and Fransson, 2002). To allow some control over the periodicity of the flow-field downstream of the (9 passage) annular sector of rotor blades, sophisticated semi-flexible polyurethane sidewalls were employed. To mitigate the problems associated with exhausting swirling flow into a constant pressure plenum, a long exit-duct was used.

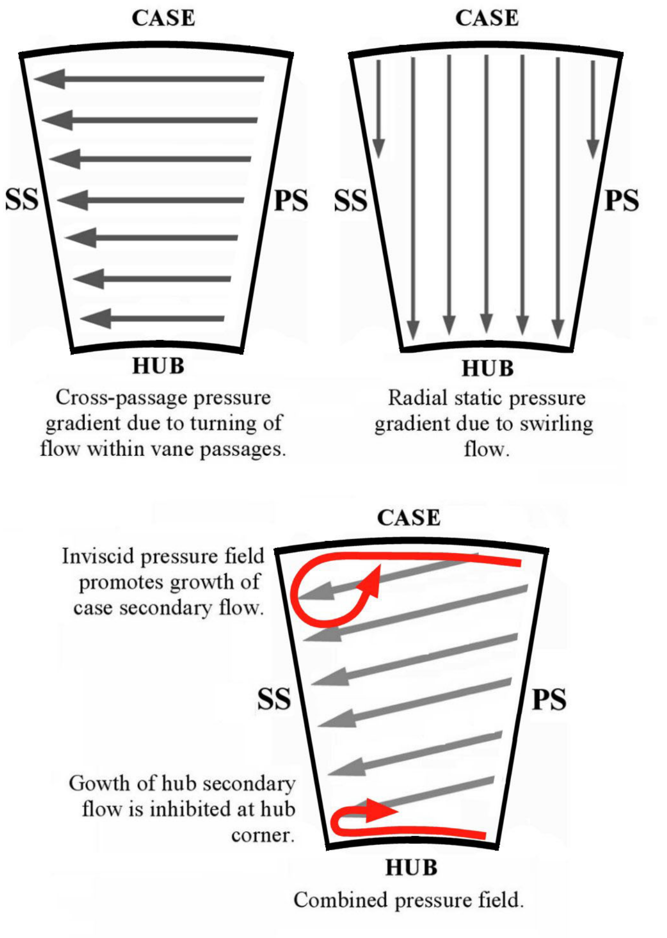
A novel technique for flow conditioning in annular sector experiments has been developed (Povey et al., 2004) that has been demonstrated – in a five-vane annular sector – to achieve very good vane-to-vane periodicity, whilst maintaining the radial pressure field established in the swirling flow downstream of the test vanes. The technique employs an annular sector of half-impulse-type deswirl vanes to condition the flow downstream of the test vane sector. The technique is reviewed in this paper, and the application to heat transfer experiments is discussed. A new annular sector heat transfer facility, in which engine nozzle guide vanes are to be tested, has been developed in Oxford, and is described.

PRESSURE GRADIENTS AND SECONDARY FLOW DEVELOPMENT

The radial pressure gradient established in regions of swirling flow contributes to the overall inviscid pressure field in such a way as to promote growth of the case secondary flow but to inhibit growth of the hub secondary flow. This is shown diagrammatically in Figure 1 – arrows point from higher to lower pressure. Although radial pressure gradients arise naturally in swirling flow, annular cascade experiments normally include only isolated turbine stages – or part stages – and the designer is therefore faced with the challenge of establishing representative conditions at inlet and exit of the cascade – the conditions that would exist in a working engine – which, in general, will be different from those conditions that would be achieved in the experiment in the absence of additional flow conditioning.

Cascade inlet conditions

In the working engine environment, there are radial and circumferential gradients in the combustor exit-flow of total temperature, total pressure and free stream turbulence. In general however, there is little swirl at combustor exit, and high-pressure nozzle guide vanes are usually designed for axial inlet flow. There have been very few experiments to date in which spatial variations in inlet flow properties have been simulated. In principle, it would be possible to establish a radial total pressure gradient upstream of a turbine stage by using gauzes with varying porosity, a technique that has been applied in studies of compressors but so far not of turbines. Similarly, if required, an inlet swirl angle distribution could be generated using inlet guide vanes, although wakes and secondary flows would present problems for the designer of such a system. In experiments in which heat transfer rates are to be measured, the importance is recognized of establishing the correct free stream turbulence intensity, and it is relatively common to include a turbulence grid upstream of (or within) the cascade inlet contraction. Turbulence grids are generally designed to generate uniform turbulence across the inlet plane.



Cross-passage pressure gradient due to turning of flow within vane passages.

Radial static pressure gradient due to swirling flow.

Combined pressure field.

Figure 1: Development of secondary flows in an annular cascade.

Cascade exit conditions

The radial static pressure gradient at the exit of an annular cascade will affect both the performance of the stage, and measurements made downstream of the stage. Although it may not be necessary to employ a rotor at the exit of a stationary cascade, some means of setting the boundary conditions is normally required. Perhaps the simplest means of flow conditioning, and, consequently, a commonly employed technique, is to allow the exit-flow to develop though an extended annulus of constant radius, and then to exhaust as a free jet to a plenum at constant pressure. This is shown diagrammatically in Figure 2a. In this scheme, it is usually the case that the vane exit static pressure at mid-span is close to the pressure of the downstream plenum. For swirling exit-flow therefore, in which a radial pressure gradient is established, the hub end-wall boundary layer is subject to an adverse pressure gradient towards the exit of the annulus. This can lead to flow separation. In the case of highly swirling exit-flow, the blockage and unsteadiness associated with separation can lead to disturbances in the upstream flow-field. Two problems in particular have been identified. Firstly, fluctuations in vane aerodynamics associated with unsteadiness, which are known to markedly affect even time-mean heat transfer rate distributions, and, secondly, deviation of the upstream flow induced by gross separation, and the associated possibility of redistribution of the vane exit radial velocity (and pressure) field. Under certain conditions of flow therefore, the extended constant annulus may be an inadequate solution to the flow-conditioning problem.

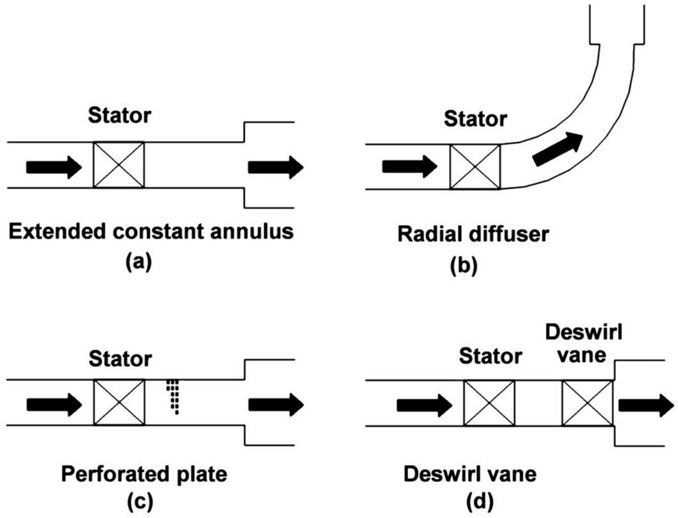


Figure 2: Methods of setting annular cascade exit conditions: (a) Extended constant annulus; (b) Radial diffuser; (c) Perforated plate; (d) Deswirl vane.

Several techniques have been developed to establish the correct exit boundary conditions in cascades with highly swirling exit-flow. The Whittle Laboratory at Cambridge University employs in a transonic annular cascade (Hodson and Dominy, 1993) a radial diffuser, as shown Figure 2b. By increasing the mean radius of the flow-path, by conservation of fluid angular momentum, the whirl velocity of the flow is reduced. This results in a small enough pressure difference between the hub and case boundary layers that the flow can be exhausted to a constant pressure plenum without flow separation. It is worth noting however, that only by very careful design can separation be avoided in the diffusive flow along the duct. Squire et al. (1986) employed perforated plates downstream of a test vane cascade. The plates had span-wise variations in open-area, allowing a radial pressure gradient to be established. The scheme is shown diagrammatically in Figure 2c.

The Oxford *deswirl system* (Povey et al., 2001, 2003), shown diagrammatically in Figure 2d, consists of a novel impulse-type vane (designed to turn flow towards the axial direction) and a downstream choke mechanism. Using this system, the radial pressure gradient established in the swirling flow downstream of the annular cascade of test vanes is undisturbed (in the region upstream of the deswirl vanes). The deswirl vane exit-flow is axial, and can be exhausted without unsteadiness to a downstream plenum at constant pressure. The system is also very compact, and mechanically robust.

The deswirl vane concept

The deswirl vane is shown schematically in Figure 3. The concept is that of an impulse-type vane truncated at half chord, where the flow direction is axial. The vane passage is of constant area (in a plane perpendicular to the stream-wise direction) and therefore, if boundary layer growth is neglected, there is no static enthalpy change or static pressure drop within the passage. In transonic flows it is desirable to maintain constant flow velocity, as acceleration of the flow can lead to shocks, whilst diffusion can result in boundary layer separation. In reality, the effect of boundary layer growth within the deswirl vane passage is to cause the mean stream-wise velocity to increase slightly. It would be a simple matter to design the vane passage to be mildly diffusive, to offset the effects on the velocity field of boundary layer growth, although this is not necessary. Experimental and computational studies demonstrate that for high subsonic deswirl vane inlet flow velocities ($M > 0.7$), areas of supersonic flow can develop within the vane passage, as the flow is accelerated over the suction surface. For deswirl vane inlet conditions from $M = 0.1$ to $M = 0.8$, separation within the passage was not observed in either computational or experimental studies however. The relatively sharp leading edge, aligned with the inlet flow, was designed to minimise leading edge shock formation. A CAD model of an annular cascade of deswirl vanes, is shown in Figure 4.

A COMPARISON OF FLOW IN AN ANNULAR SECTOR AND IN A FULLY ANNULAR CASCADE

Experiments were conducted in a fully annular cascade and in an annular sector cascade (partitioned from the same annular cascade) to determine the degree to which periodicity could be achieved in a test sector, when deswirl vanes were used in both instances to condition the downstream flow.

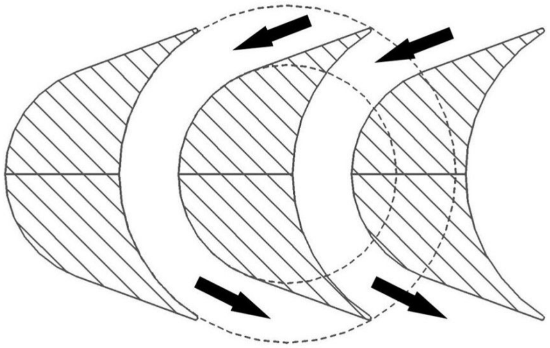
The experiments were conducted in a blow-down – atmospheric to vacuum – test facility at the University of Oxford. The annular facility, which was modular in design, is pictured in Figure 5. It consists of a curved inlet duct, an annular cascade of intermediate pressure (IP) guide vanes, an extended IP vane exit-duct, an annular cascade of deswirl vanes and a choke mechanism. The pressure boundary conditions of the test (IP) vane were first characterized in the fully annular environment. The annular facility was then modified, with the introduction of sidewalls (the designs of which are critical to the sector performance and are discussed below), and a comparative study performed.

The IP vane-count was 26 (0.270 engine scale), and 26 deswirl vanes were used for downstream flow conditioning. Both annuli of vanes were constructed from resin using the technique of stereo-lithography. The predicted area-mean IP vane exit-flow angle was 71.9˚, and the area-mean exit Mach number was 0.76.

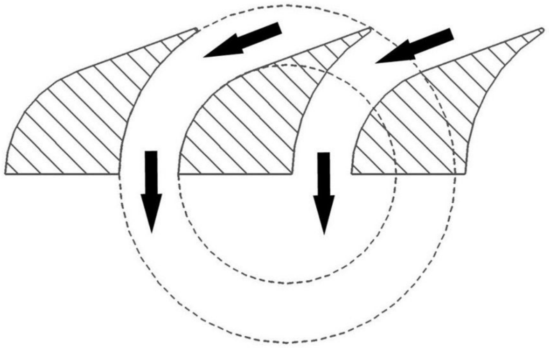
The design details and operating conditions of the facility are summarised in Table 1, below. The predicted deswirl vane inlet flow conditions were based on the results of a computational simulation conducted using the Rolls-Royce code JA63. The IP vane, IP vane exit-duct and deswirl system, were all included in the computational model.

The annular deswirl vane cascade and rotatable choke mechanism have been shown by experiment (Povey et al., 2001, 2003) to reproduce the radial pressure gradients downstream of an annular cascade of test vanes that exist in the working engine environment, in which the IP vane operates as part of an IP stage.

This paper reviews experiments which demonstrate the usefulness of the deswirl system not only in the fully annular environment, but also in the annular sector environment. If the deswirl system is used for flow conditioning downstream of a test vane, the problem of achieving engine representative flow conditions in the annular sector environment reduces to the problem of establishing periodicity. The degree of periodicity that is achieved is highly dependent on the sidewall design.



Impulse turbine



Deswirl vanes

Figure 3: An impulse turbine blade design, and the corresponding impulse-type deswirl vane.

The influence of sidewall profile on the sector flow-field, and on the periodicity at the IP vane exit-plane within the sector, was assessed by comparing pressure measurements conducted in sectors with different sidewall designs to measurements conducted in the fully annular facility. Two five-passage sector designs were investigated (6 IP vanes and 6 deswirl vanes, subtending an angle of 69.2º at the facility axis). Sector sidewalls were designed and manufactured (stereo-lithography hardened resin) so that they could be attached within the annular exit-duct of the test facility, thereby partitioning a sector of vanes. Thus, the same instrumentation could be used for both fully annular and annular sector tests. A CAD drawing of a four-passage sector (IP vanes removed) is presented in Figure 6 (a five-passage sector was used for experiments reported in this paper).

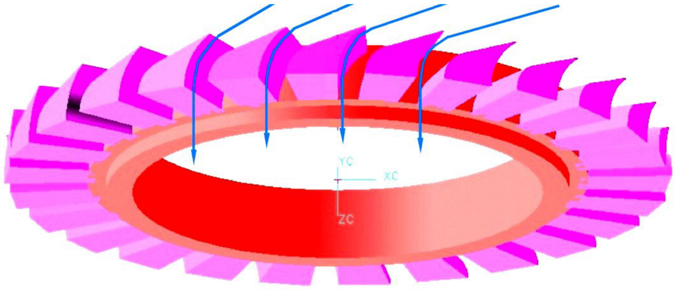


Figure 4: Annular cascade of deswirl vanes.

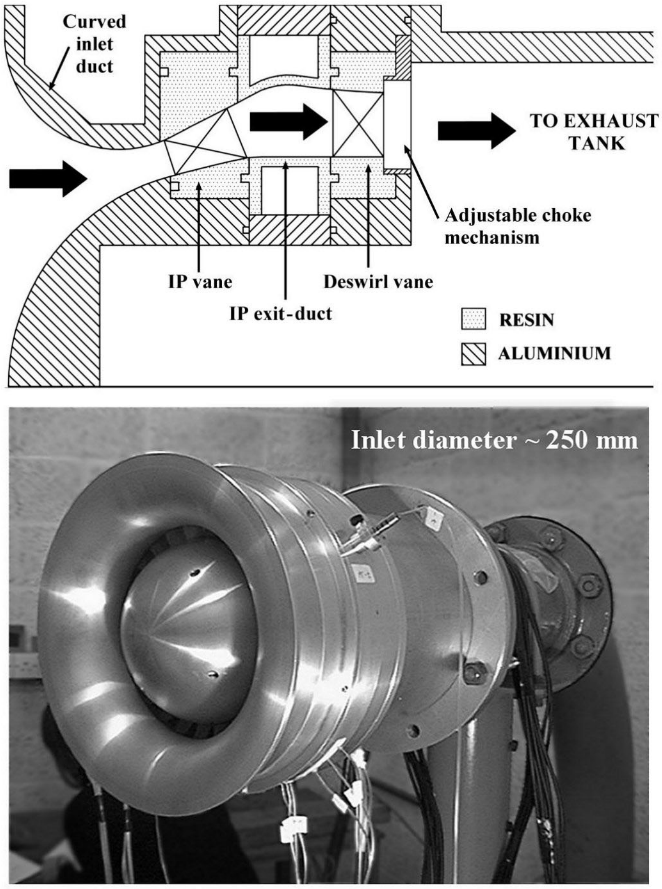


Figure 5: The working section of the test facility.

Parameter	*Target*
IP vane inlet total pressure, bar	1.00
IP vane inlet total temperature, K	291
Inlet Mach number	0.45
Inlet whirl angle	0º
IP vane axial chord (mid-span), mm	23.0
Linear scale factor	0.270
IP vane throat area, m^2	3.565×10^{-3}
Deswirl vane throat area, m^2	3.967×10^{-3}
Re based on IP vane axial chord (at $M = 0.76$)	2.88×10^5
Mass flow rate (at $M = 1.0$), kg s^{-1}	0.853
Predicted deswirl vane inlet Mach number	0.76
Predicted deswirl vane inlet whirl, degrees	71.9
Deswirl vane LE metal angle, degrees	63.1
Design incidence angle, degrees	8.8
Deswirl vane hub/case chord, mm	15.48/15.48
Deswirl vane hub/case pitch, mm	18.34/23.49

Table 1: Facility design details and operating conditions.

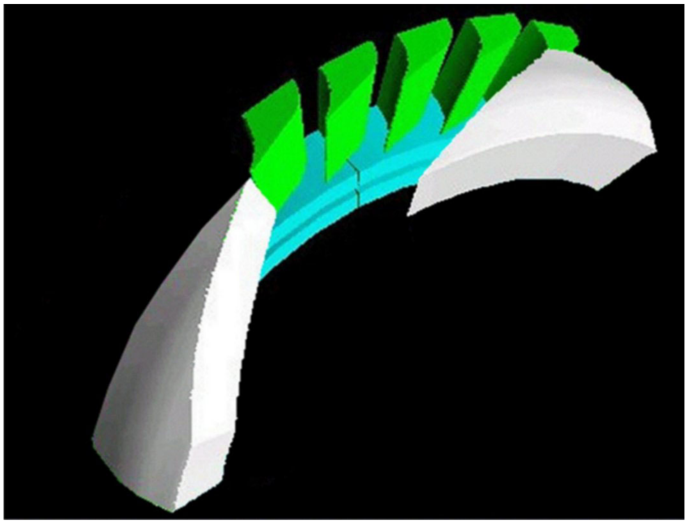


Figure 6: A four-passage annular sector of deswirl vanes.

Sidewall design philosophy

The annular sector is designed to reproduce the flow of a fully annular facility. The sidewalls must therefore cause the minimum possible deviation of the flow streamlines that would have developed in a fully annular cascade. The design is necessarily influenced, however, by the need to accommodate axial and tangential lean (or sweep) of the test vane at the test vane trailing edge, and therefore relatively three-dimensional sidewall designs are unavoidable.

The exit-flow of a vane cascade is often complex, with significant non-uniformities in velocity, whirl angle and yaw angle. For such a flow-field, an obvious starting point in the sidewall design process might be to match the angle of both the left-hand and right-hand sidewalls to the pitch-wise mean flow angle calculated at each radial height and at each axial plane. There are, however, many additional subtleties that must be considered in the design process if sufficiently periodic flow, with satisfactory overall diffusion/acceleration and the desired radial pressure gradient, is to result. If the flow is caused to turn in either direction by the sidewalls, for example, a cross-sector pressure gradient is established. This is most analogous to the cross-passage pressure gradient established within a guide vane passage. The angle of the sidewall about the axis, and the variation of this angle with axial distance, therefore exerts a pronounced influence on the periodicity of flow within the sector. Further general considerations pertaining to sidewall design are discussed by Povey et al. (2004). Measurements conducted for a number of different sector geometries are presented in the same paper.

In this paper, pressure measurements for only a single sector design are presented, and are compared to measurements conducted in the fully annular facility. The sector design is shown schematically in Figure 7. The sidewalls were parallel throughout the exit-duct, with a constant mid-span wall angle of 71.9º, matched to the mean predicted whirl angle (for the case of fully annular flow) at the deswirl vane inlet plane.

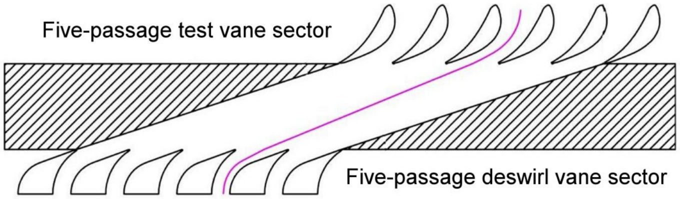


Figure 7: Schematic of sector sidewall design.

The lowest test vane pressure ratio at which the sector was operable was determined by the ratio of effective areas of the test vane and the deswirl vane, and was such that test vanes could be operated choked. Higher-than-minimum downstream pressures were effected by adjusting the downstream choke mechanism (by increasing the blockage).

INSTRUMENTATION AND PROCESSING

Static pressure measurements were conducted throughout the sector duct. Particular emphasis was placed on measuring the circumferential distributions of static pressure at the IP vane exit plane, however, so that the degree of (vane-to-vane) periodicity could be quantified. Measurements were made at circumferential intervals of ½ a vane pitch on both the hub and case walls. These measurements are presented in this paper. The same pressure tappings were used for both the fully annular tests and the sectors tests.

EXPERIMENTAL RESULTS

As we have noted, the principal objective in the aerodynamic design of an annular sector cascade is to reproduce exactly the flow conditions that would exist in the equivalent fully annular facility. It may reasonably be assumed that if inlet and exit flow boundary conditions identical to those measured in the equivalent fully annular cascade are established across all or part of an annular sector cascade, then across this part of the annular sector cascade the flow conditions will be identical to those in the fully annular facility. This will be assumed in the following discussion. Although measurements were conducted throughout the sector, for brevity, only selected pressure distributions are presented.

The measured circumferential pressure distributions at the IP vane exit plane for the case of fully annular flow are presented in Figure 8, at the hub and the case walls, at a range of downstream blockages. The blockages, expressed as a percentage of the total deswirl vane throat area, were 0, 5 and 10 per cent. The pressures have been non-dimensionalised by dividing by the inlet total pressure, and are plotted against IP vane pitch. The sign convention is such that pitch increased from the suction to pressure surface of the vane. Small pitch-to-pitch differences in measured pressure arise because of the slight aperiodicity of the pressure tappings – the minimum spacing was only 4.5 mm. In general, the flow was highly periodic, as expected: the IP and deswirl vane counts were the same, ensuring pitch-to-pitch flow-path similarity.

Measurements conducted in the annular sector are presented in Figure 9. The same conditions of downstream blockage were used as for the fully annular tests. Excellent periodicity was obtained across the left-hand four passages of the sector (minimal cross-sector pressure gradients). For 10 per cent blockage, at the hub, the variation in mid-passage pressure ratio across the four passages was between 0.540 and 0.570, corresponding to a Mach number range between 0.98 and 0.94. At the case, the variation in mid-passage pressure ratio across the four passages was 0.660 to 0.675, corresponding to a Mach number range of 0.79 to 0.77. In these four passages, the forms of the measured distributions agreed very well with the measurements conducted in the fully annular environment.

The results demonstrate the suitability of the deswirl vane for setting annular sector boundary conditions. For heat transfer or aerodynamic studies in which engine representative flow is required in only a single passage, this degree of periodicity would be highly satisfactory. When the central passage (for example) is exactly matched to the target operating point of the vane, by adjusting the downstream blockage, adjacent passages would be matched in terms of pressure ratio to within 1.9 per cent at the hub and to within 0.8 per cent at the case. (For clarity, it is worth noting that because the flow was accelerated slightly by turning it away from the axial direction, the measured pressures were lower in the annular sector than for fully annular flow. Greater blockage was therefore required to achieve the same test vane pressure ratio.)

Consider the region of elevated pressure in the right-most passage. For 10 per cent blockage, the mid-passage pressure ratios at the case and hub were 0.76 and 0.68 respectively. The corresponding measurements in the adjacent passage were approximately 0.66 and 0.54. There are two causes of this region of elevated pressure. Because the sidewall angle (71.9º) is greater than the IP vane pressure surface metal angle (69.7º) the location of the throat of the right-hand passage is moved from the trailing edge (of the far right-hand vane) to the trailing edge of the adjacent vane. Thus, the right-most tappings are upstream of the throat, and high measured pressure is therefore expected. There is a region of high pressure up to a vane pitch spacing from the wall, however, and this is caused by overturning of the IP vane exit flow. The mean metal angle is 65.7º, whilst the sidewall angle is 71.9º. The flow is therefore turned away from the axial by approximately 6.2º. As it is only necessary to achieve representative conditions in a single passage of the sector, a small region in which the flow is not periodic is of little concern to the designer of the annular sector cascade.

Measurements conducted downstream of the test vane sector, at the deswirl vane inlet plane, demonstrated that the flow here was highly periodic, and confirmed that the radial pressure gradient established in the swirling flow had not been disturbed, even far downstream of the test vanes.

FLOW VISUALIZATION EXPERIMENTS

Flow visualization experiments were also conducted using an oil-paint method, to better understand the flow within the sector passage. The experiments confirmed that the flow within the exit-duct was well behaved, and that there were no separations. The analogy between secondary flow development within an annular sector and a single nozzle guide vane passage was also demonstrated. The results are discussed by Povey et al. (2004).

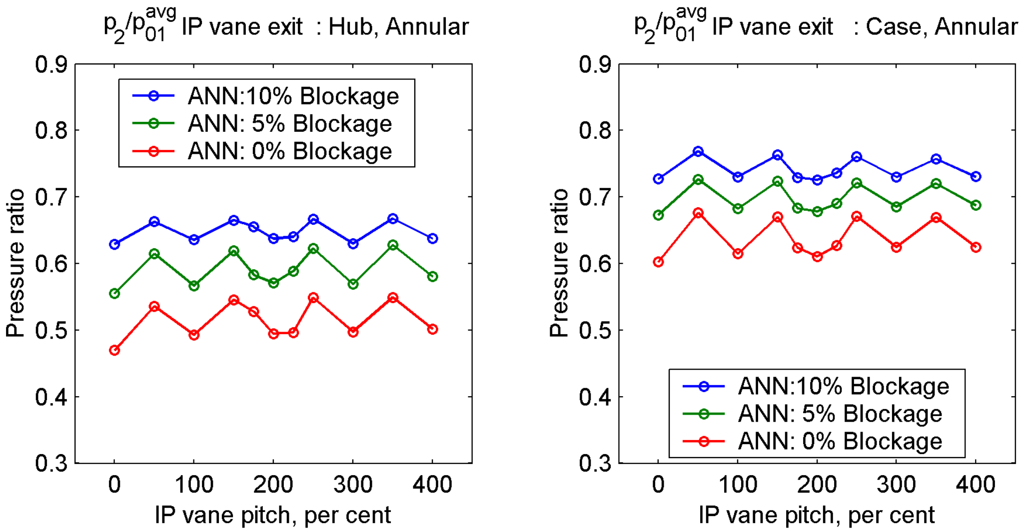


Figure 8: Circumferential pressure distributions at the IP vane exit plane hub and case walls: Fully Annular Cascade.

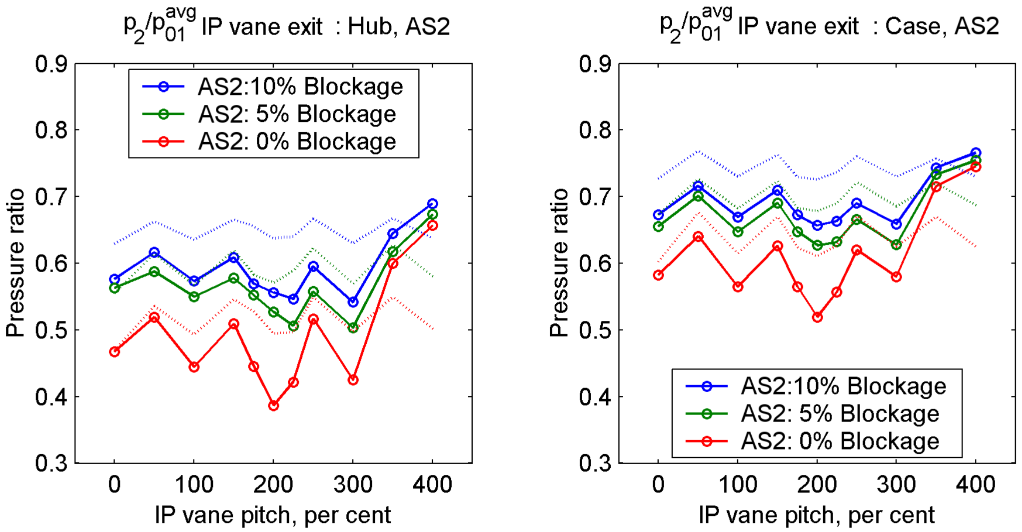


Figure 9: Circumferential pressure distributions at the IP vane exit plane hub and case walls: Annular Sector.

THE OXFORD ANNULAR SECTOR HEAT TRANSFER RESEARCH FACILITY

A new annular sector heat transfer research facility has been developed in Oxford for the measurement of the steady-state surface metal temperature distributions of modern highly film-cooled nozzle guide vanes. The facility capitalizes on the success of the deswirl vane technology in establishing engine-representative pressure boundary conditions in the sector environment. It will provide a relatively inexpensive means for conducting measurements of vane metal temperature and film-cooling effectiveness for actual engine components, in an environment in which both thermal and aerodynamic similarity – to engine conditions – can be achieved. A significant reduction in the costs of both facility manufacture and operation are possible because the sector facility operates with only a fraction of the mass flow rate required for a fully annular facility (12 per cent to 20 per cent of annular mass flow rate). Thus, sufficiently long run times (100 s or more) are possible using a regulated blow-down-type facility that vane metal temperatures reach equilibrium. A schematic of the facility is shown in Figure 11.

FACILITY MANUFACTURE

The facility was designed to be modular (Figure 11), to allow for rapid interchangeability of the test vane sector and the deswirl vane sector. The former are engine components, whist the latter were manufactured from resin using the technique of stereo-lithography hardening, and were formed as a single component with integral sidewalls. Both are pictured in Figure 10. The sector sidewalls were also manufactured using the stereo-lithography technique.

The test vane sector was clamped in place between two plates with integral feel slots, into which was machined a sector-shaped slotted recess, as shown in Figure 11. The deswirl vane sector was housed in a similar manner, in a slot which was extended circumferential so that clocking with respect to the test vane sector was possible: this allows the sector sidewalls to be altered without requiring facility design changes.

FACILITY COMMISSIONING AND GENERAL OPERATION

The facility has been designed so that, in the first instance, a five-passage sector of high-pressure nozzle guide vanes can be tested. At an upstream total pressure of $p_0 = 2.2$ bar, and at ambient inlet total temperature, the predicted overall mass flow rate though the test sector at choked conditions is approximately 2.0 kg/s. Using air at ambient temperature both Mach number and Reynolds number can be matched to engine conditions.

Figure 10: The test vane sector (engine components) and the deswirl vane sector (resin).

The maximum run time of the facility in this configuration is approximately 200 s. To commission the facility, heated air at the correct momentum flux ratio will be will be used for 'coolant' films. The hub and case streams are independently regulated and metered, as indicated in the schematic in Figure 11, and are fed from the same air supply as the main stream. A coolant-to-mainstream temperature difference of approximately 30 K will be established, so that wide-band thermochromic liquid crystals can be used to transduce the test vane surface temperature distribution. Miniature video cameras inserted though ports in the cascade housing, as shown in Figure 12, will be used to record the surface temperature once thermal equilibrium has been reached. Calibration of the liquid crystals will occur in situ.

A brief analysis of the dimensional scaling necessary to achieve full aerodynamic and thermal similarity with engine conditions is given below. Depending on the level of similarity required, which must be appropriate to the measurement, either heated 'foreign gas' (see below) or highly cooled air (a liquid nitrogen heat exchanger) must be used for the coolant stream. Provision has been made in the design of the facility to incorporate both such systems.

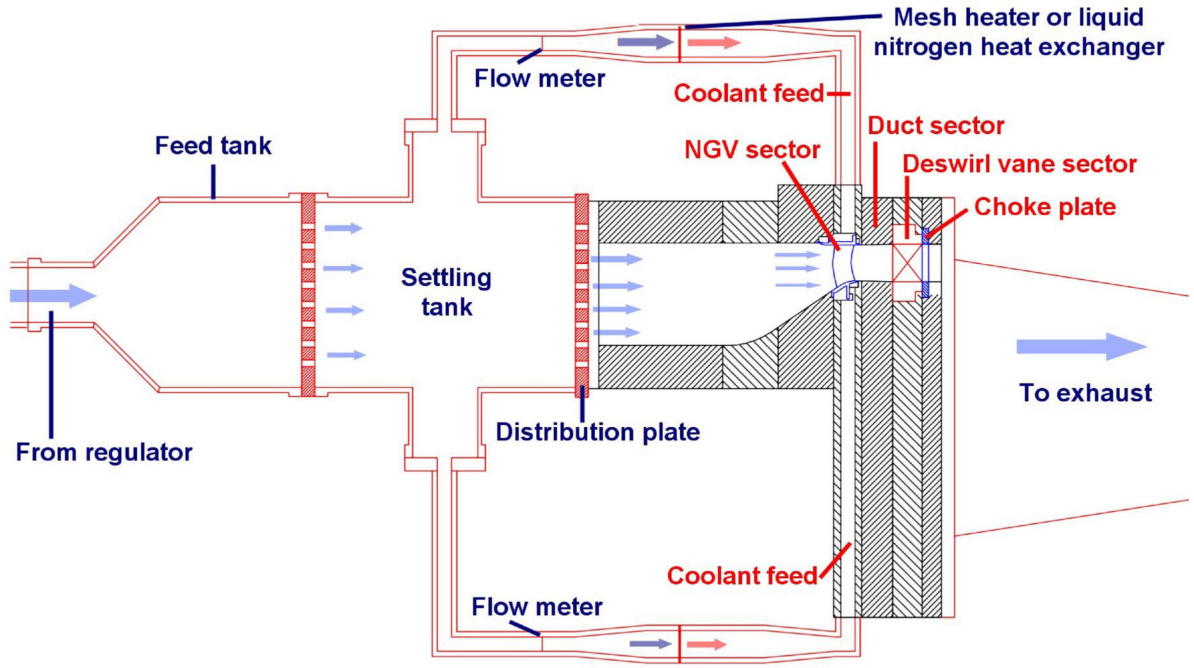


Figure 11: Schematic of the Oxford annular sector heat transfer facility.

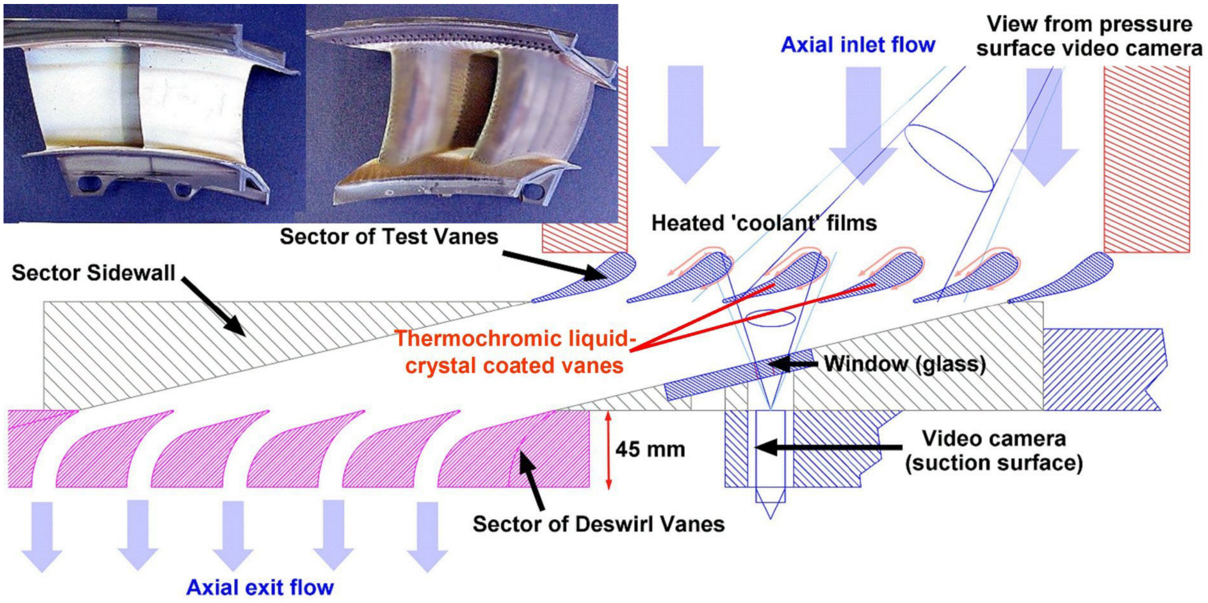


Figure 12: Schematic of the working section of the Oxford annular sector heat transfer facility.

DIMENSIONAL SCALING

The equations of motion for compressible viscous flow can be reduced (see, for example, Lakshminarayana, 1996) to the following dimensionless groups:

Mach number	$M = v/a$
Reynolds number	$\mathrm{Re} = \rho v L/\mu$
Prandtl number	$\mathrm{Pr} = \mu c_p/k$
Ratio of specific heats	$\gamma = c_p/c_v$

In the engine environment, coolant and mainstream flow temperatures of order 800 K and 1600 K are typical. The coolant-to-mainstream density radio is therefore of order $\rho_c/\rho_m = 2.0$. For aerodynamic testing it is therefore also important to model experimentally this density difference. This is usually achieved by using a dense 'foreign gas' for the coolant flow stream. This avoids the difficulties associated with generating and managing gas streams with large temperature differences.

The use of foreign gas to simulate density differences between the coolant stream and the main flow stream has been studied by Teekaram et al. (1989), in the case of heat transfer experiments, and by Day et al. (1997), in the case of aerodynamic experiments. It is now a widely used technique. A discussion of the extent of overall flow-field similarity that may be achieved for a number of different foreign gas mixtures is given by Jones (1999).

With the correct choice of foreign gas mixture it is possible to simultaneously match – at least approximately – all of the parameters listed above, on both the internal and external surfaces of the vane, whilst approximately matching the density ratio, where

Density ratio	ρ_c/ρ_m

Two gas mixtures that are relatively inexpensive, and for which the value of γ can be exactly matched to the value for cooling air (~1.4) are, by weight, 30% SF_6 and 70% Ar, and 55% CO_2 and 45% Ar. Where mixing processes affect heat transfer processes, such as in the turbulent mixing of cooling films on the vane surface, the ratio of the heat specific heats of the coolant flow and the main flow c_p^c/c_p^m must also be correctly matched to engine conditions to achieve non-dimensionally representative mixed out gas temperatures (and therefore cooling effectiveness). An exact match is not possible for most foreign gas mixtures, and therefore a small correction is usually required (Jones, 1999). For this reason, a foreign gas mixture of CO_2 and Ar (or CO_2 and air) is often preferred, as the correction factor is smaller than for most other mixtures.

For film-cooled vanes, in addition to the non-dimensional groups listed above, it is necessary to consider the aerodynamic interaction of the films with the main flow. Parameters of interest include (see, for example, Lakshminarayana, 1996):

Blowing rate ratio	$B = \rho_c v_c/\rho_m v_m$
Mass flow rate ratio	$\rho_c v_c A_c/\rho_m v_m A_m$
Momentum flux ratio	$I = \rho_c v_c^2/\rho_m v_m^2$

Where aerodynamic similarity is paramount, Day et al. (1997) advocate matching the effective blockage caused by the surface coolant films. To do so, it is necessary to match the momentum flux ratio.

Finally, consideration must be given to the ratios of the conductivities of the coolant gas, mainstream gas and metal. It is usually not possible to match these to engine conditions exactly, and therefore a small correction is often required.

It is clear that, with care, it is possible to match to a reasonable approximation both the thermal and aerodynamic boundary conditions in an annular sector cascade to those of the engine environment. It is not necessary to achieve exact matching however, as very powerful comparisons can be made directly, between different cooling system designs, or indirectly, by using data for validation of computational predictions, provided that the most important non-dimensional parameters are well matched.

CONCLUSIONS

A direct aerodynamic comparison has been conducted of the flow in an annular cascade facility, with that in an annular sector facility of five vane passages.

In the fully annular cascade, engine representative pressure boundary conditions for a test vane cascade were established by using deswirl vanes, which allow even highly whirling transonic flow to be exhausted without unsteadiness to a plenum at constant pressure.

By partitioning a five-passage sector of test vanes, and by using a sector of deswirl vanes for downstream flow conditioning, the applicability of the deswirl technology to the annular sector boundary condition problem was investigated. Excellent periodicity was obtained across most of the sector, and it was demonstrated that the radial pressure gradient downstream of the test vanes (established in the swirling exit-flow) was not disturbed. Fully engine-representative pressure boundary conditions can therefore be established using only a small number of test vanes. The technique represents a significant improvement over previous methods.

The new technique is well-suited to the testing of highly three-dimensional vane profiles, and it is hoped that it will allow designers to exploit the obvious advantages of annular sector cascade testing: the reduced cost of both facility manufacture and operation, and the use of engine parts in place of two-dimensional counterparts.

For heat transfer investigations of modern high-pressure turbine vanes/blades, components that are, in general, highly three-dimensional and which have very complicated cooling systems, it is becoming unsatisfactory to use anything but actual engine components. For these critical components, the geometry, film-cooling flows and pressure gradients must all be simultaneously correct for the results of experimental studies to be regarded as truly engine-representative. The applicability of the new annular sector technique to such experiments is clear, and a new heat transfer research facility has been developed in Oxford to pilot the technique.

The new facility will be used, in the first instance, for measurement of the steady-state surface metal temperature distribution of a modern highly film-cooled nozzle guide vane.

It is hoped – more generally – that the technique will provide a relatively inexpensive means for conducting similar measurements (of vane/blade metal temperature distributions and film-cooling effectiveness) of actual engine components, in an environment in which both thermal and aerodynamic similarity – to engine conditions – can be achieved. A significant reduction in the costs of both facility manufacture and operation are possible because a sector facility operates with only a fraction of the mass flow rate requirement of a fully annular facility (12 per cent to 20 per cent of annular mass flow rate). Long run times are therefore possible using blow-down-type facilities.

The novel techniques described in this paper offer a number of improvements over previous cascade methods, and have applicability to both aerodynamic and heat transfer studies. The application to the measurement of film-cooling effectiveness (or surface heat transfer rate) using actual engine-parts (both nozzle guide vane and rotor) is perhaps the most exciting of these possibilities.

REFERENCES

Day, C.R.B., Oldfield, M.L.G., Lock, G.D., 1997, "The influence of film cooling on the efficiency of an annular nozzle guide vane cascade," ASME paper 97-GT-521.

Gladden, H.J., Gauntner, J.W., 1975, "Experimental verification of film-cooling concepts on a turbine vane," ASME 75-WA/GT-21.

Hirsch, H., (Editor), 1993, "Advance methods for cascade testing," AGARDograph 328, AGARD-AG-328.

Hodson, H.P., Dominy, R.G., 1993, "*Annular and Rotating Cascades"*, AGARDograph 328, Chapter 3, AGARD-AG-328

Jones, T.V., 1999, "Theory for the use of foreign gas in simulating film cooling," International Journal of Heat and Fluid Flow, 20 (1999) pp. 349-354.

Lakshminarayana, B., 1996, "Fluid dynamics and heat transfer of turbomachinery", John Wiley and Sons.

Povey, T., Jones, T.V., Oldfield, M.L.G., 2004, "On a novel annular sector cascade technique", ASME paper GT2004-53904.

Povey, T., Chana, K.S., Oldfield, M.L.G., Jones, T.V., Owen, A.K., 2001, "The design and performance of a transonic flow deswirling system", Proceedings of the IMechE Advances of CFD in Fluid Machinery Design Seminar, London 13 June 2001.

Povey, T., Chana, K.S., Jones, T.V., Oldfield, M.L.G., 2003, "The design and performance of a transonic flow deswirling system – an application of current CFD design techniques tested against model and full-scale experiments." In: (Editors) Elder, R.L., Tourlidakis, A., Yates, M.K., "Advances of CFD in fluid machinery design," IMechE Professional Engineering Publishing: pp. 65-94, ISBN 1 8058 353 9.

Radeklint, U.R., Hjalmarsson, C.S., 1998, "A new test facility for testing of cooled gas turbine components," ASME Paper Number 98-GT-557.

Squire, L.C., 1986, "Effects of Probe Supports on Measurements in Steam Turbines," ASME Paper Number 86-GT-213.

Teekaram, A.J., Forth, C.J.P., Jones, T.V., 1989, "The use of foreign gas to simulate the effect of density ratio in film cooling," ASME Journal of Turbomachinery 3, pp. 57-62.

Wiers, S.H., Fransson, T.H., 1998, "A new annular sector cascade test facility to investigate steady state cooling effects," 14th Symposium on Measuring Techniques in Transonic and Supersonic Flow in Cascades and Turbomachines, University of Limerick, 1998.

Wiers, S.H., Fransson, T.H., 2000, "Experimental investigation of the periodicity in a sector of an annular turbine cascade," 15th Bi-annular symposium on Measuring Techniques in Transonic and Supersonic Flow in Cascades and Turbomachines, Firenze, Italy, 21st to 22nd September 2000.

Vogt, D.M., Fransson, T.H., 2002, "A new turbine cascade for aeromechanical testing," presented at The 16th Symposium on Measuring Techniques in Transonic and Supersonic Flow in Cascades and Turbomachines, Cambridge UK, September 2002.