THE WHITTLE LABORATORY
TRANSONIC ANNULAR CASCADE WIND TUNNEL

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ABSTRACT

A new research rig has been constructed at the Whittle Laboratory, Cambridge for aerodynamic studies in an annular cascade of high pressure stator blades. The rig makes use of the laboratory´s continuously running transonic, closed circuit wind tunnel in which the density and pressure ratio can be varied independently. For a typical nozzle guide vane configuration this allows Mach numbers in excess of 1.3 to be achieved over a range of Reynolds numbers from 1×10^5 to 1×10^6.

Research using this rig places emphasis on the study of secondary flows. The rig instrumentation includes a three-axis traverse which allows measurements to be made both downstream from the cascade and within the blade passages.

The facility is constructed in a modular fashion which permits geometrical changes to be made simply and cheaply, enables easy handling of the various rig components and greatly simplifies rig instrumentation.

INTRODUCTION

A part of the loss of available energy that occurs in axial flow turbines arises from the essentially two-dimensional flow of the fluid over the blade sections. Typically this accounts for less than half of the total fluid dynamic loss in the turbine although the proportion varies significantly with turbine geometry. These two-dimensional flows have been widely investigated both experimentally and computationally, not least at the Whittle Laboratory. The remaining ´three-dimensional´ losses result from such influences as rotation and radial pressure gradients, tip clearances, seal leakage, interactions between rotors and stators and wall boundary layers. In the absence of tip leakage and rotation effects the character of the near-wall flow through the blade passages depends critically upon the boundary layers on the annulus walls at inlet to the blade row. Secondary flows develop which redistribute the ´old´ loss in the inlet boundary layers and which result in the growth of new wall boundary layers with their associated loss generation.

Moves towards higher pressure ratios and higher turbine entry temperatures in modern aero engines result in smaller core mass flows for a given thrust with correspondingly smaller components. This leads to low aspect ratio, high hub/tip ratio designs in which the proportion of the overall loss that is attributable to secondary flows is high. Manufacturers are also driven towards low aspect ratio designs with their associated 3-D losses by commercial and reliability constraints which require turbines to be designed with the minimum number of vanes and blades. The ability to control and minimise secondary losses is therefore becoming increasingly important.

The annular cascade wind tunnel has been commissioned to investigate in detail the nature of the transonic, secondary flows in nozzles that are fully representative of current designs both to gain a better insight into the control of secondary flows and to provide the detailed experimental data that are essential for the validation and development of the latest generation of viscous, three-dimensional numerical prediction methods.

THE RIG

The annular cascade research rig (fig. 1) is installed in the Number 2 wind tunnel of the high speed laboratory of the Whittle laboratory. The wind tunnel forms part of a closed circuit, variable density ($0.04 < \text{density} < 2.4$ kg/m3) system in which the Mach number and Reynolds number can be controlled independently [2].

The rig is constructed in a modular fashion in order to maximise its flexibility, thereby allowing it to be adapted for future projects by changing or modifying specific modules whilst retaining many common parts. Further advantages of the modular design include ease of access to all parts of the rig and ease of assembly since each module is of manageable size and weight. All of the hub sections are hollow to allow access for instrumentation and inspection.

Air is supplied to the working section via a contraction which reduces the inlet duct area from $0.43m^2$, corresponding to a 0.74m diameter inlet pipe, to an annulus area of $0.033m^2$ (hub diameter 0.357m, casing diameter 0.412m). This leads into a short, parallel section which is included to allow boundary layer control techniques to be applied to the hub and casing upstream of the blade row. For these initial studies the walls of the cascade working section are also straight and parallel to the wind tunnel axis. The blades are mounted from the casing end only and silicone sealant is applied at both the hub and tip of each blade to prevent leakage. Four of the blades are mounted in a removable perspex cartridge and a matching, perspex window is set into the hub. Since the arrangement of surface pressure tappings and other types of instrumentation is often specific to a particular cascade the use of interchangeable cartridges allows a variety of cascades and instrumentation techniques to be used without the need for the replacement of the entire blade row casing. Further benefits are ease of access for the inspection and recording of passage surface flow visualisation patterns and the ability to prepare one cartridge with its appropriate instrumentation whilst performing tests using another. The use of perspex allows optical access to three blade passages.

A three-axis traverse mechanism enables detailed measurements to be made of the flowfield at exit from the cascade and provides limited access to the flow within the blade passages. Circumferential motion is achieved by rotating a complete section of the casing relative to the fixed blades. Radial traversing is provided by a motorised linear ball slide which is itself rigidly mounted to a rotary table allowing the probes to be yawed about a radial axis. All three traverse axes are stepper motor driven and they are controlled remotely by the High Speed Laboratory's control and data logging computer system.

In order to achieve transonic cascade exit flow conditions at high mass flow rates using the existing compressors it is necessary to diffuse the flow from the cascade before it exhausts into a large, enclosing plenum. In the light of the results from model testing [1] a simple, circular arc radial diffuser has been adopted to achieve the required result. Two compressors are available to supply air to the system and these may be operated either in series for maximum pressure ratio or in parallel to achieve high mass flow rates (table 1).

The scale of the rig is governed largely by restrictions that are imposed by the available air supply but conveniently this allows an annulus size to be chosen that is representative of the full scale core of a medium sized aero engine (40kN sea level dry static thrust class). Commonality of blading components between Rolls-Royce plc. and the Whittle Laboratory is thus possible.

The required wind tunnel operating conditions for such a project (Cascade exit Reynolds numbers from 1×10^5 to 1×10^6; Mach numbers from 0.5 to 1.2) are adequately met by the available air supply.

	Available PRESSURE RATIO	Maximum MASS FLOW [kg/s]
Compressor 1	2.5	4.6
Compressor 2	1.6	7.0
Compressor 1 & 2 [parallel]	1.6	11.6

STAGNATION TEMPERATURE at Cascade Inlet : 290 - 310K
Maximum POWER CONSUMPTION : 1.125 MW

Air Supply to the Transonic Wind Tunnels
Table 1

RIG PERFORMANCE

Details of the geometry of the first research nozzle are provided in table 2.

At inlet to the blade row neither 3-hole probe measurements nor hub and casing surface oil flow reveal any detectable swirl.

The inlet wall boundary layers have been measured, with the blades removed, at an axial plane corresponding to the leading edge of the initial cascade. These are shown in figure 2. In terms of displacement thickness to chord ratio the hub and casing inlet boundary layers have values of 0.006 and 0.008 respectively at the nominal design exit flow conditions (Mach number = 0.82, Reynolds number = 9×10^5).

Hub Diameter	0.357 m
Tip Diameter	0.412 m
Hub / Tip Ratio	0.867
Annulus Area	0.033 m^2
Number of Blades in Cascade	34
Blade Chord	0.040 m
Blade Height	0.028 m
Inlet Flow Angle	0.0 degrees
Mean Exit Flow Angle	65.0 degrees
Reynolds Number (at Cascade Exit)	1.0×10^6
Mach Number Range (at Cascade Exit)	0.7 - 1.05

Cascade Geometry (1st Build)
Table 2

Without any deliberate generation of inlet turbulence the free stream turbulence measured at inlet to the cascade is 0.8%. This level of turbulence increases to 3.2% by the addition of an upstream turbulence grid.

The diffuser provides a pressure recovery equal to 50% of the isentropic exit dynamic head ($P_{01} - P_2$) with 65 degrees of swirl at inlet to the diffuser.

The periodicity of the flow is shown clearly by the loss contours of fig.3 and also by the blade surface oil flow visualisation of fig. 4. Of particular interest is the blade to blade repeatability of a local separation that occurs near mid span (fig. 4) where the blade camber is greatest on these highly three-dimensional vanes.

MEASUREMENT TECHNIQUES

Static pressures on the blade surfaces are measured within a single passage chosen from the three passages formed by the cartridge mounted blades. The basic instrumentation consists of a row of 0.25mm diameter pressure tappings at mid-span on both the suction and pressure sides of the passage. On some vanes additional, similar tappings are added at different radial locations. Typically there are between 12 and 20 static pressure tappings on each surface at any given radial position. In order to minimise any disturbance of the instrumented surfaces the static pressure tappings are connected to the pressure measurement system by internal spanwise pathways which are drilled along the length of the blades. When this is not possible, for instance in the case of some parts of highly twisted and bowed blades, hypodermic tubing is laid in slots which are cut into the blade surface. Epoxy resin is used to return the blade surface to its original profile.

Wall static pressure tappings may be positioned in the hub and casing blade cartridges located, as required, for the cascade under investigation.

The static pressure at inlet to the cascade is measured on both the hub and casing using 0.25mm diameter pressure tappings which are located at approximately one third of an axial chord upstream from the leading edge plane. A conventional pitot is positioned at the same location for the measurement of the inlet stagnation pressure. In order to establish the correct operating conditions for the cascade the inlet stagnation pressure and exit static pressure must be known. The latter is taken as the average of six individual pressure measurements, three on the hub and three on the casing, which share a common axial position downstream from the trailing edge plane.

The inlet stagnation temperature, which typically ranges from 290K to 310K, is measured using a single thermocouple in the low speed flow upstream of the inlet contraction and working section.

The small scale of the blade passages and their associated flow phenomena dictates the requirement for probe miniaturisation in order to achieve acceptably high resolution of the flowfield and to minimise any flowfield disturbances. Considerable effort has therefore been put into the development and construction of accurate and reliable miniature probes and into an investigation of the Reynolds Number sensitivity of such probes [3].

Downstream from the cascade a five-hole cone probe is used to investigate the flowfield at various planes. The probe is aligned with the nominal mean exit flow direction and the local flow angles, Mach number and total pressure are determined from the probe calibration. Integration of these local values is then carried out using a constant area mixing calculation in which the equations for the conservation of mass, momentum and energy are applied to provide the mixed-out values of the cascade efficiency, exit flow angle, Mach number and other required conditions. Exit area traverses are also performed using a pitot rake in cases where the measurement of the total pressure field is sufficient. Close to the casing, where probe / wall proximity effects are inevitable, measurements are made using a miniature flattened pitot probe and are therefore limited to total pressure only.

In order to investigate the early development of secondary flow phenomena it is necessary to perform limited area traversing within the blade passage. To minimise the blockage caused by the probe a single pitot tube (typically 0.8mm diameter) is adopted.

The boundary layer profiles at the cascade inlet, on the passage endwalls and on the blade surfaces are measured by traversing a flattened pitot tube (0.14mm thickness) from the free stream or some other appropriate datum to the blade or endwall surface. The exact point at which the probe touches the surface is determined by electrical contact. The velocity and density profiles are then determined once the local static pressure and inlet total temperature are found.

Further boundary layer information, in particular with regard to boundary layer state, is routinely collected from hot wires and surface mounted hot-film gauges. Details of the hot film technique have been widely reported (e.g. [4]).

The interpretation of the measured data is significantly enhanced by the use of surface oil flow visualisation. For this work a non-evaporative method has been adopted using silicone oil containing a fluorescent pigment in suspension. The results are photographed whe illuminated by ultraviolet light. For secondary flow studies more tha one pigment may be used in order to trace the source of the gas flow that are revealed by the surface patterns. An example of the highl complex surface flows arising in low aspect ratio, transonic nozzle is shown in Figure 5. The photograph shows the effects of the tw passage vortices and their relative spanwise extents influenced by th radial pressure gradient. Also shown is a closed separation bubbl with radially inward fluid migration evident in the separated region. These features can be matched to the corresponding loss distributio across the span at the trailing edge plane (figure 6).

CONCLUSIONS

A transonic annular cascade facility has been designed constructed and successfully commissioned at the Whittle Laboratory Cambridge. This facility permits the detailed aerodynamic study o nozzles that are fully representative of current designs at thei correct Mach numbers and Reynolds numbers and it provides th flexibility to accommodate a wide range of future research projects.

ACKNOWLEDGEMENTS

The design and construction of this rig and the initial annula cascade research project were carried out under the joint Rolls-Royc plc. and S.E.R.C. funding (S.E.R.C. Grant Ref. GR/C/86051).

The contributions of numerous individuals during the course o this work have been greatly appreciated, in particular those of Dr. D.S. Whitehead, the instigator of the project, Drs. J.D. Denton, H.P. Hodson and J-J. Camus at the Whittle Laboratory and also Mr. J.P Simons and Mr. C.G. Graham of Rolls-Royce plc.

REFERENCES

1. Heyes, F.J., "Investigation of the Flow in a Radial Diffuser", Part II Project Report, Cambridge University Engineering Dept., Cambridge, 1986.

2. Gostelow, J.P. and Watson, P.J., "A Closed Circuit Variabl Density Air Supply for Turbomachinery Research", ASME 76-GT-62, 1976.

3. Hodson, H.P. and Dominy, R.G. "An Investigation into the Effect of Reynolds Number and Turbulence upon the Calibration of 5-Hol Cone Probes", 9th Symposium on Measuring Techniques for Transoni and Supersonic Flow in Cascades and Turbomachines, Oxford, 1988.

4. Hodson, H.P., "The Detection of Boundary Layer Transition an Separation in High Speed Turbine Cascades", 7th Symposium o Measuring Techniques for Transonic and Supersonic Flow i Cascades and Turbomachines, Aachen, 1973.

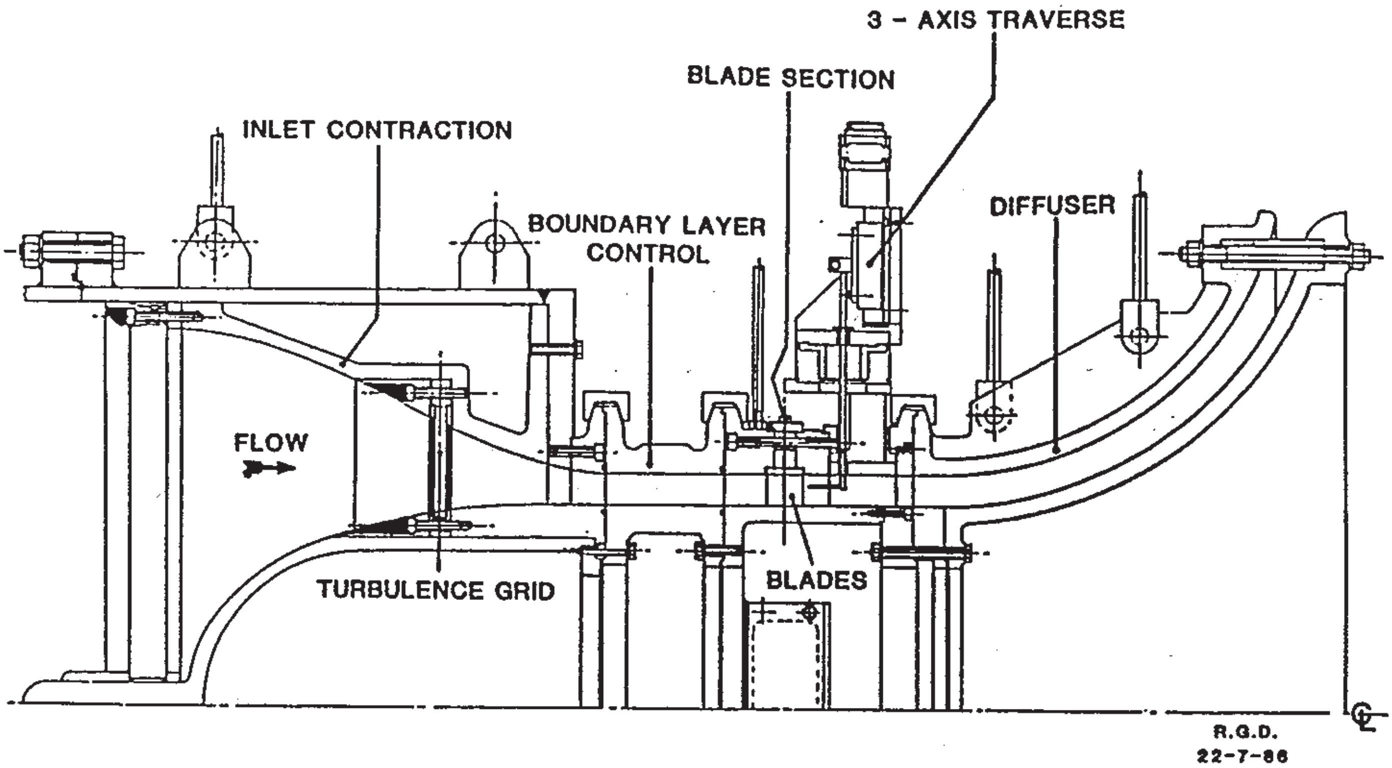
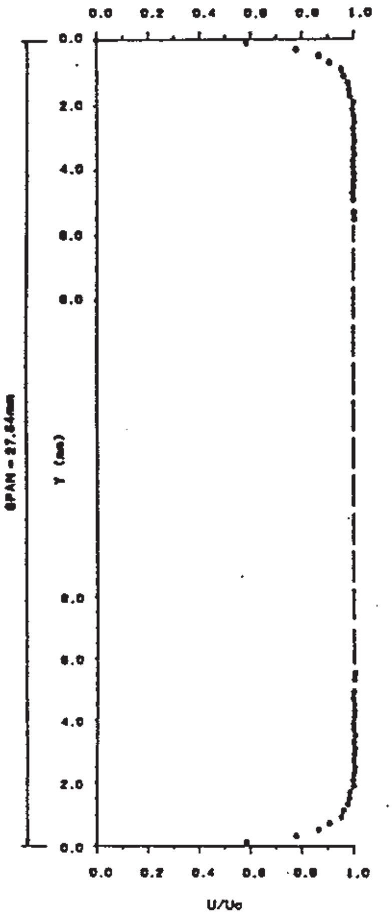


Figure 1. The Whittle Laboratory Transonic Annular Cascade Rig



Outer Wall Boundary Layer

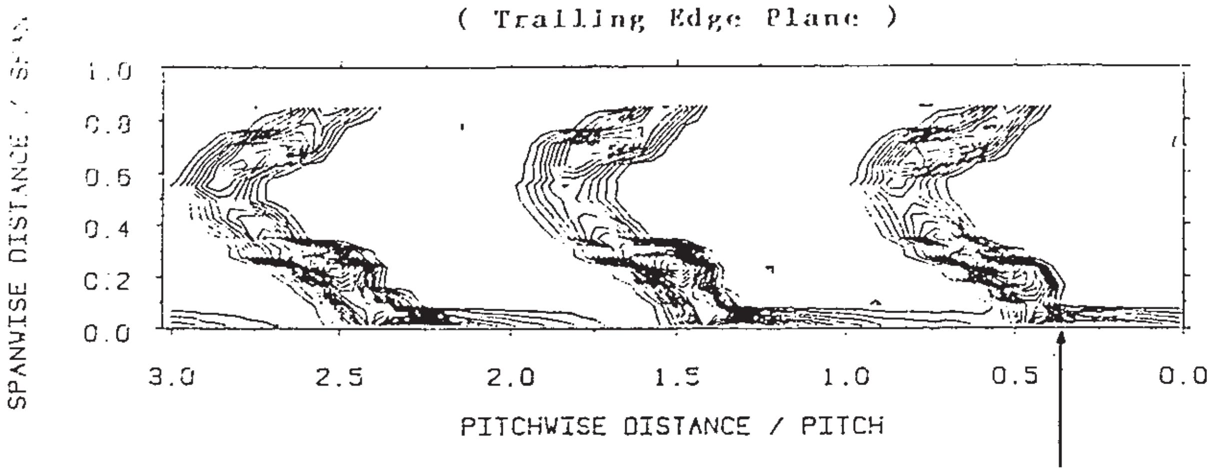
Displacement Thickness (mm).. 0.327
Momentum Thickness (mm)...... 0.228
Shape Factor................. 1.436

Inlet Mach Number............ 0.23
Inlet Reynolds Number........ 3.25 x 10^5
(Based on Blade Chord)

Inner Wall Boundary Layer

Displacement Thickness (mm).. 0.224
Momentum Thickness (mm)...... 0.142
Shape Factor................. 1.578

Figure 2. Inlet Boundary Layers (Blade Leading Edge Plane)



Incomplete sealing between
blade and hub
(this blade only)

Figure 3. Periodicity : Total Pressure Loss Contours
(Contour Interval 0.03, Mach No. 0.82, Reynolds No. 1×10^6)

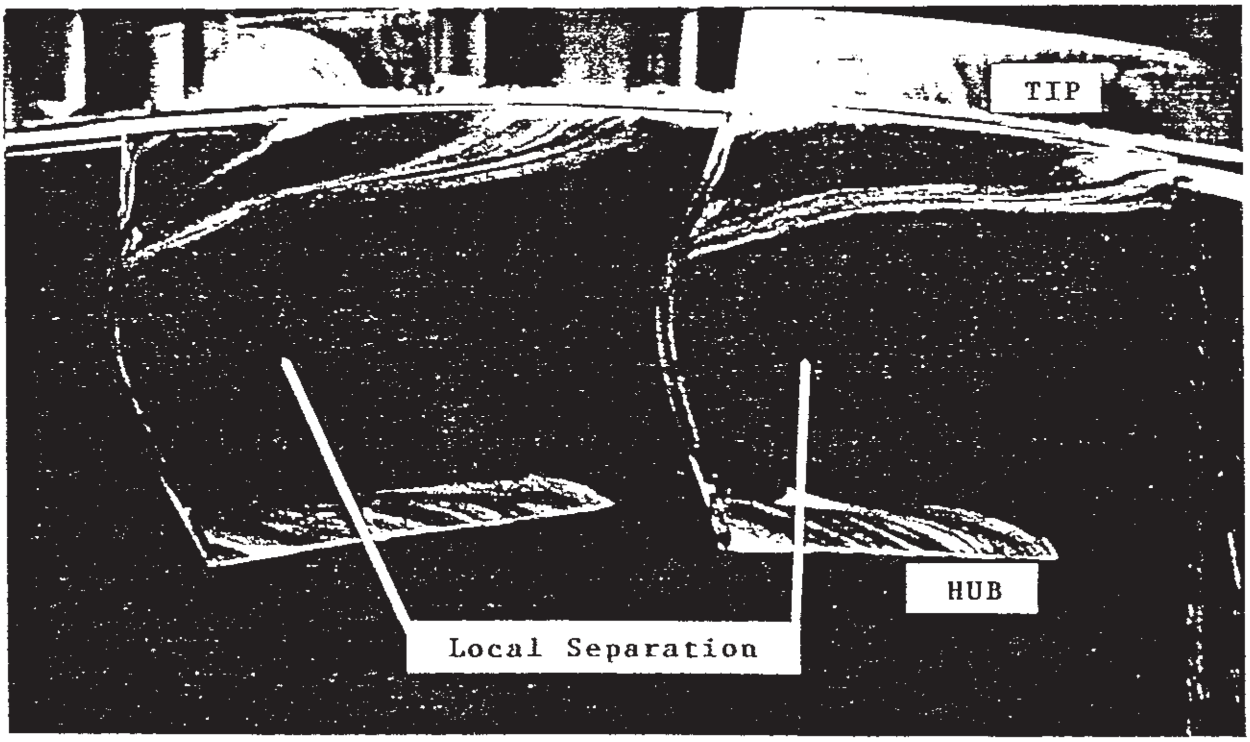


Figure 4. Periodicity : Blade Surface Oil Flow Visualisation

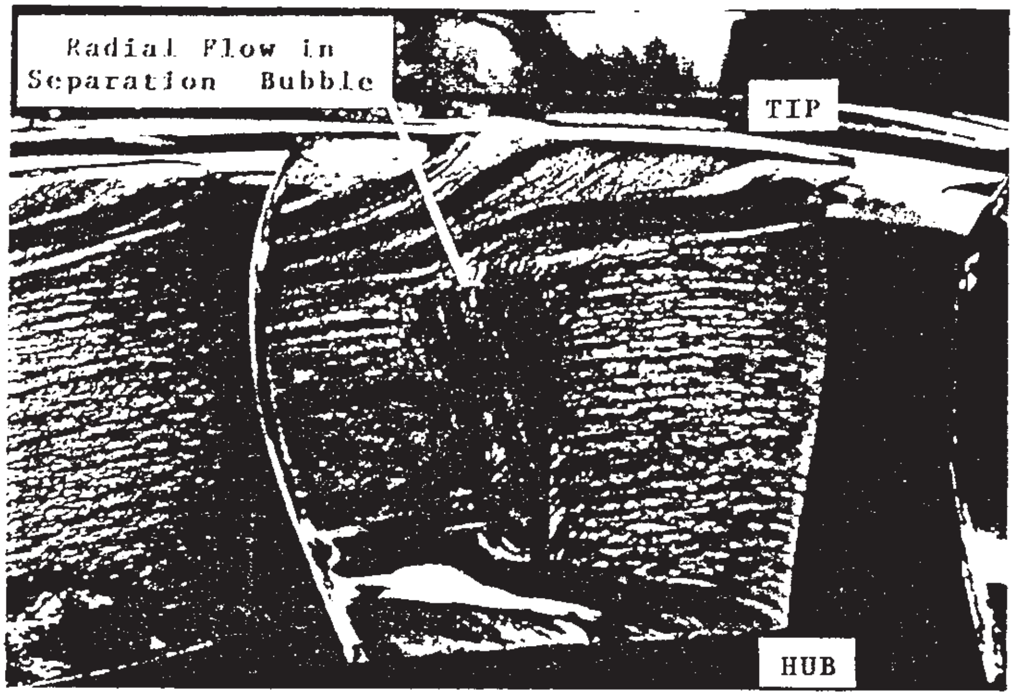


Figure 5. Blade Surface Oil Flow Visualisation

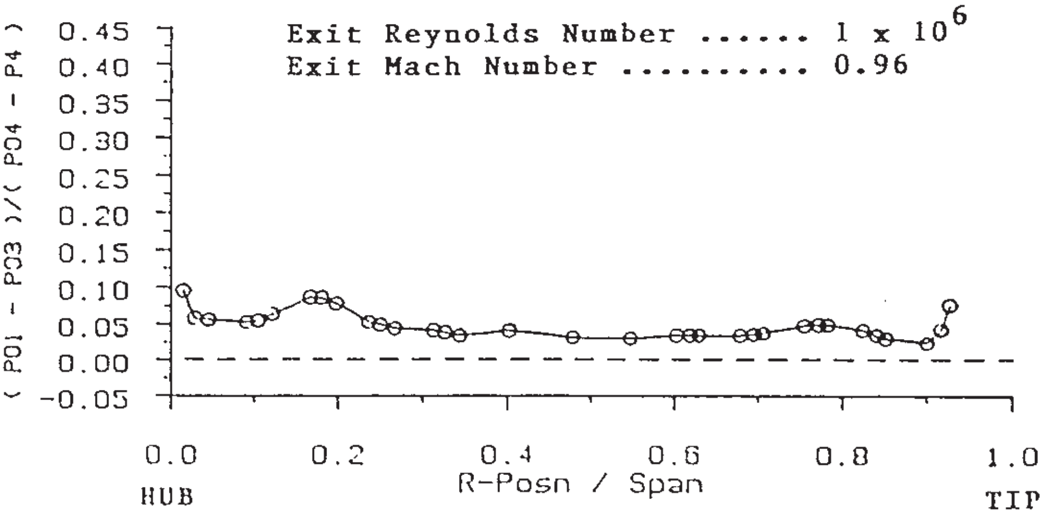


Figure 6. Spanwise Total Pressure Loss Distribution

(Trailing Edge Plane)