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AERODYNAMIC PERFORMANCE OF A COOLANT FLOW OFF-TAKE DOWNSTREAM OF AN OGV

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ABSTRACT

Within the compression system of a gas turbine engine a significant amount of air is removed to fulfil various requirements associated with cooling, ventilation and sealing. Flow is usually removed through off-takes located in regions where space is restricted, whilst the flow is highly complex containing blade wakes, secondary flows and other flow features. This paper investigates the performance of a pitot style off-take aimed at providing a high pressure recovery in a relatively short length. For this to be achieved some pre-diffusion of the flow is required upstream of the off-take (i.e. by making the off-take larger than the captured streamtube). Although applicable to a variety of applications, the system is targeted at an intercooled aero-engine concept where the off-take would be located aft of the fan Outlet Guide Vane (OGV) root and provide coolant flow to the heat exchangers.

Measurements and numerical predictions are initially presented for a baseline configuration with no off-take present. This enabled the OGV near field region to be characterised and provided a datum, relative to which the effects of introducing an off-take could be assessed. With the off-take present a variety of configurations were investigated including different levels of pre-diffusion, prior to the off-take, and different off-take positions. For very compact systems of short length, such that the gap between the OGV and off-take is relatively small, the amount of pre-diffusion achievable is limited by the off-take pressure field and its impact on the upstream OGV row. This pressure field is also influenced by parameters such as the non-dimensional off-take height and splitter thickness. The paper analyses the relative importance of these various effects in order to provide some preliminary design rules. For systems of increased length a significant amount of flow pre-diffusion can be achieved with little performance penalty. However, the pre-diffusion level is eventually limited by the increased distortion and pressure losses associated with the captured streamtube.

NOMENCLATURE

A	area
BHG	blade hub gap
C	OGV blade chord
Cp	static pressure rise coefficient
CS	capture streamtube
f	Darcy friction factor
h	off-take height (Fig.3b)
L/E	leading edge
LP	low pressure
(F)OGV	(Fan) outlet guide vane
P, p	local stagnation, static pressure
PR	pre-diffusion
RE	rotor exit
S	off-take mean height (Fig.16)
U	axial velocity normal to the traverse plane
X	distance from OGV to off-take leading edge
a	off-take splitter radius (Fig.16)
m	mass flow
r	radius relative to rig centerline
t	off-take splitter thickness (Fig.3b)
x	axial distance measured from OGV
α	kinetic energy flux coefficient
θ	wake momentum thickness
δ*, δ**	wake displacement/kinetic energy thickness
Subscripts	
amb	ambient conditions
b	blade
i, o	inner, outer
Superscripts	
~	Mass-Weighted
-	Area-Weighted
^	Momentum Mixed

1. INTRODUCTION

Within a gas turbine engine air is removed (or bled) from the compression system in order to fulfill various requirements associated with, for example, cooling and sealing. In addition, these requirements may be extended for some future, low emission aero-engine architectures currently being considered (e.g. intercooled engines). With this in mind more attention is being given to the method by which flow is removed from the compression system so as to optimize overall system performance. For example, some investigations have concentrated on removing air such that it also benefits the mainstream flow (e.g. Walker et al. [1] and Merchant, A. [2]) , whilst other investigations have considered the quality (i.e. pressure) of the flow provided by the off-take geometry. This can be important in terms of minimizing the amount of work that must be done on the bleed flow, for a given application, prior to its removal from the compression system. The current paper is concerned with the performance of an off-take located within the by-pass duct of an intercooled aero-engine (Figure 1). The intercooled engine is a new concept developed within the NEWAC (New Aero Engine Core Concepts) program. Of particular interest is the quality of the flow being removed, the purpose of which is to supply coolant to the heat exchanger (HX) modules. However, some of the findings with regard to off-take performance are also of significance to other applications.

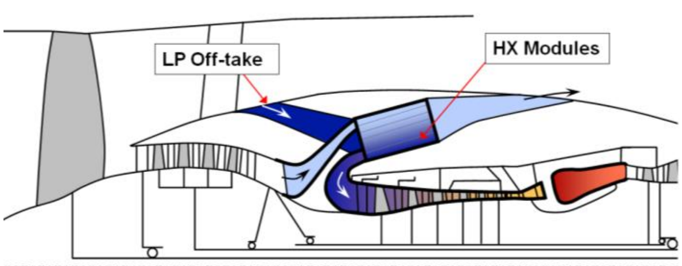

Figure 1: NEWAC Schematic of Intercooled Engine[3]

Engine bleed off-takes are usually located in regions where space is restricted and the flow being removed is highly complex and includes blade wakes, secondary flows and other flow features. In addition, it is usually desirable to diffuse the off-take flow, whilst minimising any total pressure loss, to reduce the subsequent downstream losses associated with ducting of the bleed flow and its eventual usage. One option is to use a flush intake, but to maximize the static pressure recovery typically requires a shallow off-take angle and hence a long axial length[4,5]. However, an alternative is to use a pitot (or 'scoop') type inlet as illustrated in Figure 2. Furthermore, if the off-take area is larger than the capture streamtube area then some diffusion of the flow can take place upstream of the off-take (referred to here as 'pre-diffusion'). The remaining diffusion can then occur within the ducting downstream of the off-take (referred to as 'controlled diffusion'). Clearly there is likely to be some optimum balance between the amount of pre-diffusion (PR), controlled diffusion (CD), system losses and length. Nevertheless the concept does provide the potential for an off-take system of relatively short length but which will provide a high pressure recovery. However, the pressure field generated by the off-take can (i) locally influence the upstream turbo-machinery blading and (ii) impact on the losses associated with mixing out of the blade wakes and other flow field features. Whilst some work has been done on the effects on wake mixing within a controlled diffuser (see for example Barker and Carrotte[6,7] and Stevens et al.[8]), little has been done in terms of the effects of local pre-diffusion on the flow.

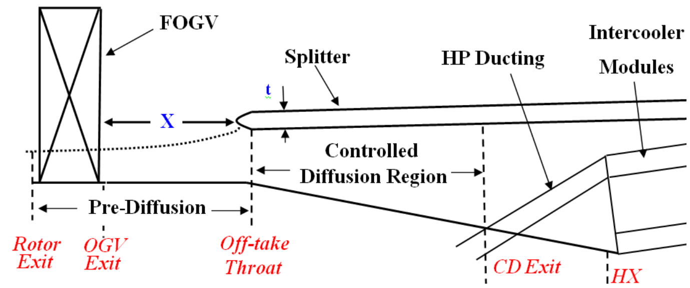

Figure 2: Off-take Concept Schematic

This paper looks at the performance of a pitot style off-take and, in particular, the pre-diffusion process upstream of the off-take. The off-take is located downstream of a stator row that has been modified to broadly simulate the flow in the hub region of a Fan Outlet Guide Vane (FOGV). To assess the quality of the flow captured a methodology is presented by which the incremental loss, associated with introduction of the off-take, can be identified for a range of operating conditions. Also considered is the location of the off-take and the upstream influence of its associated pressure field. This enables a suitable distance between the OGV and off-take to be determined for a range of geometries and operating conditions.

2. EXPERIMENTAL FACILITY

All experimental data were obtained on a low speed isothermal test facility operating at nominally atmospheric conditions. As already described the off-take must operate in a complex flow field environment. Hence, a 1½ stage axial flow compressor (IGV, rotor and OGV) is used to generate the unsteady blade wakes, secondary flows, loss cores and other turbo-machinery features that can potentially have an important influence on the off-take performance. However, it would be prohibitively expensive to build and operate a facility in which the compressor was representative of an engine LP fan, with the downstream by-pass duct also being included. Hence what must be considered is the most efficient methodology for accurately simulating the compressor and off-take aerodynamic interactions whilst avoiding the need to build a large scale and expensive test facility.

Test Section Concept

Experimental accuracy is improved if the off-take height can be made sufficiently large to avoid significant instrumentation blockage effects and enable good spatial measurement resolution. However, to avoid the need to construct a large LP fan and by-pass duct the approach adopted was to design a compressor of modest aspect ratio which could be modified to simulate the conditions in a fan OGV hub region. In particular, a gap was introduced at the hub of the OGV (over the first ⅓ chord), the size of which could be varied to modify the hub region flow. In this way the loss cores and other flow features could be modified so that their size and depth, relative to the off-take height, was broadly comparable with that likely to be encountered within the by-pass duct. It must be acknowledged there are some compromises that must be made using this methodology. For example, there may be differences between the generated flow field structures and those present within an engine, whilst this methodology can result in a relatively small by-pass duct into which the flow accelerates (which is not representative of the engine configuration). However, the strategy is thought to enable the most significant features to be captured, without the need for a prohibitively large scale and expensive test facility whilst, subsequently, a more detailed design process would account for some of the more subtle effects.

The off-take geometry is aimed at the intercooled preliminary engine design defined within the NEWAC programme[3,9]. However, using the OGV blade hub gap (BHG) loss cores of the correct size, relative to the off-take height, can be generated for this style of high by-pass ratio engine. Further, changing the hub gap is relatively easy and provides an efficient method for modifying the inlet conditions to the off-take and assessing the effect on system performance. In addition, if required this enables off-takes for different applications (e.g. core compressor) to be studied.

Compressor Design

Design of the compressor was undertaken in conjunction with Rolls-Royce plc., with the compressor having a mean radius of 320.1mm and passage height of 71.1mm. The rotor is operated at a fixed non-dimensional mass flow condition ($m\sqrt{(RT)}/AP$) and speed ($(N\pi D/\sqrt{(\gamma RT)})$) corresponding to a flow co-efficient (U/U_b) of 0.44. Mach numbers associated with the mean axial velocity component through the compressor were of order 0.1 (approximately 34m/s), with a Reynolds number based on OGV chord of approximately $1.9\text{x}10^5$. Although this is not as high as typical engine conditions Cumpsty[10] reports that for OGV Reynolds numbers above $1.5\text{x}10^5$ any undesirable transitional effects are avoided. Further, the Reynolds number sensitivity of the OGV row is also suppressed by the presence of the relatively high levels of turbulence (>3%) generated by the rotor. Consequently, the wake mixing within the downstream test section should be well represented. To characterize the compressor efflux and wake mixing an initial configuration was employed consisting of a simple parallel passage downstream of the OGV (Figure 3a). Data from this configuration were then used as a datum relative to which configurations incorporating an off-take could be assessed.

Off-take Geometry

As illustrated in Figure 3b a splitter was introduced to create a total pressure off-take at some variable distance, X, downstream of the OGV. The ability to alter this distance is important as the investigation needs to consider the compromise between (i) a system of short axial length (i.e. small gap) and (ii) the need to avoid strong off-take and compressor aerodynamic interactions which would adversely affect system performance. Throughout the measurements the splitter thickness, t, was fixed at 7.5mm and the leading edge was elliptical with a fineness ratio of 2. The off-take height, h, was set to 20mm and, as already mentioned, was a compromise between (i) the desire for a large passage height to improve measurement resolution and reduce probe blockage effects and (ii) a small passage height to avoid significant acceleration of the bypass flow at high levels of pre-diffusion. The level of pre-diffusion is changed by throttling the off-take mass flow. The effective area ratio for the pre-diffusion is then defined as A_{throat}/A_{RE} where A_{throat} is the area of the throat plane and A_{RE} is the area of the capture streamtube at system inlet (for the off-take system this is defined as rotor exit). The latter is obtained from the measured inlet data by computing the radius at which the off-take mass flow is captured.

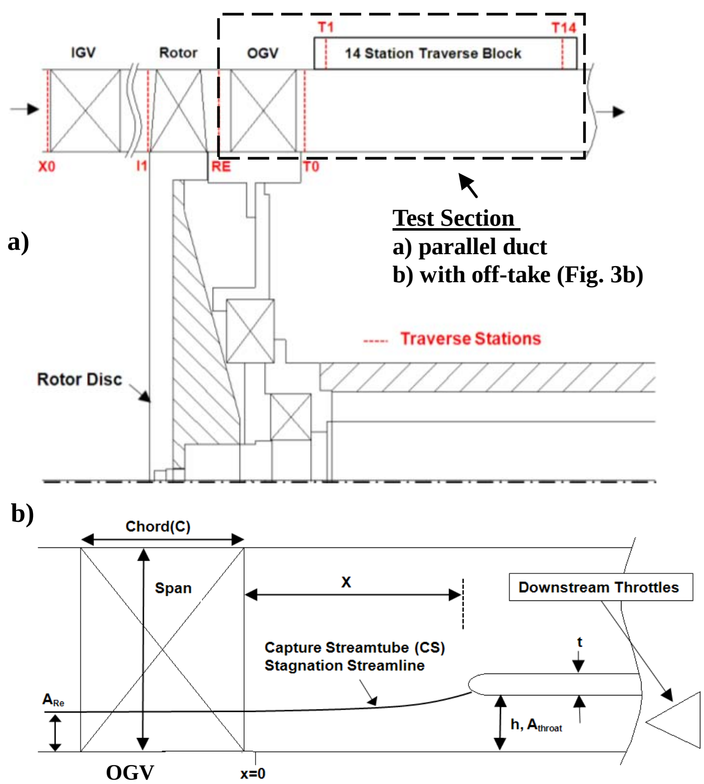

Figure 3: Test Rig Configurations a) Parallel Duct b) with Off-take

Instrumentation, Data Reduction and Errors

In general aerodynamic performance was assessed using suitably calibrated miniature five-hole probes (ϕ = 1.76mm), used in a non-nulled mode, as described by Wray and Carrotte[11]. As indicated in Figure 3, area traverses could be conducted at rig inlet (X0), rotor inlet (I1), rotor exit (RE), OGV exit (T0) and various traverse planes (T1 – T14) through the system. Probes were traversed in the radial direction with a positional accuracy of better than ±0.1mm. Circumferential movement was achieved by rotating the IGV and OGV blade rows, together with the inner casing, with an estimated accuracy within ±0.05°. A National Instruments LabVIEW based data acquisition and control system was used to monitor and adjust the compressor operating point, perform probe traversing and acquire experimental data. This enabled the compressor non-dimensional speed and flow coefficient to be maintained within ±0.08% and ±0.18% respectively of their prescribed values for the duration of the experiment. All measurements were corrected to standard day conditions (P_{amb}=101325Nm^{-2}, T_{amb}=288.15K).

At a given plane, spatially averaged values can be obtained through suitable averaging techniques. The spatially averaged velocity normal to the traverse plane ($\bar{U}$) was obtained by area weighting whilst the spatially averaged pressures could be derived based on a mass weighted ($\tilde{P}, \tilde{p}$) or momentum mixed ($\hat{P}, \hat{p}$) basis (see, for example, Barker and Carrotte[6]). The mass weighted pressures do not include any losses associated with the subsequent mixing out of the distorted profile downstream of the measurement plane. As an alternative the momentum mixed values ($\hat{P}, \hat{p}$) can be derived giving pressures that would be obtained if the flow had been allowed to mix out to a uniform profile at constant momentum[6]. In addition, for spatially non-uniform incompressible flow, which is predominately in the axial direction it can be shown that[12]:

$$\tilde{P} = \tilde{p} + \alpha\left(\frac{1}{2}\right)\rho U_m^2 \quad \text{where} \quad \alpha = \frac{1}{A}\int_A \left(\frac{u}{U_m}\right)^3 dA \qquad (1)$$

The kinetic energy flux coefficient, α, represents the ratio of mass-weighted kinetic energy of a non-uniform flow to that of a flow with the same mass flow rate[12]. Hence this provides a method by which the distortion of the profile can be quantified; increasing from a value of unity as the profile becomes more distorted.

Changes in the spatially averaged pressures between any two planes can be expressed in terms of a total pressure loss (λ) and static pressure rise coefficient (Cp) with the change in pressures being non-dimensionalized[13] by a suitable reference dynamic pressure:

$$\lambda_{1\text{-}2} = \frac{\tilde{P}_1 - \tilde{P}_2}{\tilde{P}_1 - \tilde{p}_1} \quad \text{and} \quad Cp_{1\text{-}2} = \frac{\tilde{p}_2 - \tilde{p}_1}{\tilde{P}_1 - \tilde{p}_1} \qquad (2)$$

Note that the coefficients can also be calculated using momentum mixed (as well as mass weighted) values. Typically these coefficients are referenced to the rotor exit plane. In this way any change in OGV performance, due to the presence of the off-take, is included in the analysis. The mass weighted total and static pressures at a given traverse plane were repeatable to better than 5Pa. Hence, the total pressure loss and static pressure rise coefficients, measured relative to rotor exit, are thought to be repeatable to better than ±0.005. The calculated mass flows at each traverse plane were accurate to within 1.5%.

3. NUMERICAL METHODS

CFD models and meshes were generated using Gambit with solution of the RANS equations computed using Fluent (v6.3). Models of increasing complexity were used starting with simple 2D axi-symmetric models in order to isolate effects such as the pre-diffusion process and the upstream pressure field generated by the splitter leading edge. 3D models were then used to enable inclusion of compressor generated inlet conditions and investigation of the wake mixing and the interaction of this process with the pre-diffusion. Inlet conditions were taken from the five-hole probe and hot-wire data measured at OGV exit. Computational meshes were generated to be predominately quadrilateral with refinement in regions of interest to improve capture of, for example, the wake mixing or the impingement of flow on the splitter leading edge. Similarly, care was taken to ensure appropriate meshing of the wall regions in line with the turbulence model and wall modelling approach chosen. Initially, inviscid predictions were made to remove these viscous turbulent effects and isolate the 1st order pressure driven phenomena. This was useful to identify which aerodynamic processes were dominant. In choosing an appropriate model for turbulence closure it is important to consider the phenomena within the flow. In the current study the flow will contain (i) the development of a boundary layer under the influence of an adverse pressure gradient, (ii) the possibility of flow separation, (iii) a free shear layer between the off-take and bypass flow, (iv) impingement of the flow on the leading edge of the splitter and (v) strong shear forces and anisotropic flow in the mixing of compressor wakes. No single RANS model will capture all of these; some are more successful for particular flows. However, for this combination of phenomena a Reynolds stress model was chosen for the majority of the computations. This is because it accounts for the effects of streamline curvature, swirl, rotation, and rapid changes in strain rate in a more rigorous manner than eddy-viscosity models. Hence it has greater potential to give accurate predictions for the current work. However, it is somewhat limited in the fact it is fundamentally a high Reynolds number model and uses a wall function to bridge the viscosity-affected inner boundary layer and the fully-turbulent outer region. Wall functions are unable to accurately predict the onset of separation due to their modelling assumptions. Thus some predictions were also made using a k-ω model as it is a so called low Reynolds number model designed to be applied throughout the boundary layer. As mentioned earlier care was taken to ensure the correct near wall mesh resolution for each wall modelling method. For example a wall function approach requires a relatively coarse near wall mesh (y+ greater than ~30-60) but resolving the boundary layer requires a much finer mesh (y+ of order 1-2) and with it added computational expense.

4. RESULTS AND DISCUSSION: NO OFF-TAKE

The first phase of the investigation was aimed at establishing the characteristics of the flow field issuing from the compressor and its subsequent mixing out within a constant area annular duct. This provides a datum to which the effect of introducing an off-take, into this flow field, can be assessed.

4.1 OGV Exit Flow Field Conditions

Example OGV exit axial velocity contours are presented in which the OGV row was operated with different hub gaps (Figure 4). Not surprisingly as the hub gap is increased so the velocity deficit in the hub region increases and a well defined loss core structure develops. In this way the velocity deficit and loss core sizes, associated with the hub region, can be varied.

As already indicated of particular interest in this investigation is the use of an off-take within the by-pass duct of a relatively high by-pass ratio intercooled engine. Hence numerical predictions of the fan OGV were undertaken for several large by-pass ratio engines for which an example OGV exit flow field is presented (Figure 5). Also indicated is a typical off-take capture streamtube for the application being considered. This indicates the potential importance of the hub flow field on the captured streamtube. At a given radial location, relative to the intake capture height, non-dimensional velocity, momentum and energy[6] deficits can be calculated from this flow field. This has been done for two engine configurations, representing what is thought to be a suitable range of values, and these are compared with those obtained when the hub gap was 0.42% of the blade height (Figure 6). It is thought this indicates that the structures generated, relative to the intake height, are reasonably representative of those captured by the off-take within the Fan OGV engine environment. This hub gap was therefore selected as the primary configuration for investigating the off-take performance. However, measurements were also obtained for the case with no hub gap (0% BHG) so that the sensitivity of the off-take performance to changes in the capture stream tube flow field could be assessed.

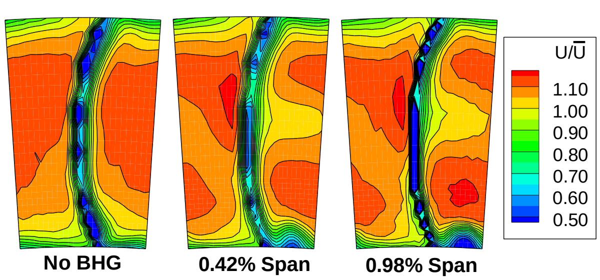

Figure 4: Normalized Axial Velocity Contours at OGV Exit with varying Blade Hub Gaps

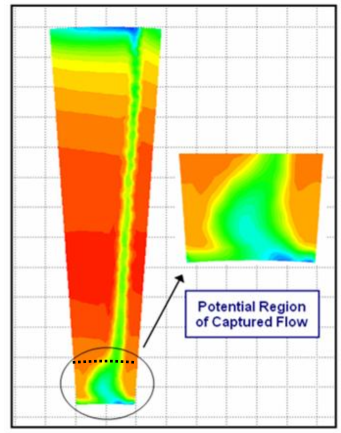

Figure 5: CFD Total Pressure Contours at FOGV Exit

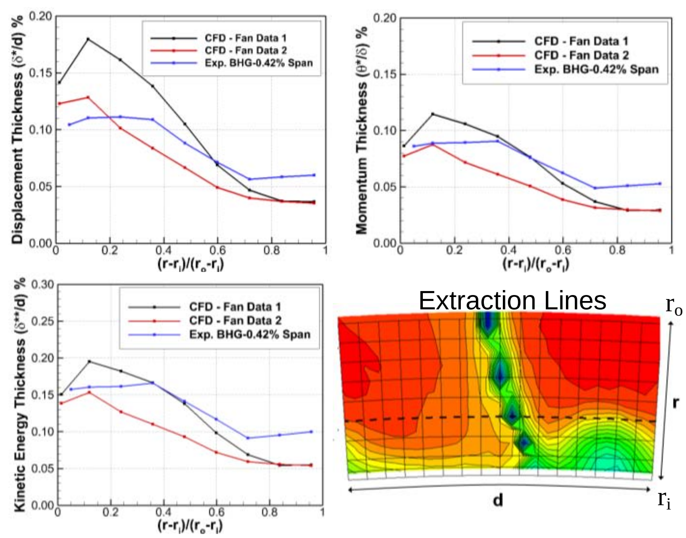

Figure 6: OGV Exit Capture Streamtube Comparison

4.2 Flow Field Characteristics

As indicated in Figure 3 data were obtained at up to 14 axial planes within the downstream duct for which some example measurements are presented (Figure 7). The axial location of each plane (x) is expressed relative to the OGV chord (C). As expected the data indicates mixing out of the compressor exit velocity fields with downstream location.

Further analysis of these measurements provides a more detailed characterization of the flow field. For example, the variation of kinetic energy flux coefficient with downstream location is presented for both configurations and indicates a rapid mixing out of the profile within approximately 1 blade chord of the OGV exit plane (Figure 8). This is accompanied by a rise in static pressure as the mixing produces a more uniform velocity profile (and hence reduced blockage). In addition, the circumferentially averaged profiles are also presented for both configurations (Figure 9), and it is interesting to note that introduction of the OGV hub gap does have a significant effect on the radial profiles. However, for a given configuration the profiles are reasonably invariant with downstream location. In other words there is very little mixing out of the profile in the radial direction, and the profile development is dominated by mixing in the circumferential direction. This is in agreement with several authors (for example Barker and Carrotte[6,7] and Denton[14]) who found that in modern compressor blading the radial distortion of the profile is relatively weak. This is despite, in this case, additional distortion being introduced into the radial profile by the blade hub gap. Instead it is the high velocity gradients in the circumferential direction, and the associated turbulent shear stresses, that tend to dominate the profile mixing. This mixing mainly occurs in the near field region (i.e. within 1 blade chord) where the circumferential velocity gradients are high. Further downstream the mixing results in reduced velocity gradients which, in turn, reduce the level of mixing. However, axial length constraints mean that it is desirable for any off-take to be located in the near field region which will therefore affect, and be influenced by, the mixing processes in this region.

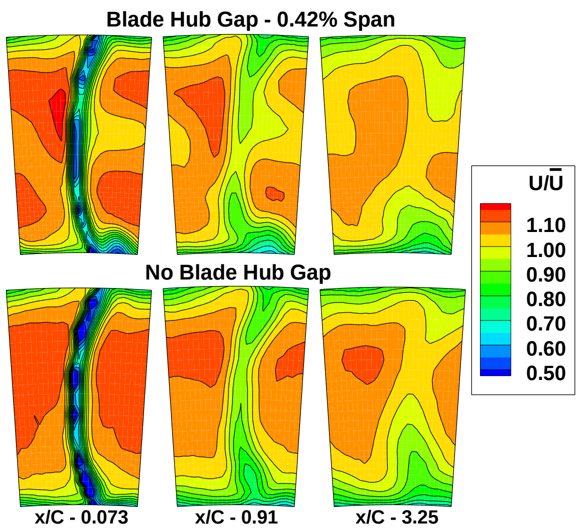

Figure 7: Normalized Axial Velocity Contours at Various Downstream Planes

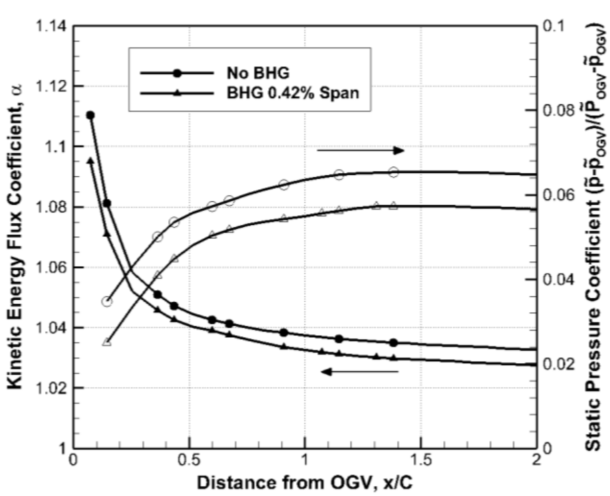

Figure 8: Kinetic Energy Flux Static Pressure Coefficient

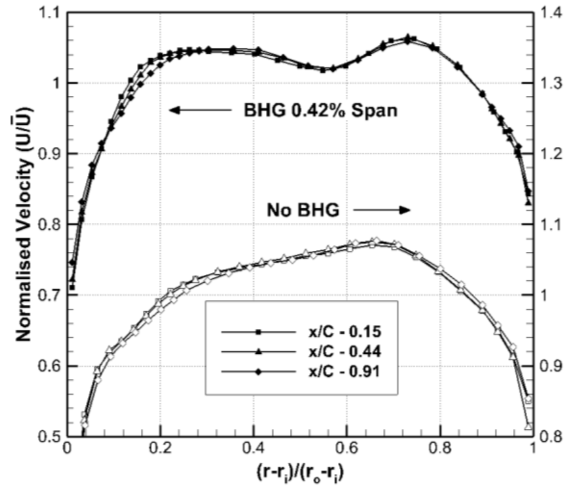

Figure 9: Circumferentially Averaged Normalized Velocity Profiles at Axial Locations through Duct

4.3 Overall Performance Data

The losses associated with the flow field development downstream of the OGV row provide a baseline to which any incremental losses, associated with the subsequent introduction of an off-take, can be evaluated. The calculated mass weighted and momentum mix pressures at the various axial planes are presented relative to the mass weighted pressures at the OGV inlet plane (Figure 10). In this way any effect on OGV performance, associated with the introduction of an off-take, will be included in the subsequent analysis. In addition, for the hub gap configuration, values derived from numerical (CFD) predictions of the flow field, downstream of the OGV, are also included. Good agreement with the experimental data over the first chord length suggests the dominant mixing processes are being captured by the numerical methods that have been used in this study. Deviation from the experimental data further downstream, where wall friction dominates, potentially reflects the limitations of the wall function used by the Reynolds stress model.

At the OGV exit plane the momentum mix values indicate the pressures that would be obtained if the profile had been allowed to mix out at constant momentum (i.e. downstream mixing losses are included). On this basis it might be expected that the momentum mix based values will be constant with distance down the duct, but instead a gradual increase in loss is observed. This is because mixing is not undertaken at constant momentum due to the wall friction associated with the duct inner and outer casings. From the change in momentum mix values, with downstream location, a Darcy friction factor of 0.021 can be calculated. This is in general agreement with the experimental data used for classic pipe loss estimation allowing for the difference in profile. Not surprisingly at OGV exit the mass weighted values indicate a lower loss (i.e. they do not include any downstream mixing losses). However, the difference between the mass weighted and momentum mix values decrease within 1 chord length as these mixing losses are realised. Downstream of this location the mass weighted losses then exhibit a similar characteristic, of increasing loss due to skin friction. Also included are the momentum mix values based only on the circumferentially averaged profiles (i.e. where it is assumed there is no circumferential distortions of the flow field). Comparison of the various loss values show that at OGV exit most of the mixing loss is associated with mixing out of the circumferential flow field distortions, as expected, with only a small amount of loss being associated with mixing out of the radial profile. However, further downstream the reduction in the circumferential distortions mean that the losses associated with mixing out of the radial profile become proportionately more significant.

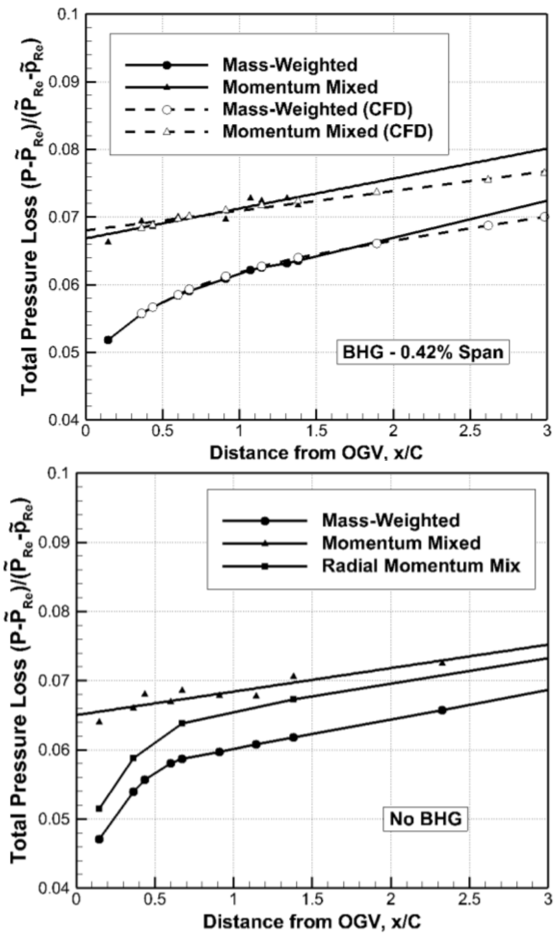

Figure 10: Whole Plane Pressure Losses through System a) BHG 0.42% Span b) No BHG

The experimental results obtained with and without the OGV hub gap are broadly comparable. For example, it is not surprising that the change in momentum mixed values due to skin friction is approximately the same for each configuration. However the results do indicate that introduction of the hub gap tends to increase the mass weighted loss, across the OGV row, but reduce the downstream mixing losses. It therefore appears that loss core development within the OGV passage, by inclusion of the hub gap, leads to smaller velocity gradients at OGV exit so that downstream mixing losses are reduced slightly.

4.4 Captured Streamtube loss analysis

The above loss characteristics are based on measurements across the whole plane. However, only a portion of this flow field will be captured by the intake, and it is the loss associated with this captured flow that is of particular interest. With this in mind a stream tube analysis has been applied to the experimental data. At any plane the mass flow contained between a given radial location and the inner casing can be calculated and the pressures, associated with this streamtube, obtained. In this way specific capture streamtubes can be identified along with the losses that occur within them as they progress downstream. Some example data is presented (Figure 11) for streamtubes containing different amounts of mass flow. However, these are expressed in terms of the pre-diffusion level they represent if this amount of flow was captured by the intake (when present). A high level of pre-diffusion (e.g. PR1.55) implies a small amount of mass flow is captured by the intake, and this corresponds to flow adjacent to the hub. Hence this flow will have associated with it a high level of loss generation as it passes through the OGV row and downstream duct. With decreasing levels of pre-diffusion more of the higher quality flow, away from the hub, is included so that the captured flow is of higher quality (i.e. losses reduce). The level of pre-diffusion can therefore have a significant impact on the pressure of the flow within the intake throat. Hence the capture of low pressure (i.e. high loss) flow may not be a reflection of poor intake performance, or the effects of pre-diffusion on the captured streamtube. Instead it could merely reflect the quality of the flow within the streamtube with or without the presence of the off-take.

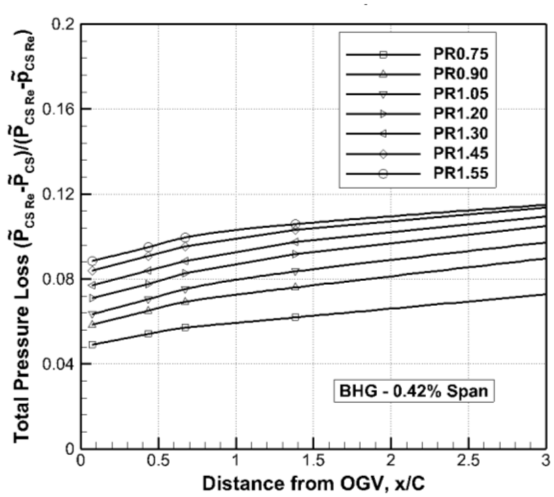

Figure 11: Pressure Loss Development for Various Mass Flows through Datum Duct

Whilst the above analysis provides a baseline to which the performance of the intake can be assessed, it should be remembered that errors can be introduced due to radial movement of the flow as it passes downstream. In other words the streamtube outer radius may not be fixed with circumferential location, but may become distorted as the radial velocity components promote the local radial movement of fluid. This process cannot be captured in the aforementioned analysis of the experimental data. Hence with this in mind numerical predictions were undertaken in which the actual streamtubes could be defined via the release of particles at the OGV exit plane (Figure 12). As the flow progresses downstream so the streamtube outer radius will distort. Comparisons can therefore be made with the loss, based on the actual streamtube, with that assuming a constant outer radius. Comparison of these results suggests errors typically of up to 5% in the calculation of total pressure loss may occur due to the radial movement of fluid.

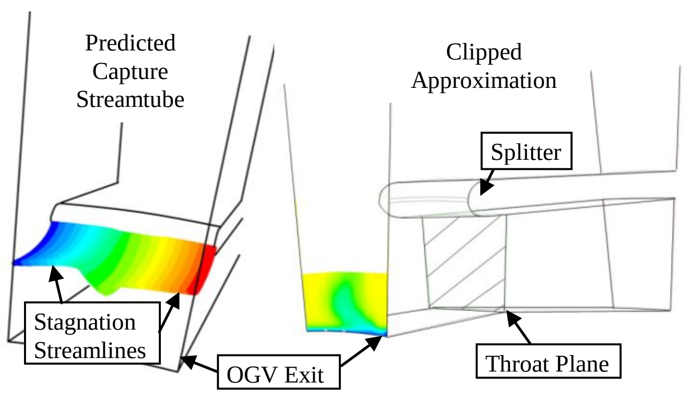

Figure 12: Visualization of Predicted Capture Streamtube and Constant Outer Radius Approximation

5. RESULTS AND DISCUSSION: WITH OFF-TAKE

The second test configuration added a pitot style off-take to the parallel passage with the aim of assessing the interaction between the flow field issuing from the compressor, the axial location of the off-take, the level of pre-diffusion and the quality of the flow captured by the off-take. A further aim was to develop simple design rules for the location of the off-take in a generic system.

5.1 OGV/Off-Take Pressure Field Interaction

The off-take will generate a pressure field that can pass into the upstream OGV row and significantly affect its performance. For example, increased local diffusion in the fan OGV hub region may be particularly significant if aerodynamic loading is already high, whilst the effects may be strong enough to also influence the upstream rotor. However, the intention here is not to investigate how the flow field *within* the OGV (or rotor) is affected by the off-take since this is dependent on the OGV geometry associated with a given application. Instead the objective is to indicate the relative magnitude of the interaction for a given configuration. This has been quantified in terms of the static pressure field perturbation at OGV exit, due to introduction of the off-take, relative to the mean dynamic pressure at this location. Thus a large perturbation suggests a significant incursion of the off-take pressure field within the OGV (and hence a strong interaction). Furthermore, for a preliminary design process this allows a sensible limit to be imposed which indicates the perturbation that could be tolerated, by the OGV, without significantly affecting its performance. Inspection of existing features within engines that cross the main gas path (e.g. auxiliary drive shafts, load bearing struts within transition ducts etc) suggests perturbations of order 20% can be tolerated without significant changes to the associated upstream blade row. Hence by way of illustration in what follows a value of 20% has been applied (although it is relatively trivial for other values to be used).

Experimental measurements at OGV exit indicate the 2 main pressure field effects namely;

i) The splitter leading edge potential field. This will be present for any level of pre-diffusion, with the upstream pressure rise being greatest along the stagnation streamline.

ii) The pressure rise associated with diffusion of the capture streamtube upstream of the off-take (i.e. pre-diffusion). This will be greatest along the inner casing.

The magnitude of these effects, and which effect is dominant, will be a function of off-take position, geometry and operating conditions. Figure 13 illustrates the effect of moving the off-take closer to the OGV for a given level of pre-diffusion. When the off-take is at x/C=0.27 (i.e. 2 splitter thicknesses downstream of the OGV), and for a pre-diffusion of 1.16, a local increase in static pressure is observed at a non-dimensional radius of 0.25. This is associated with the splitter potential flow field, although it is located slightly inboard of the splitter due to deflection of the stagnation streamline caused by the pre-diffusion. In addition, this perturbation is greater than the 20% criteria limit set previously. Not surprisingly if the off-take is moved downstream the influence of this potential field is reduced. Thus it can be argued, for example, at this level of pre-diffusion (1.16) the off-take must not be within approximately 2.5 splitter thicknesses of the OGV if the 20% pressure perturbation criteria is not to be exceeded. Similarly, Figure 14 shows some example data to illustrate the effects of pre-diffusion on the OGV exit static pressure profile (for a fixed off-take location). As the amount of pre-diffusion increases the upstream effect at OGV exit becomes notable, with the static pressure rising adjacent to the inner casing. It can be seen in this case the wall static pressure approaches that of the 20% limit at a pre-diffusion of 1.44. Consequently, this represents the maximum pre-diffusion for this axial gap, with higher levels of pre-diffusion requiring a larger distance between the OGV and the off-take. Additionally, it is also worth noting in Figure 14 the static pressure profiles at inlet to the OGV (i.e. rotor exit) have also been included. These indicate the rotor exit flow field is insensitive to the above changes in axial gap and pre-diffusion. In other words the off-take pressure field does not penetrate upstream of the OGV row.

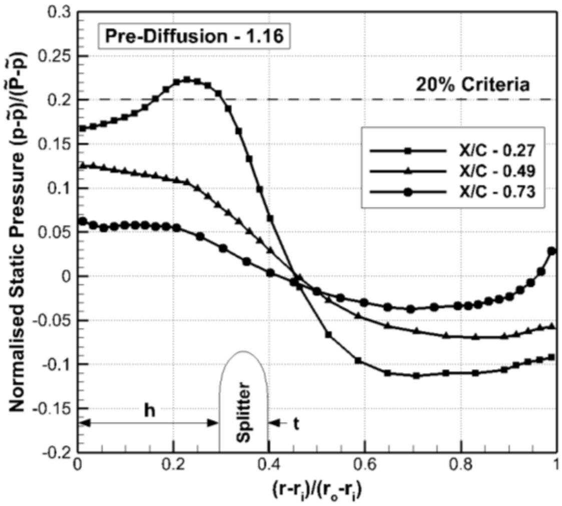

Figure 13: OGV Exit Static Pressure Variation with Off-take Proximity (PR1.16)

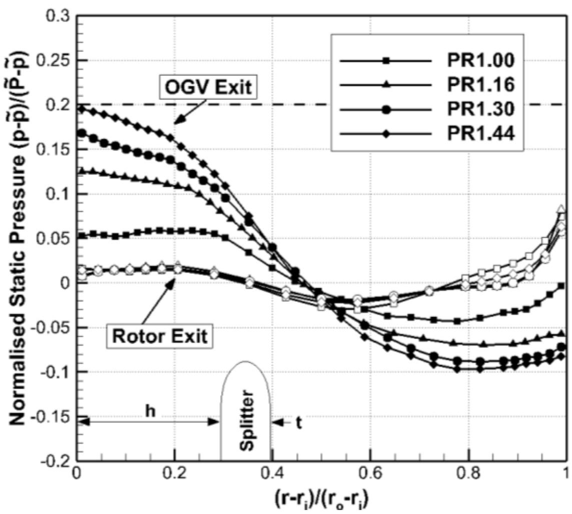

Figure 14: OGV Exit Static Pressure Variation with Pre-Diffusion (X/C=0.49)

These example results illustrate how the pressure field, upstream of the off-take, is influenced by a variety of factors (e.g. off-take axial location and height, pre-diffusion, splitter thickness etc). It is therefore not clear which are the most relevant parameters by which the off-take pressure field should be characterized. However, understanding the relationship between these various factors is important to enable off-takes to be designed of minimum length but with the upstream pressure field staying within the allowable criteria at OGV exit.

Preliminary Design Maps

The pressure field generated by the off-take will be mainly dictated by inviscid effects if the flow field is relatively well behaved. For example, comparing the results of inviscid and fully turbulent CFD predictions shows that, when made suitably non-dimensional, changes in the static pressure rise along both the splitter stagnation stream line and the inner wall are virtually identical (Figure 15). Furthermore, additional CFD calculations, with flat and experimentally derived inlet profiles, indicate the pressure field is also broadly insensitive to the inlet condition. These findings suggest that analysis techniques can be developed based on relatively simple inviscid flows.

Various models were developed using inviscid potential flow theory in which various features (doublets with circulation, Rankine half bodies etc.) were located in a free stream. An example of one such model is presented (Figure 16). Using this potential flow approach equations can be developed for the flow along the stagnation streamline and the inner wall (here a plane of symmetry). These indicate that the pressure field along these streamlines is dominated by the amount of pre-diffusion in conjunction with the distance upstream of the off-take (x) and the splitter radius (a). These latter 2 parameters should be made non-dimensional by the off-take mean height (S). Consequently a non-dimensional design space can be defined, based on the potential flow theory, that provides geometry and pre-diffusion information for a given static pressure criteria. Some example data is presented (Figure 17 and 18). A potential flow model can enable the prediction of the pressure field associated with a specific configuration to be generated in a matter of seconds rather than hours when using RANS CFD models. Figure 17 indicates the static pressure rise location along the inner casing associated with a 20% pressure rise. Hence for a pre-diffusion of 1.4 and non-dimensional splitter thickness ratio (a/S) of 0.11 a minimum gap between the OGV and off-take of approximately 1.3 off-take mean heights (x/S=1.3) is required. Any less and the 20% pressure perturbation at OGV exit will be exceeded. This minimum gap must be increased to an x/S value of 1.85 for a splitter thickness ratio (a/S) of 0.20. A similar diagram is presented in Figure 18 relating to the pressure rise along the stagnation streamline. The characteristics of both these charts indicate that, for a given splitter thickness ratio (a/S), the amount of pre-diffusion that can be achieved is significantly limited as the off-take location (x/S) gets closer to the OGV exit plane. In contrast, when the gap between the off-take and OGV is relatively large the amount of allowable pre-diffusion is much greater before the pressure field perturbation, on the OGV exit plane, reaches its limit. It is relatively easy to generate different maps for different pressure perturbation criteria. Hence if the allowable pressure perturbation at OGV exit is set to 10% (Cp=0.1) then a corresponding design map can be generated. Using this methodology preliminary design maps covering a range of geometries and operating conditions can be obtained which provide a useful guide and show the relative importance of different off-take features on the pressure field. However, there will be errors associated with this simplified approach and the magnitude of these errors will vary in different regions of the design map. In addition, such an approach can be restrictive. For example, the potential flow approach is more suited to a cylindrical leading edge whereas the leading edge of the splitter is more likely to be elliptical. With this in mind inviscid CFD calculations, that are still relatively computationally inexpensive, can also be undertaken to provide more accurate design maps and enable greater flexibility in the geometry being investigated. For example, calculations were performed with full splitter geometries incorporating a circular leading and an elliptical leading edge. The effect of both these are shown in Figure 17 and 18. With a full splitter but a cylindrical leading edge the data suggest a slightly larger gap is required than suggested by the potential flow model. With an elliptical leading edge the data suggests, as expected, the potential field is reduced and a smaller gap can be tolerated.

The preliminary design maps provide a useful guide in determining off-take geometries of potential relevance to a particular application. These geometries then form the basis for more detailed studies and CFD calculations (3D, viscid) that should be carried out to provide a more accurate assessment of performance and enable further development of the off-take geometry.

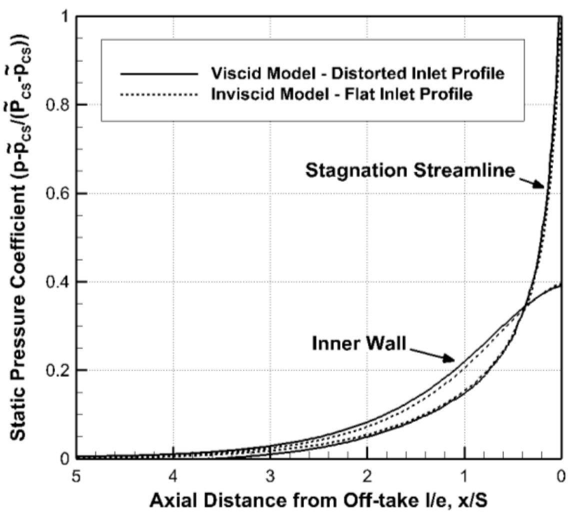

Figure 15: Comparison of CFD Predictions

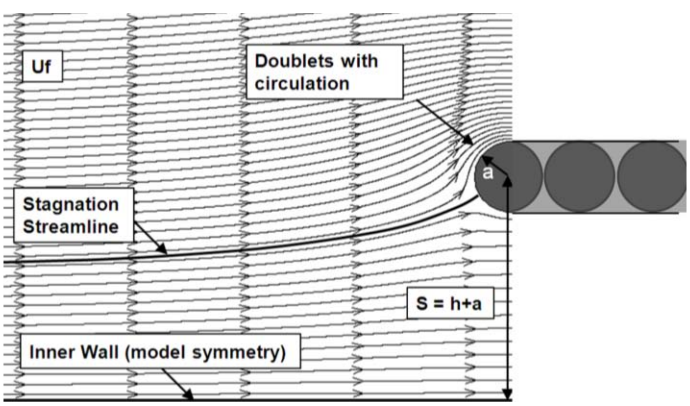

Figure 16: Potential Flow Model

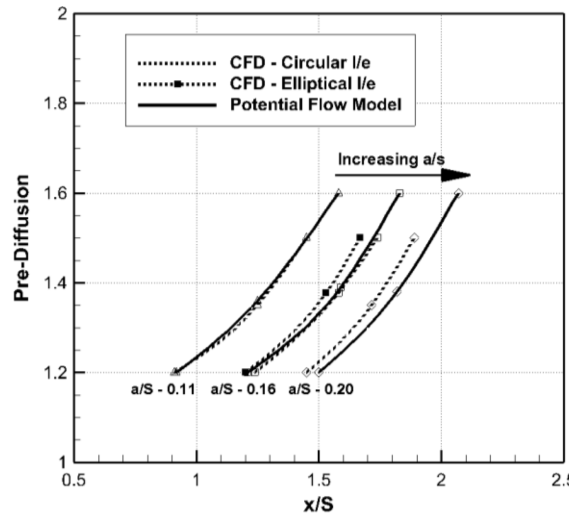

Figure 17: Off-take Location Design Envelope based on Inner Wall Static Pressure (Cp-20%)

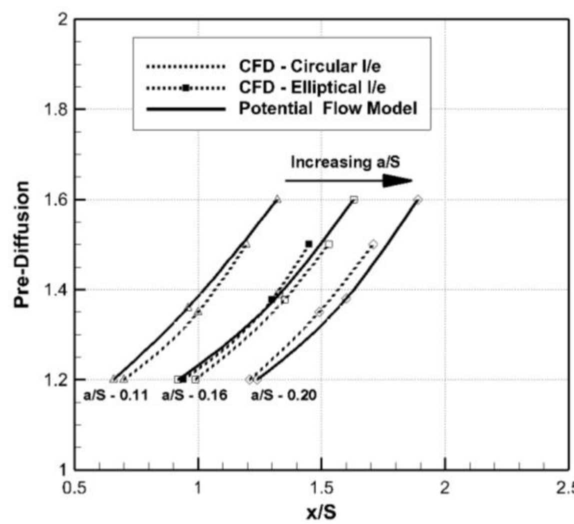

Figure 18: Off-take Location Design Envelope based on Stagnation Streamline Static Pressure (Cp-20%)

5.2 Captured Streamtube Losses

In addition to the off-take pressure field and its interaction with the OGV blade row, what must also be considered is the quality of the flow captured by the intake.

With no off-take present the turbulent stresses acting on the flow result in a mixing out of the profile downstream of the OGV row (see Section 4). However the pressure rise due to any flow upstream of the off-take will generate pressure forces that oppose this mixing process. By way of illustration some example numerical (CFD) results are presented showing the magnitude of the turbulent and pressure based forces acting on different regions of a captured streamtube (Figure 19). The operating condition is equivalent to an experimental pre-diffusion value of approximately 1.4 and an off-take location (X/C) of 0.73. In the blade wake region there is a rapid rise in the mainly turbulent shear forces downstream of the OGV which then decay further downstream as the velocity gradients reduce. The resulting transfer of momentum into the low velocity wake region causes the flow to accelerate. Similar forces are applied to the loss core, but these tend to be of lower magnitude in the near field region due to the reduced velocity gradients. With no off-take present these forces dominate the flow field development and its subsequent mixing out to a uniform profile. However, with the off-take present significant pressure forces are introduced, as the flow is diffused upstream of the off-take, which oppose the mixing out of the flow field. Hence whilst in the OGV near field region the turbulent forces continue to dominate, leading to initial mixing out of the profile, eventually these pressure forces become dominant. This results in local deceleration of the flow causing the velocity defects, in the loss core and wake regions, to increase leading to a more distorted profile. Eventually at high pre-diffusion levels these forces may be of sufficient magnitude to cause the flow to reverse in the loss core or blade wake regions. This is further complicated by the boundary layer along the inner casing which will also thicken, and eventually separate, due to the pressure gradient.

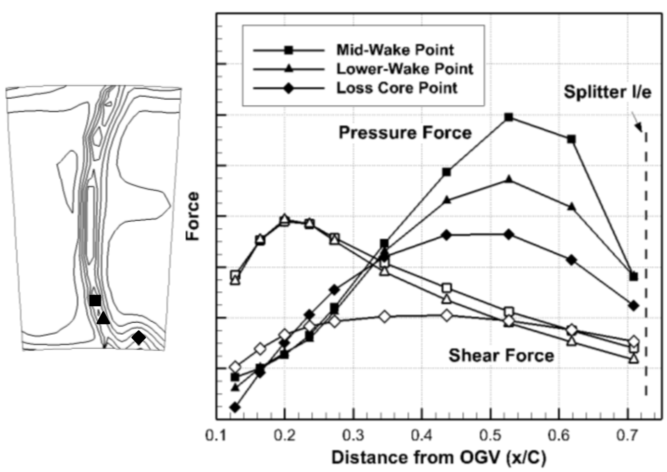

Figure 19: Shear & Pressure Force Comparison (X/C-0.73)

The balance between the turbulent based mixing out of the profile, and the effects of flow diffusion upstream of the off-take, account for the flow characteristics observed at the off-take throat plane. As the amount of pre-diffusion is increased so do the levels of distortion at the throat plane (as reflected by the kinetic energy flux coefficient values). This is indicated by the results obtained for 3 different axial off-take positions (Figure 20). When the gap between the OGV and off-take is relatively small some increase in distortion is observed with increasing pre-diffusion, but in this case the amount of pre-diffusion is limited by the allowable pressure field perturbation at OGV exit (Section 5.1). However, as the gap between the OGV and off-take is increased more pre-diffusion is possible, resulting in the profile at the off-take throat becoming more distorted. Eventually at high pre-diffusion levels (greater than 1.45) local regions of reverse flow are measured at the off-take throat plane. Such distortion of the off-take flow will affect any subsequent diffusion of the flow that might be attempted downstream of the off-take. Not surprisingly the level of distortion, associated with the captured streamtube, is affected by the OGV generated flow field. Hence with the loss cores minimized by removal of the OGV hub gap the levels of distortion for a given level of pre-diffusion do reduce. Nevertheless, these differences are small relative to the overall trend of increasing levels of distortion with pre-diffusion. This also suggests the most significant effects are being captured by the simplified geometry used within the experimental test facility.

In addition to the distortion mass weighted total pressure losses, between OGV inlet and the off-take throat plane, are presented for the flow within the captured streamtubes. For the 3 off-take locations the levels of loss are broadly comparable (Figure 21), but it should also be noted that some level of loss would have been incurred with no off-take present.

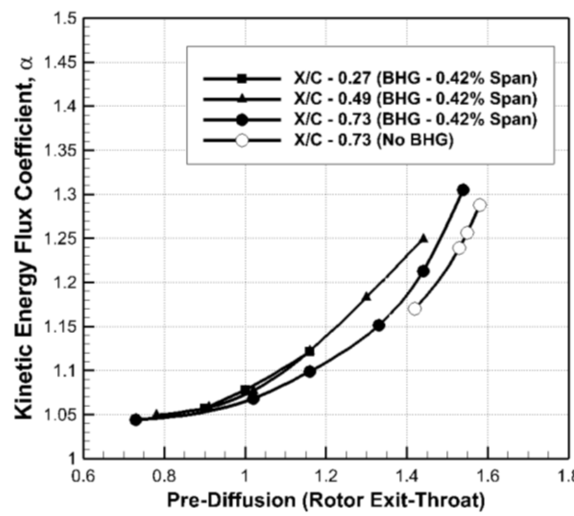

Figure 20: Throat Plane Kinetic Energy Coefficient

With this in mind the loss values for one off-take location are presented (Figure 22) and compared with those obtained with no off-take. In other words for each level of pre-diffusion the loss associated with that captured streamtube has been calculated from the no off-take case (see Section 4). It can be seen that at pre-diffusion levels less than 1.0 (i.e. when the flow is accelerating into the off-take) additional losses are incurred by the streamtube entering the off-take. Analysis of the experimental measurements and numerical predictions indicate this is due to flow acceleration, friction and local incidence effects associated with the flow entering the off-take. Increased losses are also observed at pre-diffusion levels greater than 1.5. As already indicated at these high pre-diffusion levels the flow field is highly distorted and contains regions of reverse flow and potential separation of the inner casing boundary layer. Consequently this results in increased pressure losses relative to the baseline (no off-take) condition. However, at pre-diffusion levels between 1.0 and 1.4 the mass weighted pressure losses incurred by the flow are, if anything, less than those obtained for the baseline configuration with no off-take. However, the losses based on the momentum mixed values are also presented and indicate that these losses will eventually be realized as the profile mixes out further downstream. Nevertheless, the data does suggest that for pre-diffusion levels between 1.0 and 1.4 the losses of the mixed out streamtube (with and without off-take) are broadly comparable. It is only at very high levels of pre-diffusion, or when the flow is accelerated into the off-take, that significant increases in pressure loss are incurred. This also suggests that within a complete system (i.e. including both pre-diffusion and controlled diffusion) there will be an optimum diffusion split between the pre-diffusion and controlled diffusion processes. This is the subject of a continuing study.

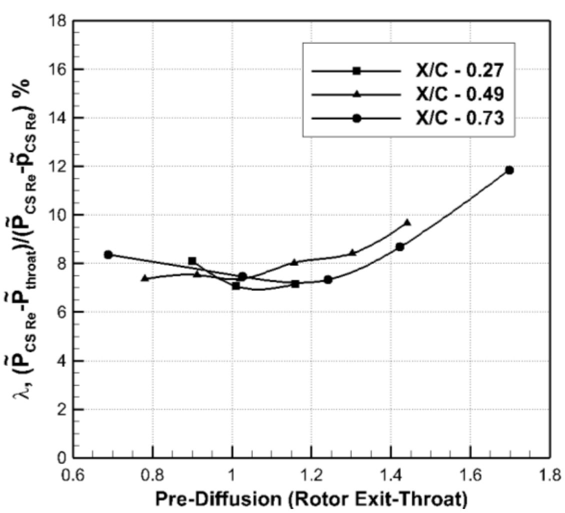

Figure 21: Throat Plane Total Pressure Losses

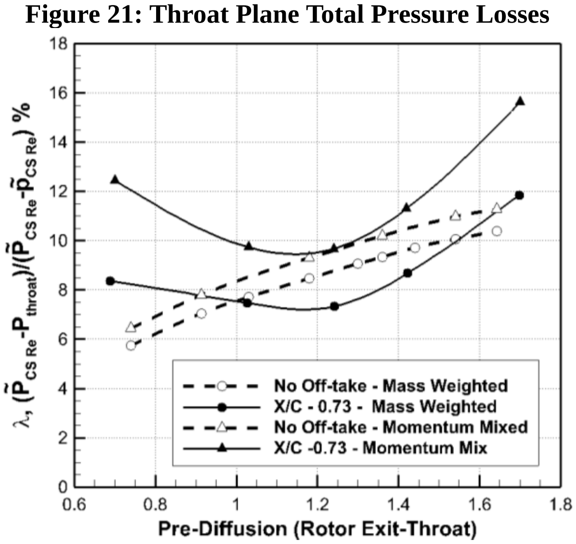

Figure 22: Throat Plane Total Pressure Losses

6. CONCLUSIONS

Results have been presented which define the performance of a pitot style off-take located downstream of an OGV row. Experimental measurements were undertaken in which an OGV blade row was modified to simulate the conditions at the root of a Fan OGV row. The experimental data was also supplemented by various numerical predictions.

The primary aim of the off-take is to obtain a high pressure recovery within a relatively short axial length. The results indicate that when the distance between the OGV and off-take is small, resulting in a compact off-take system, the amount of pre-diffusion is limited by the off-take pressure field and its impact on the upstream OGV row. Information is presented that enable this minimum gap to be determined for a given off-take geometry (e.g. splitter thickness, off-take height) and pre-diffusion level. However, if the off-take is moved further downstream then the effect of the pressure field on the OGV row is reduced. In this case the amount of pre-diffusion is then limited by the more distorted profile and the increased losses that are generated. Nevertheless for modest pre-diffusions (1.0 to 1.4) introduction of the off-take has minimal effect on the mixed out losses.

The current paper concentrates on the flow captured by the off-take. However additional work, that will be reported elsewhere, also considers the performance of the controlled diffuser, downstream of the off-take, and the potential effect of the intake on the by-pass duct flow.

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