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# Stator well flows in axial compressors

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**Abstract**

This paper reports a study of the flow conditions in spaces often found beneath the stationary blades of modern compressors – stator wells. The design of the stator wells in a modern high-pressure turbofan can be a limiting factor. This study shows good comparison with existing experimental data upon the pressures and velocities in related geometries. The deleterious effects upon machine performance of the flows between the stator well and the mainstream are considered. The purpose of this paper is to show that these effects, especially seal leakage, can be reduced by the incorporation of fins on the rotating component of the downstream well. This works by increasing the tangential velocity in this region, so reducing the pressure there and thus the inter-well leakage for a given radial clearance in the intermediate labyrinth seal and hence the outflow into the mainstream from the upstream well. © 2000 Elsevier Science Inc. All rights reserved.

*Keywords:* Stator well; Compressor; Leakage; Sealing; Ingress; Egress

## 1. Introduction

Since the introduction of the gas turbine by Whittle and Von Ohain the hot components of the engine, the combustion system and the turbine, have posed materials problems. Steady improvement in materials properties and the effective use of cooling of the hot components has allowed maximum cycle temperatures to increase continually with the consequent result that the optimum pressure ratio has risen concurrently. With pressure ratios of 60:1 and above now under consideration for large turbofans, compared with the 4:1 of the early engines, temperatures in the high pressure stages of the compression process long ago passed the maximum turbine gas temperature of the early engines and now pose their own material and cooling problems.

Although compressor delivery temperatures are now approaching 1000 K the use of refractory metals developed under the stimulus of the turbine requirement is continuing to allow the complication of blade cooling systems common in turbines since the 1960s to be avoided in compressors. The discs that support the blades, however, with their exposure in engine operation to variable thermal cycling and consequent stresses, are even more critical to the integrity and life of an engine than the blades themselves.

The magnitude and criticality of the thermal cycling are set in the main by the interaction between the discs and the main fluid stream, occurring principally near the peripheries. If the mainstream could be confined to its principal annular passage through the blades, prediction of temperature changes in the discs would be relatively straightforward even with the geometrical complexities of compressors in a modern gas turbine, as demonstrated by the example of Fig. 1. In practice the need to separate moving and stationary components results in an inevitable exchange of hot mainstream fluid with the stator well cavities between the discs. The nature of engine representative stator wells are shown in Fig. 1 and an idealised geometry (currently the subject of extensive rig tests) is shown in Fig. 2. The extent of the ingress and the corresponding egress of the same fluid, often combined with an independently applied flow of cooling air to the internal disc cavities below, determine the temperatures throughout the discs. Further, because pressures increase through the stages of a compressor, a net inflow to the stator wells usually occurs at the downstream seal, to emerge at the upstream exit. Depending upon the relative magnitude and circumferential distribution of the egress, it can divert the mainstream flow with a significant adverse effect upon the aerodynamic efficiency of the compressor.

The fluid dynamics and heat transfer in rotor–stator systems have been studied in detail and widely reported in the literature, and this work is directly relevant to the code validation in the present study. The rotating cavity, in which both discs rotate in the same direction, with a continuous radial flow of coolant are also well understood (Owen and Rogers, 1989). The nature of the flow in the rotating cavity that is sealed at the rim and has an axial flow of coolant through the bores of the discs is still largely unknown since vortex breakdown occurs and the flow becomes 3D and unsteady. There is

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**Notation**

| | |
|---|---|
| $A$ | flow area |
| $C$ | labyrinth tooth clearance |
| $Cp_r$ | pressure coefficient $\rho r_o^2 \Delta p_r / \mu^2$ |
| $P$ | static pressure |
| $P_{o1}$ | inlet total pressure |
| $P_u$ | upstream labyrinth pressure |
| $r$ | radial co-ordinate |
| $r_i$ | inner radius of stator well |
| $r_o$ | radius of rotor at mainstream hub |
| $r_r$ | radius of stator well inner seal lip |
| $u_r$ | local rotor speed |
| $V$ | velocity |
| $V_\phi$ | circumferential velocity |
| $V_r$ | radial velocity |
| $Z$ | axial co-ordinate |
| $Z_r$ | axial width of downstream stator well |
| $\Delta p_r$ | pressure drop from periphery to radius $r$ |
| $\mu$ | absolute viscosity |
| $\rho$ | density |
| $\omega$ | angular velocity |

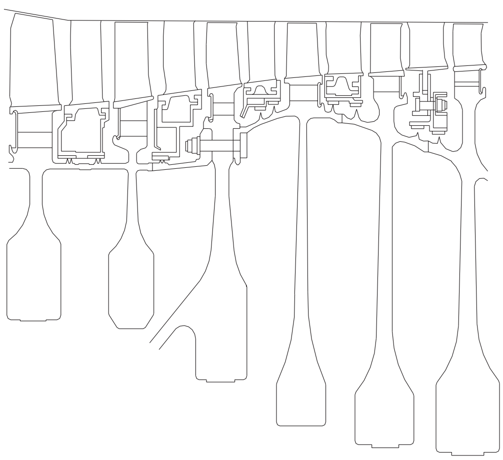

Fig. 1. The HP compressor system of a modern turbofan gas turbine.

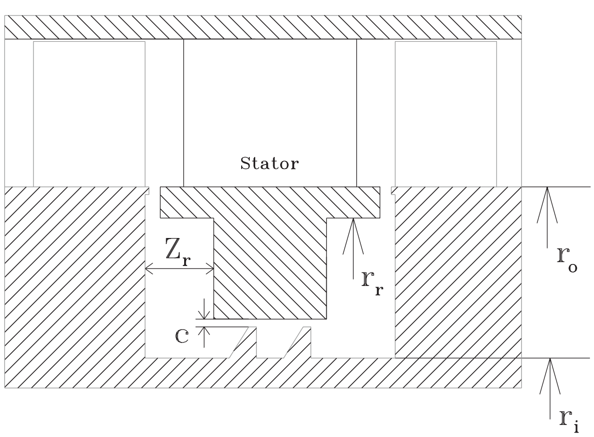


Fig. 2. The datum stator well.

also much less understanding of the interaction of emerging seal flows with the mainstream at the periphery of the system or of the flows themselves within the stator wells at the outer radii throughout the compressor (Bayley, 1999). Wisler and Beacher (1989) considered the effect of the geometry at the stator blade ends and the associated main and secondary flows upon the efficiencies of compressors. Athavale et al. (1995) presented a numerical analysis methodology and solutions for the interaction between flows in the mainstream and those in the cavities below (or radially inside) the disc peripheries. They obtained good agreement between their predictions and the experimental observations of Daniels et al. (1992).

Heidegger et al. (1996) report an extensive numerical analysis also of flows in stator wells and their interaction with the mainstream, demonstrating the magnitudes of the expected consequence of the net outflows and hence of the leakage between adjacent cavities, which was observed to be dependent upon the downstream tangential velocity of the fluid in the stator well. The intercavity leakage is crucial to engine performance since it determines the upstream egress into the mainstream. Too little leakage can cause overheating of the discs in this region but generally, the need is to restrict such leakage and this applies pressure for designers to specify close clearances in the corresponding seals with the possibility of catastrophic failure if this clearance is taken up in regular engine transients. The present work uses computational fluid dynamic methods to analyse numerically the flow in stator wells and the results show how, by increasing the swirl or tangential velocities in the downstream stator well, the leakage through a seal can, to a certain extent, be controlled.

## 2. Analysis

The stator well problem in its entirety offers a considerable challenge to computational fluid dynamic modelling since it is 3D and time dependent. It should normally allow 3D flow of the mainstream through the compressor blade rows, with the time-dependent sharp pressure variations at the blade leading edges, and the periodic high shear interactions with the fluid entering and emerging from the cavities between the discs. For the present work the well-known STAR-CD code was employed, using the standard high Reynolds number $k$–$\varepsilon$ turbulence model with logarithmic wall functions. Initial validation of the system was made with related well-established fluid systems, the free disc, the closed rotor–stator system, the rotor–stator system with a radial out-flow of coolant and flow through a labyrinth seal, all predictions giving satisfactory agreement with published experimental results (Öztürk, 1998).

Attention was then turned to a stator well with the datum geometry as shown in Fig. 2, combining, with respect to the main compressor flow, upstream and downstream wells, separated by the stator shroud and a labyrinth seal with a rotor speed of 8500 rev/min. With external boundary conditions from 3D blade row calculations using the same code, a complete 3D analysis was found to give good results, although expensive of computer time. To model the stator blade row 30, 238 and 14 cells were used in the circumferential, axial and radial directions respectively. For the stator well geometry itself a total of 197 000 cells was used. In earlier work on the present programme (Öztürk et al., 1997) comparisons were made between the 3D analysis and an axisymmetric, 2D analysis. Axisymmetric solutions were achieved for 3000, 4800 and 6500 cells and, with differences between the 4800 and 6500 cell solutions on the order of 2%, grid independence was effectively demonstrated. In the upstream stator well, where the flow is driven generally outwards by the leakage through the labyrinth, the agreement between the two analyses was excellent, especially at the inner radii studied, where the 3D effects from the mainstream were largely abated.

The flow conditions in the downstream well are altogether more complex. Mainstream fluid is driven into this cavity by the pressure rise across the stator and the rate of flow is set by many factors. The circumferential periodically varying pressure above the downstream rim seal means that there are alternately varying regions of radial inflow and radial outflow. As well as the total geometry of the system, of controlling importance are, first, the clearance and impedance of the peripheral rim seal and, crucially, the effectiveness of the labyrinth seal. If the leakage through the labyrinth is sufficiently large, outflow through the peripheral rim seal at this downstream stator well, otherwise driven by the rotating surface and the circumferential pressure gradients, can be suppressed. This was demonstrated by Bayley and Conway (1964), which reports an experimental study of a rotor–stator system with an imposed inflow of fluid similar to the stator well situation.

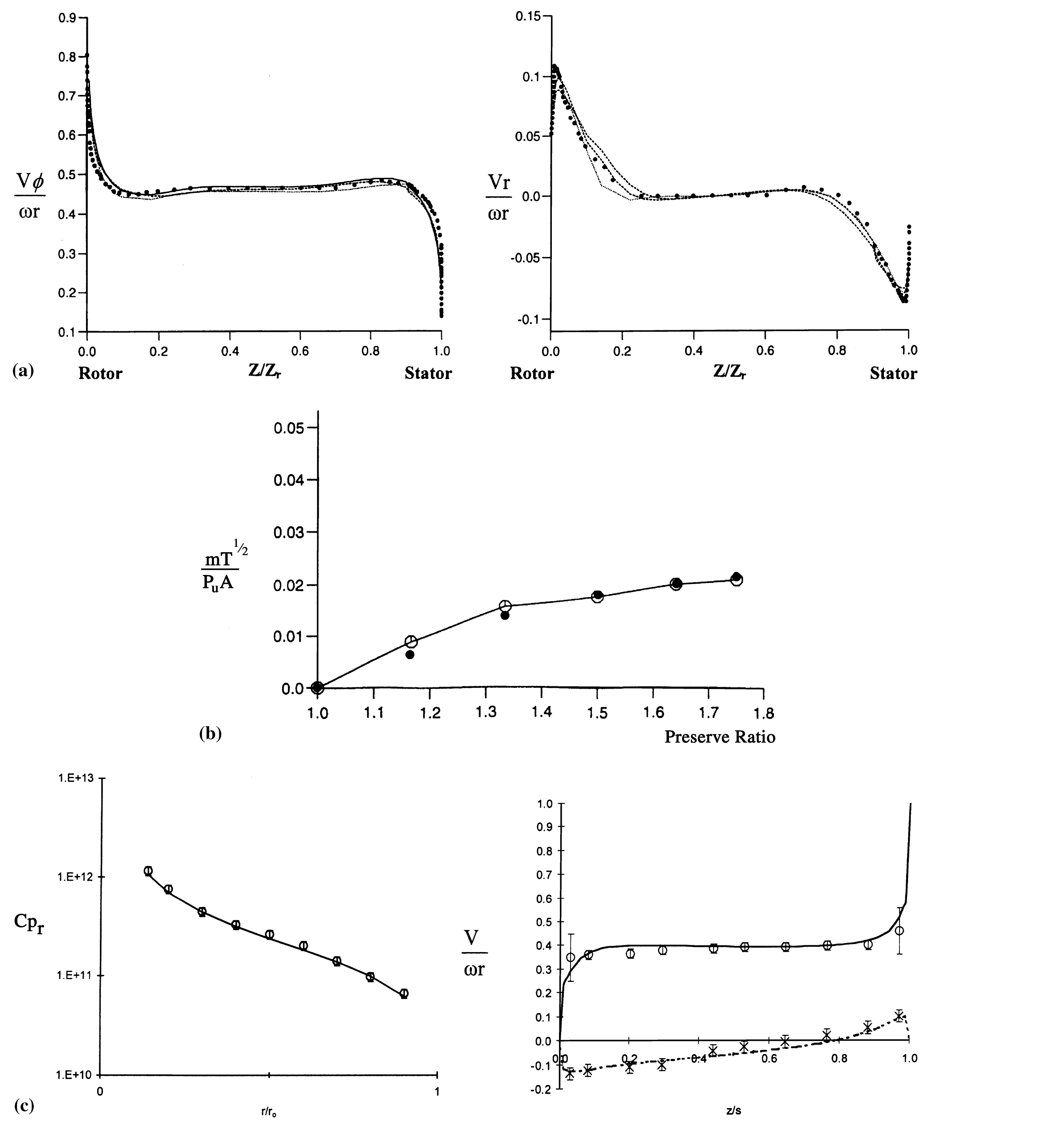


Fig. 3. (a): Predicted and observed tangential and radial velocities for a rotor–stator wheelspace at a radius ratio of 0.94 for three different turbulence models (STAR-CD). Numerical prediction with standard $k$–$\varepsilon$ model – – – –; numerical prediction with RNG $k$–$\varepsilon$ model ············; numerical prediction with two-layer $k$–$\varepsilon$ model – – – –; experimental data (Itoh et al. (1992)) •. (b) Labyrinth seal flow. The predictions of STAR-CD compared with the data of Stocker (1975), predictions –o–; measurement •. (c) Predicted and observed (a) pressures, (b) tangential and radial velocities with inflow in a rotor–stator space (FLUENT) (Scott et al., 2000), tangential velocity CFD ——; tangential velocity experiment ○; radial velocity CFD – – – –; radial velocity experiment 'corrected' ⋇.

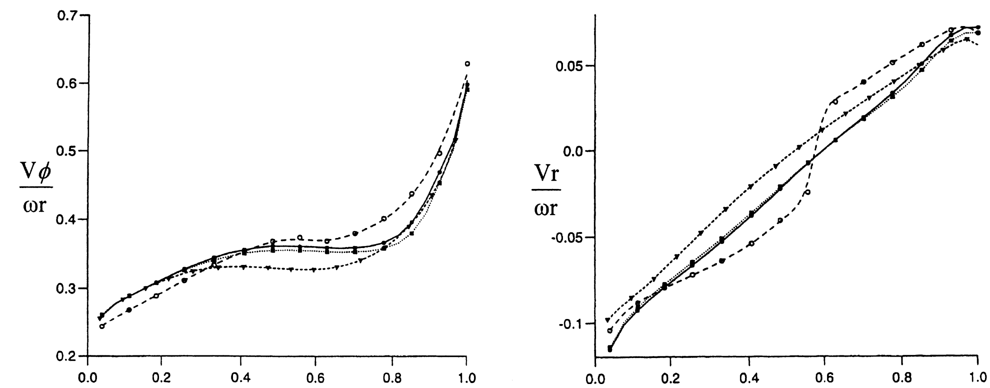


Fig. 4. Comparison of velocities predicted (Öztürk et al., 1997) for 2D and 3D analyses: (a) tangential, (b) radial. Axisymmetric solution —●—; 3D solution without stator blades ····■···; 3D solution with stator blades (compressible flow) --▼--; 3D solution with stator blades (incompressible flow) –⊖–.

The predictions of the CFD code (STAR-CD) were checked against the standard shrouded rotor–stator measurements of Itoh et al. (1992) for various conditions. This comparison is shown, for three different turbulence models, at a radius ratio of 0.94 (which is comparable to that of a stator well ratio) in Fig. 3(a). The predictions with all three models can be seen to be similar, and quite encouraging, with the central 'core' flow predicted well. The standard $k$–$\varepsilon$ model was adopted for all stator well predictions. The predictions of the code were then checked against the standard labyrinth seal data of Stocker (1975). This validation is quite a severe test since the labyrinth seal exhibits several flow separations and reattachments. The comparison shown in Fig. 3(b) is satisfactory. Although the STAR-CD code was not validated for radial inflow, the radial outflow predictions were compared with, and shown to give very similar results to, an equivalent CFD code, FLUENT, again using the standard high Reynolds number $k$–$\varepsilon$ model and logarithmic wall functions, which was checked against the radial inflow data of Bayley and Conway (1964). These predictions, shown in Fig. 3(c), from a programme complementary to the present work, Scott et al. (2000), can be seen to be in excellent agreement with the experimental data.

Fig. 4 compares the predictions of the 2D and 3D analyses for the tangential and radial components of velocity at a radius ratio of 0.3 in the downstream stator well of the present programme. The agreement between the two calculation procedures under the conditions here prevailing indicates that the computer-efficient axisymmetrical procedure is adequate and this is used in the present work for the axisymmetric situations. The case of the fins attached to the rotor in the downstream stator well obviously required a 3D analysis.

## 3. Results

Fig. 5 shows vector plots from the 2D numerical analysis of the stator well of Fig. 2 for the various geometries as listed. The nine different stator well geometries illustrated represent theoretical 'experiments' to examine the effect of axisymmetric changes in the stator well on the leakage flow through it. All the stator well geometries shown have at some time appeared, or been proposed, for engine designs. The core of rotational flow, traditionally found in systems with a rotating surface near to a stationary surface, is manifest in the figure. It is especially evident in the upstream well, although, in all cases liable to modification by the geometric changes. The inflow through the peripheral rim seals to the downstream well is

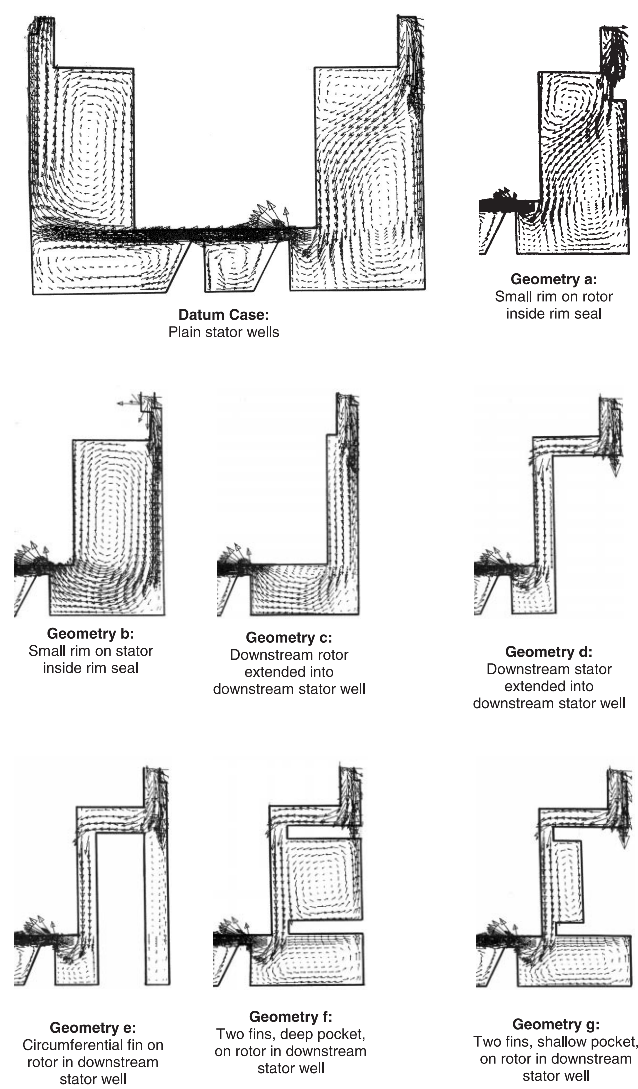


Fig. 5. Velocity vectors for the axisymmetric stator well geometries examined. Only downstream stator well shown for geometries a to g.

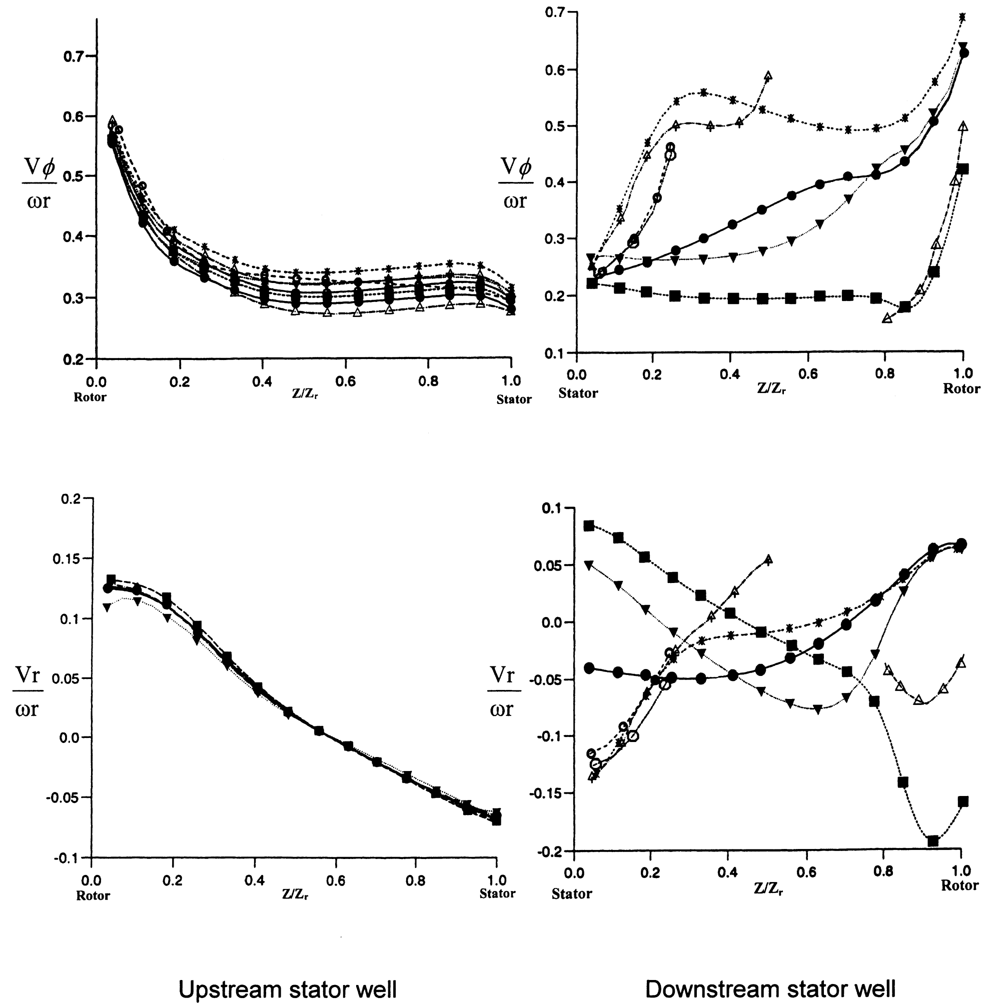


Fig. 6. Radial and tangential velocities in the upstream and downstream stator wells. -●- Datum case; ···▼··· geometry a; -■- geometry b; -ʘ- geometry c; -✱- geometry d; -○- geometry e; -△- geometry f; -▲- geometry g.

clear, as is the corresponding egress from the upstream well. Also clear is the role of the labyrinth gland in generating high velocities at its entry and exit.

Fig. 6 shows the variation in the tangential and radial components of velocity in mid-span of the upstream and downstream wells of all the geometries of Fig. 5. The left-hand figures for the upstream well showed relatively little dependence upon the differences in geometry. The tangential velocity demonstrated the characteristic core rotating at 0.3–0.5 of the local rotor surface velocity. The radial component varies almost monotonically from the slow inward migration on the stator to the centrifugally driven outward 'entrained' flow on the rotor.

The datum system of Fig. 2 had a clearance of 1 mm and further axisymmetric, 2D calculations showed that as the clearance was reduced successively to 0.5 mm and then to 0.37 mm the tangential component of velocity increased in both upstream and downstream wells. Table 1 below shows how the labyrinth leakage, taken as the mass flow rate through the upstream well, is calculated to vary with these clearances and for all the geometries tested. Also shown are the approximate core tangential velocities and although the changing well geometries, apart from the labyrinth clearance, appear to have little effect upon the leakage, there is a tendency for lower values of this to be associated with higher leakage rates through the labyrinth. A similar observation was made in the work of Heidegger et al. (1996). It may be concluded that these geometrical configurations are not worth experimenting with.

It was clear that radial fins on the downstream well rotor face would enhance the tangential component of velocity especially at the inner radii of the well by forcing the fluid close to them into solid body rotation. These fins are illustrated in Fig. 7.

In Fig. 8 predictions of tangential velocity in a downstream well with radial fin extending to $r/r_r = 0.8$ on the rotor face are plotted. The fins extend from the rotor across 50% of the axial width of the cavity and are spaced one stator blade pitch apart. Since the fins will clearly disturb the axisymmetry, for these calculations reversion was made to the 3D analysis and the results are shown as the 'open' symbols. They can be compared with the axisymmetrical predictions at three radial positions in the datum well, shown in Fig. 8 as the filled points.

At the outermost radius, $r/r_r = 0.97$, there is close agreement between the two predictions of tangential velocity near to the rotor. Towards the stator the fins appear to be having some effect, even at this radius, beyond its physical extent. Its powerful effect at the inner radii is demonstrated by the two uppermost curves where the tangential component of fluid velocity is seen to approach the rotor speed over more than half of the axial well space.

Table 1

| | Leakage (kg/s) | Core rotation/ $\omega \cdot r$ |
|---|---|---|
| Datum well – clearance | | |
| 1 mm | 0.071 | 0.35 |
| 0.50 mm | 0.049 | 0.38 |
| 0.37 mm | 0.039 | 0.40 |
| Geometry a | 0.065 | 0.27 |
| Geometry b | 0.075 | 0.20 |
| Geometry c | 0.069 | 0.38 |
| Geometry d | 0.073 | 0.52 |
| Geometry e | 0.069 | 0.38 |
| Geometry f | 0.066 | 0.38 |
| Geometry g | 0.067 | 0.48 |
| Geometry h | 0.067 | 0.49 |

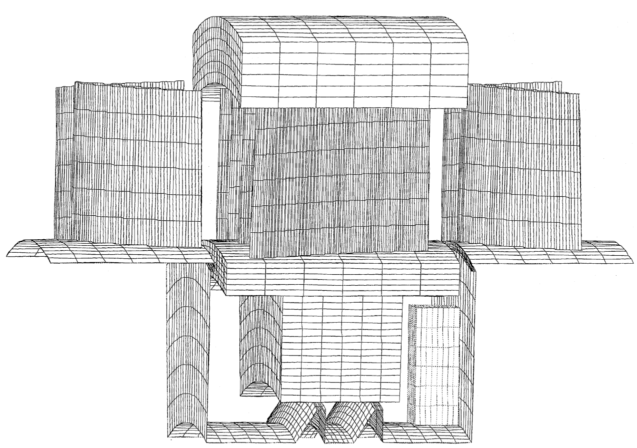

Fig. 7. Radial fins on downstream rotor face.

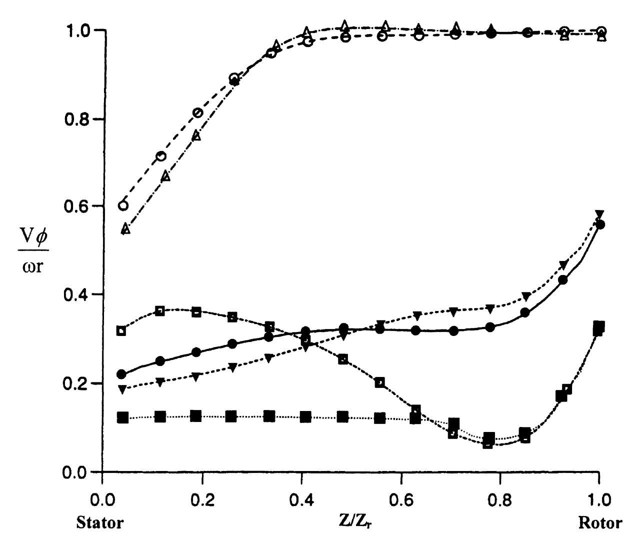


Fig. 8. Effect of radial rotor fins on tangential velocities in the downstream stator well, axisymmetric $r/r_r = 0.3$ —●—; axisymmetric $r/r_r = 0.5$ --▼--; axisymmetric $r/r_r = 0.97$ ····■····; 3D solution with fins on downstream stator well $r/r_r = 0.3$ -⊖-; 3D solution with fins on downstream stator well $r/r_r = 0.5$ -△-; 3D solution with fins on downstream stator well $r/r_r = 0.97$ ····□····.

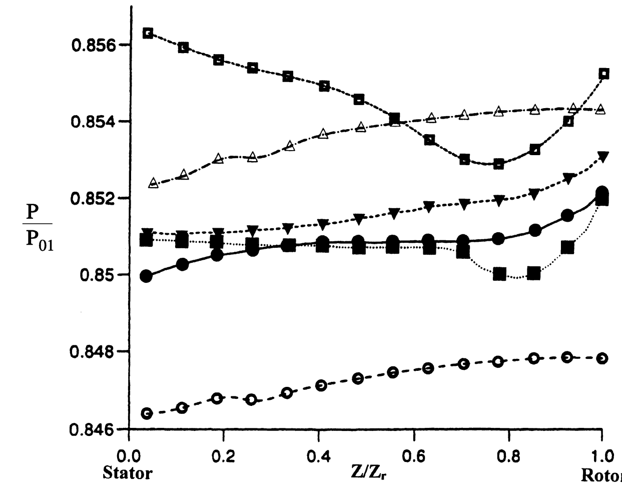


Fig. 9. Effect of radial rotor fins on the downstream stator well pressures, axisymmetric $r/r_r = 0.3$ —●—; axisymmetric $r/r_r = 0.5$ --▼--; axisymmetric $r/r_r = 0.97$ ····■····; 3D solution with fins on downstream stator well $r/r_r = 0.3$ -⊖-; 3D solution with fins on downstream stator well $r/r_r = 0.5$ -△-; 3D solution with fins on downstream stator well $r/r_r = 0.97$ ····□····.

Fig. 9 shows the corresponding pressures in the downstream well. The higher pressures due to the rotation created by the fins are apparent at the outer radii, as is the more significant lower pressure at the inner radius. Integration of the radial velocities at the upstream radial seal showed that the leakage flow, even with the datum labyrinth clearance of 1 mm, had been reduced by these lower pressures at the entrance to the labyrinth seal to 0.052 kg/s. This value is only slightly greater than that with halved clearance as shown in Table 1.

## 4. Conclusion

Flows in compressor stator wells with a range of internal geometries have been studied analytically using validated methods of computational fluid dynamics. Where comparable experimental observations are available, agreement between the analytical predictions and observation are shown to be satisfactory. 2D analyses have been as effective in regions of greatest interest in the stator wells as the more computationally expensive 3D procedures.

In general, the axisymmetric variations in geometry within the wells investigated have had little effect upon the flow conditions. The most significant changes resulted from clearances in the labyrinth gland that, as could be anticipated, controlled the flow between the downstream and upstream wells. Increased outflows from the latter are well-known to have adverse effects upon stage performance. Circumferential or annular fins in the wells to enhance tangential components of velocity were observed also to noticeably change velocities but less so in the upstream wells.

In a downstream well radial fins were found to increase the tangential component significantly, increasing the pressure near the periphery of the well, and, more significantly decreasing that near the inner radius. The resultant effect was roughly equivalent to halving the clearance in the labyrinth gland, an observation of some consequence to machine designers. Bolt heads or nuts in downstream stator wells could be expected to have a similar effect and may explain the sometimes anomalous test measurements of temperature in engine stator wells.

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