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Gas Turbine Engine Internal Air Systems

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Synopsis
The gas turbine engine internal air system provides cooling to various critical components, sealing for bearing chambers and flow paths and controls bearing axial loads. In order to supply the internal air system flow requirement, up to 20% of the engine core flow is extracted from the compressor. This can consume up to 5% of the fuel and it is therefore important to minimise the quantity of air required for the internal air system whilst maintaining functionality of the engine, acceptable component life, robustness and acceptable manufacture costs. For a large passenger aircraft a 1% reduction in specific fuel consumption could save 560 tonnes of fuel per annum and reduce direct operating costs by 0.5% (Smout et al. (2004)). It is therefore extremely important to be able to reduce the uncertainties associated with optimising the system.

A typical internal air system will include a compressor bleed take off, transfer tubes and passages to deliver the cooling and sealing air to critical components and use of differential pressure across disc surfaces to balance bearing loads. A gas turbine engine generally comprises a series of discs for the rotating blades and a stationary casing and support structure. A common feature is the cavity formed between coaxial rotating and stationary discs, which is known as a wheelspace or a rotor-stator cavity. In addition cavities are also formed between co-rotating discs. Components requiring cooling include the combustor, which is normally cooled by the main gas path, the high pressure turbine, parts of which can reach temperatures over 1600 ^{o}C (Rolls-Royce (2005)), and shafts. Components that require sealing include turbine rotor-stator cavities, bearing chambers, transmission systems and the transfer elements delivering system air to the targeted components. Types of seal used include interstitial seals such as labyrinth, bush and rim seals, carbon seals, leaf and brush seals, hydraulic seals and static seals such as strip, cloth and sigma seals.

In aircraft and electric power generation gas turbine engines alike, it is common practice for the cavity formed between a rotating turbine disc and a stationary disc to be purged with coolant air. This air reduces the thermal load of the disc and prevents the ingress of hot mainstream gas into the cavity between the rotating disc and the adjacent stationary casing. However, use of this air is detrimental to engine cyclic performance, and turbine efficiency can be adversely affected by the seal air efflux into the main annulus. The lifetime of the rotor, and the cyclic and component performance of the engine are therefore dependent on the efficiency with which the cavity is purged. The combined requirements to be able to determine the power required to overcome frictional drag, local flow characteristics and associated heat transfer has provided a sustained impetus to investigate a number of rotor-stator disc configurations.

Typically some form of peripheral rim seal is provided to limit the flow ingress or egress and limit mainstream annulus flow spoiling due to interactions with flow in the rim seal region. The flow in an axial bladed stage is highly complex with secondary flows superposed on the mainstream flow path and unsteady effects. The flow conditions are not axisymmetric, with, for instance, pressure and velocity varying with circumferential location and unsteady interactions between one blade row and another. Such asymmetries can significantly affect the conditions in the wheelspace and the associated ingestion. A large range of configurations are possible for rim seals depending on a combination of flow and mechanical requirements including: hade; location of the rim seal relative to the rotor; seal type; the presence of an additional inner seal; supply of cooling air; pressure

gradient; the presence of an inner drive arm as in a turbine or compressor stator well; contra-rotation. The possible combinations identified in this list alone result in several hundred options, indicating the challenge associated with rim seal design and quantifying ingress.

The insight developed in studies on rim seals to date reveal that the flow associated with a rim seal is three dimensional and time dependent. The numerical methods and computational power to undertake such calculations for a complete turbine stage are now available. Jakoby et al. (2004) report the findings from an investigation with unsteady cavity pressure measurements and the requirements to produce sufficiently accurate numerical predictions for both a forward and backward facing axial bladed turbine cavity. A large scale low frequency pulsating rotating structure was identified inside the forward rotor-stator cavity for certain conditions, comprising three low pressure bubbles rotating at about 80% of the rotor speed with a pattern comparable to a 'Mercedes star'. The periodic flow pattern significantly influences the pressure distribution inside the cavity and the sealing effectiveness with ingestion following the low pressure rotating structure. It has been concluded that the low frequency pulsations are not caused by the interaction of the vanes and rotating blades as the frequency of the pulsations was an order of magnitude less than the blade passing frequency. The pulsations disappeared if the superposed cooling exceeded a certain limit. In order to capture the unsteady phenomena involved a full 360° Computational Fluid Dynamics (CFD) model was used.

Many practical rotating disc applications involve protrusions and features, such as bolts and hooks, attached to either the stationary disc or the rotating disc in a rotor-stator cavity. The protrusions can significantly influence the local flow and heat transfer in the vicinity of the features and as a result the power required to overcome viscous drag.

Air extracted from the compression system for turbine cooling and rim sealing is often led through the annular passage formed between disc bores and a central shaft. This air provides a degree of ventilation of the rotating cavities formed between adjacent compressor discs. Knowledge of the flow and heat transfer within these cavities is needed for accurate disc stressing and life calculations, so an understanding of the physical mechanisms is required. A cavity formed between two co-rotating co-axial discs is thus a common feature in compressor and turbine rotor assemblies. The range of configurations possible is extensive. In general the cavity comprises two discs separated by an axial gap, with a shroud located at the outer radius. The flow behaviour in a rotating cavity is strongly dependent on whether there is a throughflow of air in the cavity and on the relative temperature between the components.

Closed cylindrical and annular cavities are a common feature in compressor and turbine rotor assemblies. It is convenient to consider the three different geometric and heating configurations. For steady state conditions in an isothermal cavity or annulus, where all the surfaces are at the same temperature as the fluid, there is no relative motion of the fluid inside the cavity and the fluid rotates as a solid body. For non-isothermal flow, buoyancy forces are generated from the centrepetal acceleration and density variations in the fluid. The buoyancy forces result in fluid motion relative to the bounding surfaces that depends on the geometrical and heating configuration. For the case of an axially directed heat flux, where there is a temperature difference between the two discs, fluid moves radially inward adjacent to the hot disc and radially outward adjacent to the cooler disc. In a cavity with no central shaft, there is an additional recirculation zone close to the axis of rotation, but in an annular cavity this feature is not present. For the case of a radially directed heat flux where there is a temperature difference between the inner and outer peripheral surfaces, Bohn et al. (1993) found a series of cyclonic and anti-cyclonic recirculations. A separate numerical study by King et al. (2005) also showed, for the case of a closed rotating cavity where the outer surface is hotter than the inner, that Rayleigh Bénard convection could occur with counter rotating cyclonic and anti-cyclonic vortices. For a rotating inviscid fluid a radial velocity is only possible if there is a

circumferential pressure gradient. Without a pressure gradient, the flow would be thermally stratified and convection would not take place. The counter rotating cyclonic and anti-cyclonic vortices generate regions of low and high pressure respectively which provide the circumferential pressure gradients enabling convection to occur.

A radial outflow is sometimes used to remove heat from a co-rotating turbine disc cavity. The flow can be characterised in many cases by a rotating inviscid core and disc boundary layers. In a gas turbine engine, air extracted from an axial compressor is sometimes drawn radially inwards between two co-rotating discs. This flow can be also characterised by a rotating inviscid core and disc boundary layers (ESDU (2006)). Practical engine geometric configurations can involve many rotating cavities with flow between successive rotating cavities and associated interactions. Simultaneous measurements of the axial and tangential velocity components V_z and V_ϕ have been made inside using Laser Doppler Anemometry (LDA) for a rig with four rotating cavities and are reported at this conference by Long and Childs (2006).

Many axial compressors make use of shrouds on the inner radius of the stator blades to provide mechanical stiffness and to reduce over tip leakage. Their inclusion requires a trench in the compressor drum. This provides an additional leakage path, interaction between the shroud/rotor clearance flows and mainstream flows, and a source of unwanted windage heating. Nozzle guide vanes are also frequently shrouded on the inner radius in order to negate ‘over tip leakage’ and for structural mechanical reasons. Rim seals are used to control the effects of interaction between the trench or stator well flow and mainstream annulus flows. Cooling air is supplied to some stator wells in order to dissipate windage heating.

An established method of introducing cooling air to the cooling passages in a turbine rotor is by accelerating it through inclined pre-swirl nozzles to achieve a high circumferential velocity component before the rotating the rotating feed holes. Thus the total temperature of the coolant airflow, relative to the rotor, is reduced with consequent benefits to the cooling system. In an ideal design, the pre-swirled coolant flow would penetrate the cavity, enter the blade feed holes in the rotating turbine disc and be pumped out through the blade cooling passages without ever coming into contact with the comparatively ‘hot’ disc cooling air. In practical engine geometries however, where disc cooling or sealing air is used to prevent the life degrading effects of mainstream gas ingestion there will be a complex adverse interaction as the pre-swirl air sweeps the hotter disc cooling air towards and into the rotating feed holes. The effectiveness of a pre-swirl system is described by the maximum achievable temperature decrease and the discharge coefficients of the pre-swirl nozzles and receiver holes. The flow inside the cavity is dominated by the interaction of the jet from the pre swirl nozzle and the main swirling flow driven by the jets and the rotor with the receiver holes. The propagation of the jet and the reduction of jet velocity distribution are clearly noticeable across the pre-swirl cavity. At the exit of the nozzle the tangential velocity can reach more than 90% of the theoretical isentropic tangential velocity. Depending on the speed of the rotor three main flow regimes could be observed, under swirl, nominal swirl and over swirl, leading to different efficiencies and pressure losses of the pre-swirl system (Childs et al. (2006)).

It is common practice for cooling air to be channelled from the compressor delivery to the turbine through the high pressure drive cone cavity. This cavity is bounded by the rotating drive shaft on the inside and the flame tube casing on the outside. Knowledge of the flow and heat transfer in this region is needed to predict rotor and cooling air temperatures. Rotor temperatures in this cavity can be a limiting factor in design, and air delivery temperatures have obvious impact on turbine cooling performance.

The theory of rotating fluids is important to a wide range of applications in engineering and science and especially relevant to the internal air system of a gas turbine engine. There are many subtle

interactions between fluids and associated structures and boundaries that produce vorticity and secondary flows. An interest in the fluid flow associated with machinery may stem from the need to know the losses associated with windage or requirements for sealing or cooling. There are fundamental differences between rotating and linear flows and it is the Coriolis terms that are responsible for the differences between the dynamics of non-rotating and rotating fluids,. These give rise to complex flow phenomena that are often non-intuitive to the practising engineer. It is these flows that make the subject area interesting and an on-going challenge despite advances in modelling and data available.

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