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ORIGINAL ARTICLE

Theoretical modelling of hot gas ingestion through turbine rim seals

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Abstract The rim seals of gas turbines are used to prevent or reduce the ingestion of hot mainstream gas into the wheel-space between the turbine rotor and its adjacent stationary casing. The ingestion is caused by local pressure differences between the mainstream and the wheel-space; ingress usually occurs where the mainstream pressure is higher than that in the wheel-space and egress occurs where it is lower. Sealing air, which is supplied to the wheel-space, flows through the seal clearance and joins the mainstream flow. Too much sealing air is inefficient; too little can lead to disastrous consequences. The nozzle guide vanes create three-dimensional (3D) variations in the distribution of pressure in the mainstream annulus and the turbine blades create unsteady effects. Computational fluid dynamics (CFD) is both time-consuming and expensive for these 3D unsteady flows, and engine designers tend to use correlations or simple models to predict ingress. This paper describes the application of simple 'orifice models', the analytical solutions of which can be used to calculate the sealing effectiveness of turbine rim seals. The solutions agree well with available data for externally-induced ingress, where the effects of rotation are negligible, for rotationally-induced ingress, where the effects of the external flow are small, and for combined ingress, where the effects of both external flow and rotation are significant.

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1. Introduction

Figure 1 illustrates a typical high-pressure gas-turbine stage showing the rim seal and the wheel-space between the stator and the rotating turbine disc. Sealing air is

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Nomenclature

A	constant for variable $C_{d,e}$
A_c	seal-clearance area
A_e, A_i	areas for egress and ingress in seal clearance
b	radius of seal
$C_{d,e}$, $C_{d,i}$	discharge coefficients for egress and ingress
C_p	pressure coefficient ($C_p = (p_2 - p_1)/\left(1/2\right)\rho\Omega^2 b^2$)
$C_{p,max}$	nondimensional pressure difference ($C_{p,max} = \Delta p/\left(1/2\right)\rho W^2$)
C_w	nondimensional flow rate ($C_w = \dot{m}/\mu b$)
$C_{w,min}$	minimum value of $C_{w,0}$ to prevent ingress
$C_{w,0}$	nondimensional sealing flow rate
C_{β_1}	modified internal swirl ratio ($C_{\beta_1} = \beta_1^2/\left(1 - r_1^2/r_2^2\right)$)
G_c	seal-clearance ratio ($G_c = s_c/b$)
K	constant in EI asymptote
$\dot{m}$	mass flow rate
p	absolute static pressure
P_{max}	nondimensional pressure parameter ($P_{max} = \left(1/2\right) C_{p,max}\, Re_w^2$)
r	radius
Re_w	axial Reynolds number in annulus ($Re_w = \rho W b/\mu$)
Re_ϕ	rotational Reynolds number ($Re_\phi = \rho\Omega b^2/\mu$)
s_c	seal clearance
U	bulk-average velocity through seal clearance
V_r, V_ϕ	radial, tangential components of velocity
W	axial velocity in external annulus
β_1	swirl ratio in wheel-space ($\beta_1 = V_{\phi_1}/\Omega b$)
Γ_c	ratio of discharge coefficients ($\Gamma_c = C_{d,i}/C_{d,e}$)
$\Gamma_{\Delta p}$	ratio of driving forces for EI and RI ingress ($\Gamma_{\Delta p} = \Delta C_p / C_{\beta_1}$)
ΔC_p	external pressure coefficient ($\Delta C_p = \Delta p/\left(1/2\right)\rho\Omega^2 b^2$)
Δp	peak-to-trough pressure difference in annulus
ε	sealing effectiveness ($\varepsilon = 1 - \Phi_i/\Phi_e$)
θ	angular coordinate between vanes
μ	dynamic viscosity
ρ	density
Φ	flow parameter ($\Phi = C_w/2\pi G_c Re = U/\Omega b$)
Φ_e	value of Φ when $C_w = C_{w,e}$
Φ_i	value of Φ when $C_w = C_{w,i}$
Φ_{min}	value of Φ_o when $C_{w,0} = C_{w,min}$
Φ_o	value of Φ when $C_w = C_{w,0}$
η_t	flow parameter for RI ingress
Ω	angular velocity of rotating disc

Subscripts

CI	combined ingress
e	egress
EI	externally-induced ingress
i	ingress
max	maximum
min	minimum
o	superposed flow
RI	rotationally-induced ingress
1,2	locations in wheel-space and annulus
*	value when $\Phi_o = 0$

supplied to the wheel-space, and it leaves through the clearances in the rim seal.

Figure 2 shows the view looking radially inward into the space between the stationary vanes and rotating blades in the annulus of an experimental rig. The figure, which was adapted from the paper of Zhou et al. [1], shows that the flow past the vanes and blades creates a three-dimensional (3D) variation of pressure radially outward of the rim seal. Ingress and egress occur through those parts of the seal clearance where the external pressure is instantaneously higher and lower, respectively, than that in the wheel-space; this non-axisymmetric type of ingestion is referred to here as externally-induced (EI) ingress. Although the sealing air can reduce ingress, too much air reduces the engine efficiency and too little can cause serious overheating, resulting in damage to the turbine rim and blade roots.

Even when the external flow is axisymmetric, so that there is no circumferential variation of external pressure,

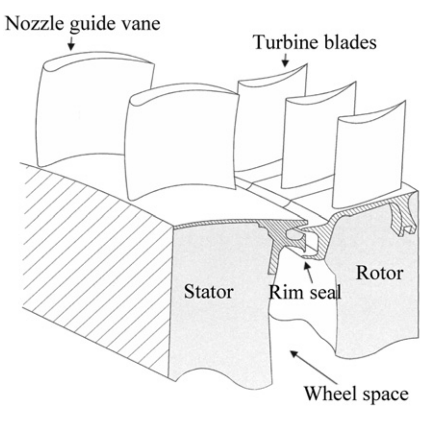

Figure 1 Typical high-pressure turbine stage showing rim seal and wheel-space.

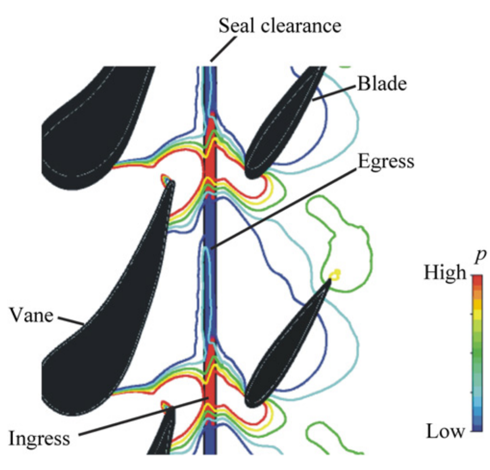

Figure 2 Computed pressure contours between vanes and blades of experimental rig (adapted from Zhou et al. [1]).