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Performance of radial–axial clearance rim seal in realistic working conditions

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ABSTRACT

Performance of radial–axial clearance rim seal (RACS) in realistic working condition is investigated and compared with axial-clearance rim seal (ACS), radial-clearance rim seal (RCS) in this paper. Authors use the numerical method of conjugate heat transfer for calculation to accurately take heat transfer between the rotor–stator cavity flow and the solid discs into account. Results show that seal effectiveness and cooling effectiveness of RACS are the best when compared with ACS and RCS, the minimum mass flow rate for seal of RACS is 75% of that of RCS, and 34.6% of ACS.
RACS has higher air-cooled aerodynamic efficiency, minimizing the mainstream performance penalty when compared with ACS and RCS. Corresponding to the respective minimum mass flow rate for seal, the air-cooled aerodynamic efficiency of RACS is 23.71% higher than that of ACS, and 12.79% higher than the RCS. Finite element analysis in turbine disc shows that RACS minimizes the flow rate of cooling air required for suppressing the radial growth of turbine disc in the three rim seal types. Mass flow rate of the required cooling air of RACS is approximately 40.9–52.9% of that of ACS, and 70–75% of RCS.

1. Introduction

In modern aviation gas turbine, about 10% to 30% compressed air of the high pressure compressor is bled from several compressor stages to complete cooling, sealing and other functions of internal cooling air system of aviation gas turbine. Using this bled flow in an efficient way is critical to compressor efficiency, cooling effect of turbine, engine reliability and life. Johnson et al. [1] showed that 50% reduction in the amount of bled flow increased the whole efficiency of 0.5% for a two-stage turbine, while reducing fuel consumption by 0.9%.

From 1998 to 2005, European research institutions participated in the Internal Cooling Air System of gas turbine (ICAS-GT and ICAS-GT 2) programs to reduce 1% rated fuel consumption of the aviation gas turbine by reducing the air consumption of the air system [2–4]. In Main Annulus Gas Path Interactions (MAGPI) program, flow and heat transfer characteristics in rim seal are of interest [5,6].

Owen et al. [7–11] developed the orifice model to estimate the ingress behavior, which was classified as RI (Rotationally-induced ingress) and EI (Externally-induced ingress). Sangan et al. [12] well validated the orifice model against the experimental data and proposed the double-clearance rim seal to reduce the required flow rate for seal. Scoibe et al. [13,14] found that the finned double rim seal reduced the minimum mass flow rate for seal approximately 10% when compared to the double-clearance one.

Bohn et al. [15–17] also focused on the effect of rim seal geometry and configuration on main flow ingestion into rim cavity of axial turbine stage, and calculated the minimum sealing flow rate by the information of main flow and seal geometry. Chew et al. [18,19] combined experimental and three-dimensional computational fluid dynamics (CFD) calculations to understand rim seal problems, and indicated that the asymmetric annulus flow provided the dominant driving force for main flow ingestion, as well the disc pumping effect increased the level of ingestion.

Luo et al. [20,21] proposed that the concentration-based and temperature-based seal efficiencies of rim seal were similar but different. Due to the increase of thermal diffusivity, the annular flow ingress ability was enhanced, and the difference of the concentration-based and the temperature-based sealing efficiencies increased with the increase of the mainstream temperature.

That is to say it is difficult to apply the concentration-based seal performance obtained from mass transfer experiment conducted in room temperature to realistic working condition with high temperature. Therefore, numerical method of conjugate heat transfer (CHT) is used to predict the heat and mass transfer between hot mainstream, cooling air and turbine discs in rotor–stator system under real aviation gas turbine working conditions. Minimum mass

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Nomenclature

b	radius of seal	m
C_F	flow coefficient, Re_w/Re_φ	
C_p	external pressure coefficient	
C_S	heat capacity of solid	J/kg·K
C_P	heat capacity of fluid	J/kg·K
C_w	non-dimensional flow rate, $\dot{m}/\mu b$	
G_c	seal-clearance ratio, $s_{c,ax}/b$	
$\dot{m}$	mass flow rate	kg/s
P	pressure	Pa
r	radius	m
T	temperature	K
Re_φ	rotational Reynolds number, $\rho\Omega b^2/\mu$	
Re_w	axial Reynolds number, $\rho W b/\mu$	
W	axial velocity	m/s
y^+	non-dimensional distance	

Greek letters

β	swirl ratio	
γ	linear strain	
ε_{seal}	seal effectiveness	
$\varepsilon_{Thermal}$	cooling effectiveness	
η	air-cooled aerodynamic efficiency	
θ	angular coordinate between vanes	
Θ_w	non-dimensional temperature	
λ	thermal conductivity of fluid	W/m K
λ_S	thermal conductivity of solid	W/m K
λ_T	turbulence flow coefficient, $m/\mu b Re_\varphi^{0.8}$	
μ	dynamic viscosity	N s/m^2
ρ	density	kg/m^3
π	thermal clearance coefficient	
Φ	non-dimensional sealing parameter, $C_w/(2\pi G_c Re_\varphi)$	
$\Phi_{\min}$	value of Φ when $\varepsilon_{seal} = 0.99$	
Ω	angular speed of disc	rad/s
ω	rotational speed	rpm

Subscript

ax	axial
a	annulus
0	cooling/sealing air
c	clearance
rad	radial
S	solid
r	rotor
s	stator
ϕ	tangential
ref	reference

Abbreviations

ACS	axial-clearance rim seal
CFD	computational fluid dynamics
CHT	conjugate heat transfer
EI	externally-induced ingress
FEA	finite element analysis
GT	gas turbine
ICAS	internal cooling air system
LE	leading edge
RACS	radial–axial clearance rim seal
RCS	radial-clearance rim seal
RI	rotationally-induced ingress
TE	trailing edge

flow rate for seal, air-cooled aerodynamic efficiency, as well the offset in hot running rim seal clearance are determined and compared in three typical rim seal types (ACS, RCS and RACS) to obtain the best one under realistic working condition.

2. Numerical method and validation

2.1. Objective for numerical method validation

Fig. 1 shows the cross section of the test rig in Univ. of Bath [9]. Radial inflow of cooling air flows into the rotor–stator cavity to cool turbine disc, and prevent hot gas ingestion from annulus to cavity region. Red parts represent the stationary components, and the blue parts represent the rotating components, stationary and rotating disc constitute a rotor–stator cavity. Axial-clearance rim seal (ACS) is the simplest rim seal structure to protect turbine discs from burn caused by hot gas ingestion.

Numerical model and method are validated against the test results published in previous work [9]. Turbine disc geometry and blade profile consistent with the test rig. The objective for validation is ACS, as shown in Fig. 1. Radius of ACS b is 190 mm, axial seal clearance $S_{c,ax}$ is 2 mm, and the seal-clearance ratio G_c is 0.0105. Axial gap between stator trailing edge (TE) and rotor leading edge (LE) is 12 mm. Details dimensions of ACS and turbine discs are also shown in Fig. 1.

2.2. Numerical method and parameter definition

In modern industrial aviation gas turbines, the heat load on high pressure turbine disc in the whole internal cooling air system is the largest. Temperature distribution in high pressure turbine disc is closely related to the convection and heat conduction of main flow, superposed cooling air in turbine cavity, and the rim seal performance.

Temperature and aerodynamic distributions in turbine discs in rotor–stator system are predicted by the conjugate heat transfer (CHT) calculation, and applied to the further thermoelastic coupling calculation as boundary to obtain the mechanical characteristics in turbine discs in finite element analysis (FEA). Diagram of the whole numerical method is shown in Fig. 2.

Flow and heat transfer characteristics of turbine cavity with rim seal are calculated in the commercial CFD program ANSYS CFX 14.5 with the steady-state assumption. Fluid region and CHT solid region can be calculated simultaneously by CFX solver. CHT calculation does not require thermal boundary conditions and heat transfer coefficient to definite solution and therefore have greater accuracy [22,23]. RANS are solved in the fluid calculated region and the Fourier equation is solved in the solid calculated region. Test showed that a CHT model with SST k–ω turbulence model seems to best capture the pressure and metal temperature trends from test rig data in the previous work [24,25]. Thus, the SST k–ω turbulence model is used in this paper. In fluid region, the governing equations are employed to solve fluid parameter, such as pressure, velocity and temperature. The energy conservation equation (Eq. (1)) is:

$$\nabla \cdot \left(\vec{u}(\rho h_t + p)\right) = \nabla \cdot \left(\lambda \nabla T + (\bar{\bar{\tau}} \cdot \vec{u})\right) + \vec{u} \cdot \vec{F} \quad (1)$$

where, h_t is total enthalpy, λ is thermal conductivity of fluid. In CHT solid region, the energy equation is used to solve temperature, energy conservation equation is simplified into the Fourier heat