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Leakage reduction by optimisation of the straight–through labyrinth seal with a honeycomb and alternative land configurations

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ABSTRACT

The labyrinth seal with a honeycomb land is one of the most typical sealing solutions used in gas turbines. The paper presents an analysis of a straight-through seal with two fins. Such seals are used in places with limited space and where design and tribological constraints are of great importance. At a small number of the labyrinth fins, an improvement in the labyrinth performance can bring notable operating benefits.

The paper presents optimisation of the seal labyrinth with different geometrical land configurations. The first part describes the labyrinth seal geometry and individual land types. The analysis covers seals with a honeycomb land, a squeezed-honeycomb land, a rhomboid land and a smooth land. The seal computational model and the optimisation task algorithm are presented. The objective function is minimization of the discharge coefficient, and the parameters are the labyrinth geometrical quantities: the fin height, the fin position, the fin thickness and the fin inclination angle. The optimisation task is solved for each land type.

The results of individual optimisation tasks are presented and discussed, and the potential for improvement in the seal efficiency by means of appropriate selection of both the labyrinth parameters and the type of the land is pointed out. The obtained values of the reduction in the discharge coefficient reach 18% compared to the reference labyrinth configuration. However, taking account of both the labyrinth and the land shape, the benefit of 22.4% is achieved in comparison to the reference configuration with a honeycomb land.

1. Introduction

In gas turbines, it is necessary to separate rotating elements from stationary ones in a manner that ensures the highest possible leak tightness of the main flow channel and of the auxiliary channels responsible for the cooling of elements exposed to high temperatures. Due to the high temperature of the turbine elements and the working medium, combined with high peripheral speeds and considerable changes in loads, clearance (non-contact) seals are typically used as the solution applied in aero-engines. The most common are labyrinth seals. The possibility of using small clearances to achieve a reduction in leakage is limited by the risk of rubbing. In order to make the clearance smaller on the one hand, and minimize the potential effect of rubbing on the other, special lands are used on the stationary elements above the seal fins. Considering the favourable density-to-rigidity ratio of the honeycomb land, this type is the most popular.

Due to the complex phenomena occurring in the flow through a labyrinth seal, the flow is rather difficult to describe. Many analytical formulae are known that characterize flows through seals (e.g. [1–4]), but their agreement with the experiment varies. In their design practice, manufacturers use sophisticated computational procedures incorporating a number of in-house-developed confidential corrections and coefficients (e.g. [5,6]).

The intensive works on new turbine designs require a search for additional opportunities for an improvement in efficiency. The application of more advanced methods of the flow analysis, the precise state-of-the-art CFD analyses, in particular, enables a better understanding of the physics of the phenomena and, owing to that, implementation of new design solutions.

Simulations of the flow through labyrinth seals are usually performed using a steady-state model based on the Reynolds-averaged Navier-Stokes (RANS) equations. In the beginning, computations were carried out for two-dimensional models of the

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Nomenclature

A	flow surface area, m^2
B	labyrinth fin thickness, m
C_D	discharge coefficient, –
L	cell dimension, m
m	mass flow rate, kg/s
p	pressure, Pa
R	individual gas constant, J/(kg K)
s	clearance, m
t	labyrinth wall thickness, m
T	temperature, K
x	distance in a radial direction, m
w	domain width, m

Greek letters

$\zeta_{geom} = s_{eff}/s_{nom}$	geometrical parameter, –
π	pressure ratio, –
κ	specific heat ratio, air $\kappa = 1.4$

Subscripts

0	total parameter
eff	effective
nom	nominal

Abbreviations

HC	honeycomb
FFA	first fin angle
FFP	first fin position
SFA	second fin angle
SFP	second fin position
FH	fin height

smooth-land seal, e.g. [7]. Using a two-dimensional model in [8], differences were obtained in the leakage mass flow rate of up to 4% compared to a three-dimensional model. The model took account of the honeycomb land and the boundary layer area. In the years that followed, simulations were performed on three-dimensional models for the channel domain width limited to single cells of the honeycomb, e.g. [9–12].

The leakage values determined by means of analytical correlations or numerical computations frequently differ from the results obtained from the experiment. The biggest divergences occur for values for which the correlations or computations were not calibrated. The differences between the results are also dependent on the number of fins, the applied land type and the channel shape. In [13] the authors compare analytical correlations to experimental results and numerical computations for the smooth-land seal. Depending on the model and the goodness of fit of the correlations, the errors totalled up to 30% for straight seals with three fins. The differences in the discharge coefficient values obtained from numerical computations and experiments were of a few to about fifteen per cent. The accuracy of the applied analytical solutions rose with a rise in the number of fins; it was also higher for stepped seals. In [14], the leakage mass flow measurement performed for a straight seal with four or five fins on a stationary testing stand is compared with the results obtained from an analytical model and from numerical calculations. The difference totals 30% and 20%, respectively. Kim and Cha [15] compare the discharge coefficient values for straight seals and for a stepped seal with five or six fins. The obtained numerical results agree with the experiment, but the applied analytical formulae give results which are by up to 10% different from it. It is found that the differences between the calculations and the experiment get smaller with a rise in the number of fins.

Numerical computations are most often performed using the two-equation k-ω SST or k-ε turbulence models. Based on previous works, it is impossible to unequivocally pinpoint the relationship between the turbulence model and the solution accuracy in relation to the experiment. The k-ω SST turbulence model is used in [11] to conduct a numerical analysis of a seal with four fins and a straight-through flow channel with a honeycomb land. The obtained results differ from the experiment by up to 11%. The k-ω SST model is also applied in [16] to characterize the flow through a smooth-land seal with six fins. In this case, the differences are at the level of 3% compared to the results of the experiment. Using the k-ε turbulence model, Denecke et al. [17] obtained results differing from the experiment by less than 7%. In [18], the agreement of the results between the calculations performed by means of the k-ε turbulence model and the experiment totals about 2%, whereas in [19] – it is about 1.6%.

The solutions aiming to improve the seal efficiency are usually related to changes in the shape of the labyrinth or modifications of the land cells.

In the beginning, the methods of finding the labyrinth optimum shape were limited to a systematic search of the design space. Rhode et al. [20] changed the fin pitch, the fin width, the step height and the stepped labyrinth seal clearance assuming that the step kept the same relative axial position.

The authors performed CFD calculations and finally tested the optimal seal experimentally. The leakage reduction was prominent.

Aboulaich et al. [21] proposed the optimal shape of a domain for a single cavity as a result of the maximum of a mathematical formula. The straight labyrinth seal was investigated using a finite-element code and the optimal shape for the laminar incompressible flow was found.

The annealing method for optimisation was used in [22] to reduce the mass flow rate through a three-finned, stepped labyrinth seal. The step position and the step height are assumed to be parameters. In comparison to the reference geometry, the discharge coefficient of the new seal was reduced by about 10%.

Advanced research of the stepped labyrinth seal with a smooth land was performed by Schramm [23]. The optimal design of the two-finned seal was proposed by means of a genetic algorithm. The reduction in the leakage coefficient totalled about 19% and 24% for the clearance 0.8 mm and 0.3 mm, respectively.

Successful results in the improvement in the stepped seal configuration were obtained in [24]. The Goal-Driven Optimisation scheme was used to find a new design of the labyrinth and cavity geometry for the rotor tip seal with a honeycomb land.

Different optimisation techniques were used in [25] – Goal-Driven Optimisation and metamodel-based optimisation with both the Design of Experiment method and a genetic algorithm. The two techniques produced the same design of the two-finned labyrinth of the straight-through type.

A reduction in the leakage mass flow can be achieved by appropriate selection of the relation between the land cell and the labyrinth dimensions. The minimum leakage for small clearances is obtained for fins that satisfy the relation $B/L > 0.5$, i.e. for the case