EXPERIMENTAL AND NUMERICAL VALIDATION STUDY OF THE LABYRINTH SEAL CONFIGURATIONS

A. Szymański, S. Dykas, W. Wróblewski, D. Frączek, K. Marugi[1]

Silesian University of Technology
Institute of Power Engineering and Turbomachinery,
Konarskiego 20, 44-100 Gliwice, Poland
artur.szymanski@polsl.pl

[1]Avio Polska Sp. z o.o.
Michała Grażyńskiego 141, Bielsko-Biała
krzysztof.marugi@avioaero.it

ABSTRACT

This article presents a validation study of the labyrinth seal testing. Both experimental and numerical simulations are performed. Literature data focused on simple labyrinth seals are surveyed, and two different configurations widely described in literature are investigated: a labyrinth seal with two straight fins against a smooth and a honeycomb land and a seal with three straight fins against a smooth land only. For experimental testing the vacuum-feeding test rig is used, with the high-precision Hot Wire Thermoanemometry method applied for the mass flow evaluation. The dimensions of specimens described in literature are adapted to the in-house test rig conditions, meeting all the geometrical requirements mentioned by the author. The computational method is based on the Reynolds Averaged Navier Stokes scheme, with various turbulence models. The results of the simulations show good agreement with the in-house experiment, whereas some discrepancies are found compared to literature data.

KEYWORDS

LABYRINTH SEAL, HONEYCOMB, SECONDARY FLOWS, EXPERIMENT, TEST RIG

NOMENCLATURE

A	flow area, m^2
b	labyrinth fin tip width, m
c	velocity, m s^{-1}
C_D	discharge coefficient, -
d	diameter, m
D	honeycomb cell diameter, m
h	honeycomb cell height, m
H	labyrinth fin height, m
L	linear distance, m
m	mass flow, kg s^{-1}
p	pressure, Pa
r	radius, m
R	gas constant, air R = 287.05 J kg^{-1} K^{-1}
Re	Reynolds number, -
s	clearance, m
t	labyrinth fin pitch, m
T	temperature, K
u	tangential velocity, m s^{-1}
v	velocity
x	distance in radial direction, m

Greek letters:

π	pressure ratio, -
κ	specific heat ratio, air κ = 1.4
ρ	density, kg/m^3
μ	dynamic viscosity, kg $m^{-1} \cdot s^{-1}$

Subscripts:

0	total parameter
ax	axial
h	hydraulic
hc	honeycomb
HT	honeycomb to fin tip distance
id	ideal
in	inlet
s	static

Abbreviations:

CFD	Computational Fluid Dynamics
HWA	Hot Wire Anemometry
IPET	Institute of Power Engineering and Turbomachinery
KIT	Karlsruhe Institute of Technology
LDA	Laser Doppler Anemometry
RANS	Reynolds Averaged Navier Stokes
SST	Shear Stress Transport
SUT	Silesian University of Technology

INTRODUCTION

Despite continuous advancements in the turbomachinery sealing technology, the labyrinth seal is still the most popular solution because it offers significant advantages, such as a high temperature and pressure capability, low maintenance costs, a reasonable price and high durability. However, the leakage volume is big compared to other solutions. Due to that, turbomachinery labyrinth seals have been the focus of interest of numerous academic and research centres for many years. The works undertaken in them, both experimental and numerical, have concentrated mainly on determining the impact of geometrical parameters on leakage (Alizadeh et al., 2014), the distribution of pressure (Waschka, 1991) or the temperature or propagation of aeroacoustic phenomena. In their experiments most researchers focus on stationary configurations, where the motion of the rotor with the labyrinth seal relative to the casing is ignored. In experimental works (Denecke et al., 2005), (Paolio et al., 2007) it is proved that this simplification may be assumed if the flow velocity over the labyrinth seal fin is higher than the rotor tangential velocity – in this case stationary test rigs simulate the flow behaviour correctly and the condition $u/c_{ax} < 1$ is satisfied. However, if the above-mentioned condition $u/c_{ax} < 1$ is not met, a substantial increase occurs in the mass flow difference between the stationary model and the rotating one. In most cases, the assumption of a non-rotating test rig gives satisfactory results. Researchers comparing the performance of the labyrinth seal with and without rotation pay attention to the static pressure uniformity in the circumferential direction. The works mentioned above also prove that the mass flow through the seal depends on many parameters, such as the inlet pressure, the inlet temperature, the Reynolds number, the angle of inflow onto the seal (initial preswirl), the pressure ratio, the seal relative motion and the architecture of the seal itself – the size of the clearance over the labyrinth fin in particular. In the experiments carried out on stationary test rigs (Doerr, 1985), (Braun et al., 2012), (Massini et al., 2014) the observed parameters are the dimensionless mass flow rate and the temperature and pressure distribution along the seal structure. These parameters make it possible to determine the loss coefficient distribution. Both a high-pressure feeding system (where the test rig is supplied with air at pressure higher than ambient) and a vacuum-feeding system are used for test stands in the presented works. In all these cases the authors emphasize the importance of the measurement of the clearance size as the parameter with the biggest impact on the measuring uncertainty. This work draws on a concept of feeding the measuring stand with air with ambient temperature at a stationary-axial architecture of the sealing. It presents the approach and the results of experimental testing carried out on an in-house stationary (the labyrinth does not move) measuring test rig of the IPET of the SUT. The aim of the tests is to establish the impact of the seal geometry on leakage. The study is performed for geometries and results widely described in literature (Braun, 2012), (Weinberger, 2014). The main reason behind this approach is to find out whether it is possible to evaluate the results obtained for some parameters against the results being an effect of measurements of a similar specimen geometry supplied with air at different parameters. This could make it possible to establish some universal correlations for the labyrinth seal discharge evaluation. The validation described herein is also the initial stage of research comprising a detailed study of the labyrinth seal structures – in the reference configuration – and their optimization. Therefore, the development of measurement and calculation procedures becomes a key issue.

EXPERIMENTAL FACILITY

The experimental part of the testing was performed using the air installation in the Turbomachinery Laboratory of the IPET of the SUT. The installation includes a Roots air blower with the output of 600 Nm^3/min (0.2 kg/s), a 3 m^3 pressure vessel and a pipeline system connecting the air installation to the research stand equipped with a measuring system. The minimum achievable pressure at the air blower inlet is 50 kPa(a). The total capacity of the installation (vessel and pipelines) exceeds 3.5m^3, which ensures maintaining stable and repeatable pressure distributions at the measuring stand inlet. Fig. 1 presents a simplified diagram of the installation. The diameter of the pipelines is DN100. Secondary air is sucked in from the surroundings through DN100 and DN 50 inlets with a throttling valve (5 and 6 in Fig. 1, respectively). The valve makes it possible to additionally regulate the pressure value in the vessel. On the stand side, the air is sucked in through an inlet preceded by a 4 m long pipe, which makes it possible to create appropriate conditions for the mass flow measurement upstream the test rig. After the air passes through the stand, it gets into the vessel and then – through the blower – into the environment. The mass flow is evaluated on the inlet pipe, 3 m downstream the pipe inlet.

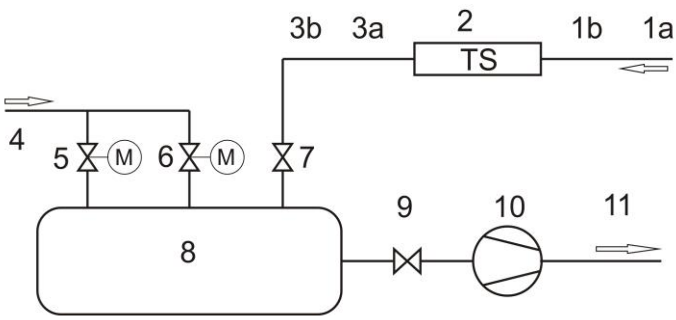

Fig. 1 Experimental installation intended for the turbine seal testing in the IPET of the SUT.

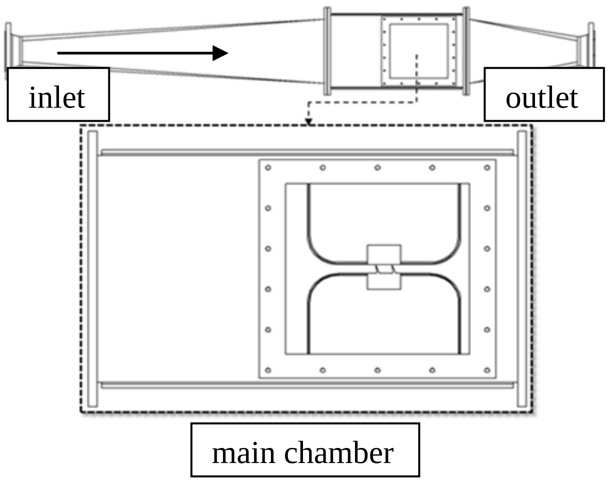

Fig. 2 Test section overview, main components

1a – test section inlet, T_0, p_0 evaluation, 1b – HWA probe no. 1 (3.5m downstream the pipe inlet, ambient conditions), 2 – test section with the measurement system, 3a – HWA probe no. 2 (7m downstream the test rig, low pressure conditions), 3b – ISA orifice plate (2m downstream the HWA probe no. 2), 4 – secondary air inlet, 5 – DN 100 valve, 6 – DN 50 valve, 7 – cut-off valve, 8 –3m^3 pressure vessel, 9 – cut-off valve, 10 – Roots air blower, 11 – exhaust to the environment

Test section

A stationary (non-rotating) test section was designed and manufactured to carry out experimental testing of the flow through labyrinth sealing using a stationary linear model of the labyrinth seal. The quasi-2D specimen approach adopted instead of the annular shape gives satisfactory results in terms of the flow behaviour in the labyrinth seal (Waschka, 1991), keeping the design reasonable in terms of financial outlays and manufacturing. Moreover, the planar design enables very accurate control of the clearance. An overview of the stand is presented in Figure 2. The stand is composed of 3 main elements: the inlet channel, the outlet channel and the main chamber where the tested labyrinth sealing structures and lands are installed. The low inlet chamber opening angle ensures smooth transition from a small diameter, DN100, to a big one without the risk of the separation phenomenon arising in the boundary layer. The test section width is more than 200 times bigger than the examined clearances, which minimizes the effect of the side walls. Based on CFD studies, the boundary layer thickness at the side walls, near the fins, is negligible compared to the specimen width and the fluid velocity. The effect of the walls does not exceed 0.1% of the main flow.

Measuring system

The mass flow measurement is a very complex procedure. Because it cannot be performed directly, very sensitive indirect methods are required. This usually involves highly effective measurements of the flow velocity and density. Three independent measurements are applied herein to evaluate the mass flow properly. Such an approach makes it possible to determine the mass flow with great accuracy for a wide range of velocities. The methods make use of a certified ISA orifice plate, with guaranteed performance and measuring accuracy, and two HWA probes. The orifice plate design is based on the EN-ISO 5167-2:2003 standard. According to its guidelines, the standard error by using the device should not exceed 2%. In the industrial environment, orifice plates working at low velocities are burdened with a significantly higher uncertainty. For the purpose of differential pressure measurements, a piezoresistive pressure transducer is used, and Pt100 temperature probes enable accurate determination of changes in the density of the medium in the measuring area. The location and selection of the measurement points are made based on the recommendations of the EN-ISO 5167-1:2003 standard. The sampling flow meter – the Schmidt SS 22.500 flow sensor is a precision measuring instrument designed to measure the flow velocity both in industrial and in laboratory conditions requiring high accuracy. However, in special cases, such as the laboratory tests carried out by the SUT, it is necessary to calibrate the hot-wire probe more precisely. The LDA technique, used to determine the velocity profile, has a high measuring accuracy and can be considered as a reference for determining the flow velocity in a wide range of the flow rate. The velocity profiles obtained during the LDA measurement were used to determine the profile coefficients, which improved the accuracy of the mass flow determination based on the HWA, ensuring that the error of the flow determination accuracy was lower than 2%. As the clearance between the fin tip and the labyrinth land is the most important factor determining the mass flow, it was measured before and after each run using blade feelers with an accuracy of ±0.005 mm. During the run, the gap was controlled with a dial indicator with an accuracy of ±0.001 mm. This made it possible to detect and evaluate the clearance deformation, which, however, due to low parameters of the inlet air and the test rig significant stiffness, was negligible. The inlet air total temperature is measured with a Pt100-class A sensor, with an accuracy of ± 0.1 K. Total inlet pressure and the pressure distribution along the seal are determined using 16 PC-28 APLISENS sensors, with an accuracy ± 256 Pa. The air humidity is measured with a hygrometer, and it is taken into account in the air density evaluation. Combining all measurement uncertainties, the maximum error of the discharge coefficient is better than 4%, provided that minimum mass flow and clearance values are maintained.

COMPUTATIONAL FLUID DYNAMICS APPROACH

The flow in the labyrinth seal channel is very complex. It involves strong jets, flow separation and appearance of vortex structures. The modelling of all these phenomena is very important for the evaluation of the sealing because the labyrinth seal effectiveness is a direct result of the possibility of kinetic energy dissipation in the seal cavities. In order to support the experiment, a CFD study is made based on the RANS scheme with the SST, the k-ω and the k-ε turbulence models and using the Ansys CFX v.17 commercial code. Three geometries are investigated herein with a separate CFD analysis conducted for each of them. These include: a labyrinth seal with two straight fins against a smooth or a honeycomb land (Weinberger, 2014), and a labyrinth seal with three straight fins with a smooth land (Braun, 2012). Details of each configuration are described in the sections below. The computational domain is three-dimensional and made with two honeycomb cells in the meridional direction (Fig. 4). The numerical model also includes an inlet and an outlet channel. In the case of the smooth land, the width is kept the same. The modelled inlet channel (30 mm long) is to align the velocity profile. The outlet channel (120 mm long) is to reduce the influence of the flow recirculation above the fins on the outlet boundary condition and eliminate the impact of boundary conditions on the flow structure.

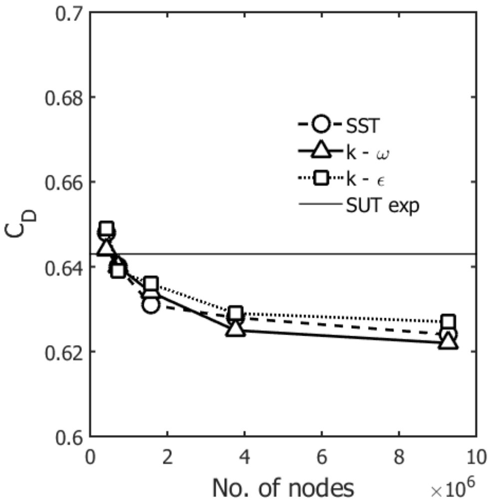

Fig. 3 Mesh study results for the labyrinth seal with two straight fins

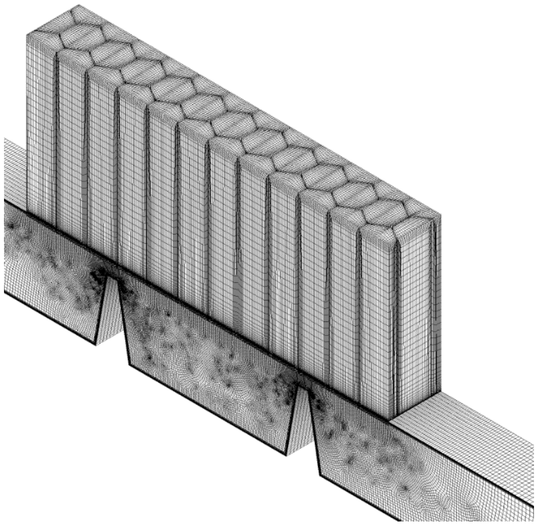

Fig. 4 Final discretization scheme for the labyrinth seal with two straight fins

Outlet pressure depends on the pressure ratio, the inlet pressure value is 100 kPa. The inlet turbulence level is set at 5%. The inlet total temperature is ambient (293 K). The static pressure measurement, used for π evaluation, is performed 50 mm downstream the labyrinth specimen. The monitor point for the pressure ratio evaluation in the CFD case is located in the same place. The compressible air ideal gas condition, with the Sutherland law for dynamic viscosity and the heat transfer coefficient, is used. The bottom honeycomb and the top wall are adiabatic. Transitional periodicity is set on the left and the right domain wall. If the honeycomb is considered, the computational domain has two parts connected through the general grid interface (GGI). The O-grid is used in the honeycomb structure and the hexahedral mesh is used in the main channel. The GGI can affect the flow conditions but it makes it possible to use an independent, denser mesh in the honeycomb and in the main channel. The GG was previously used with success in (Wittig, 1985), (Mahle, 2010),(Gao et al., 2013). A mesh-independence study was performed by comparing the C_D value (cf. Fig. 3). The grid was revised in the areas of the honeycomb cells near the fins and, proportionally, in all directions. The mesh-independence study was performed for the steady-state solution. Variation in discharge coefficient C_D at the level of ±1% was adopted as the condition to stop the calculations. This paper describes an example procedure for the mesh validation for a labyrinth seal with two straight fins with a honeycomb land. The mesh-independence study was performed for meshes with 0.4M to 9.4M nodes. The discharge coefficient value depending on the number of nodes is presented in Fig. 3. The C_D values for meshes with 1.5M and more nodes change very slowly. There is a 1.5% C_D difference between meshes with 1.5M and 9.4M nodes. Meshes with the smallest number of nodes give results only by 5% higher than the mesh with the biggest number of nodes. The highest value of C_D was obtained for the k-epsilon turbulence model, the lowest – for the k-omega turbulence model. The mesh-independence study was performed for the pressure ratio of 1.2. However, a cross-check made at higher pressure ratios (1.4 and 1.8) proved that the mesh independence was adequate. A similar mesh-study procedure is applied in each case. The mesh with 1.5M nodes was used for further calculations. The difference between the experiment and the calculations in the case of the SST model was at the level of 10%. The mesh used for further calculations is shown in Fig. 4. Further investigations, aiming to compare the three turbulence models mentioned above, indicate that the vortex structures simulated by the k-epsilon and k-omega models tend to present an inappropriate evaluation. In the case of the k-epsilon model, the separation jet downstream the second fin is not present, whereas the k-omega model does not resolve the reverse vortices appearing downstream the fins. For this reason, the SST method is selected for further estimations to cover the flow phenomenon in its entirety. A similar approach is delivered in (Bochon, 2012), (Alizadeh, 2014). The flow condition from the CFD and the experimental investigations was compared using pressure ratio π and discharge coefficient C_D:

$$\pi = \frac{p_{0in}}{p_s} \quad (1)$$

$$c_D = \frac{\dot{m}}{\dot{m}_{id}} \quad (2)$$

$$\dot{m}_{id} = \frac{p_0 A}{\sqrt{T_0}} \sqrt{\frac{2\kappa}{R(\kappa-1)}\left[\left(\frac{1}{\pi}\right)^{2/\kappa} - \left(\frac{1}{\pi}\right)^{(\kappa+1)/\kappa}\right]} \quad (3)$$

C_D describes the effectiveness of the mass flow energy dissipation relative to a single ideal nozzle. This parameter is independent of the values of the inlet parameters, and simplifies the comparison of results. The Reynolds number in the case of labyrinth seals is defined as follows (Ha, 1992), (Massini, 2014):

$$Re = \frac{\rho \cdot d_h \cdot v_{ax}}{\mu} = \frac{\dot{m}}{\mu \cdot \pi \cdot r} \quad (4)$$

Where $d_h = 2 \cdot s$ is the hydraulic diameter, v_{ax} – the axial component of velocity, and π is the ratio of a circle's circumference to its diameter. Both formulae should give the same result. However, the equation regarding the mass flow rate is easier to apply. In practice, it is extremely difficult to evaluate the axial velocity component precisely.

LABYRINTH WITH TWO FINS – TEST A

The first step of the works was to perform the measurement and conduct a CFD analysis of the labyrinth seal previously described in literature. For this purpose, the data from the KIT available in (Weinberger, 2014) were adopted. The mentioned studies describe the methodology and the results of experimental testing, among others, of a labyrinth seal with two straight fins in a configuration with a smooth wall and with a honeycomb structure (cf. Fig. 5). As part of the validation, these two structures were investigated in a similar way. The test, as described originally, was carried out on a test rig fed with air at high pressure and temperature – p_0 = 180 – 280 kPa, T_0 = 300 – 400 K and p_s = 110 – 270 kPa (outlet). These parameters are different compared to those adopted in the testing performed by the IPET of the SUT – the installation works in vacuum, the inlet parameters are ambient values (p_0=100 kPa, T_0=293 K). The geometry of the labyrinth seal is described by dimensionless parameters related to the pitch of the seal fins – t. Table 1 shows respective dimensions of the KIT model and of the calculated model made by the SUT, assuming the fin pitch of 20 mm. This dimension results from the ratio described by the KIT between the size of the honeycomb cells and the spacing of the labyrinth seal fins (D/t = 0.16). Assuming t = 20 mm, the honeycomb size then equals D = 3.2 mm. However, the numerical test assuming t = 10 mm showed a difference of up to 3%, in a wide range of pressure ratios, compared to t =20mm. The results of the test can be seen in Fig 6.

Table 1 Details of the KIT (Weinberger, 2014) and the SUT labyrinth seal geometries

Quantity	Quantity/pitch t, (KIT)	Value (KIT) for t = 20 mm, mm	Value (SUT) for t = 20 mm, mm
Clearance, s	0.02; 0.045; 0.075	0.4; 0.9; 1.5	0.4; 0.9; 1.5
Honeycomb cell height, H	0.5	10	9
Honeycomb cell size, D	0.16	3.2	3.2
Fin height, h	0.35	7	7
Fin tip width, b	0.05	1	1

Moreover, Doerr (1985) studied scaling effects on labyrinth seals. He measured discharge coefficients for several straight-through geometries. The maximum difference between scaled and reference structures reached 5.5% of the discharge coefficient (C_D). The fin opening angle and the fin inclination towards the inflow direction are 20° and 90°, respectively. In addition, special attention was paid to the distance between the first fin and the honeycomb cell edge. The required distance between the first fin edge and the honeycomb cell, x_{HT} in this case is 1 mm, according to (Weinbereger, 2014). The specimen length L = 38 mm. Special attention is also given to the evaluation of the difference between results obtained assuming boundary conditions with elevated (KIT) and ambient (SUT) parameters. Example results of such a comparison are presented in Fig. 7, concerning a labyrinth seal with a honeycomb land. As shown in the SUT CFD calculations, a comparison between the same labyrinth seal geometry fed with air at different parameters (reported by the KIT (Weinberger, 2014) and used at the SUT installation, respectively) shows a difference between the two approaches in the discharge coefficient C_D in the range of 1-5%. This value is relatively small.

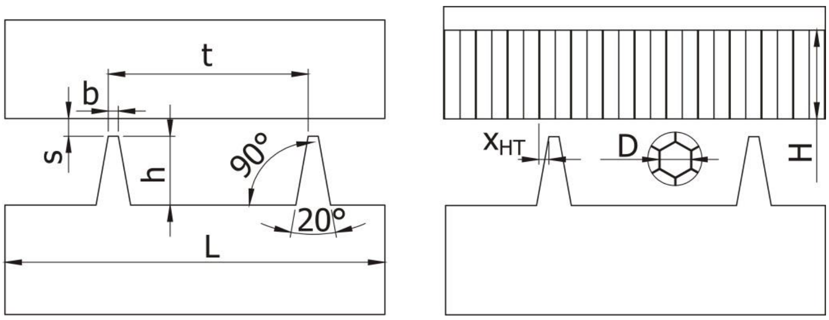

Fig. 5 Geometry of investigated labyrinth seal structures: labyrinth with a smooth land (left) and with a honeycomb (right)

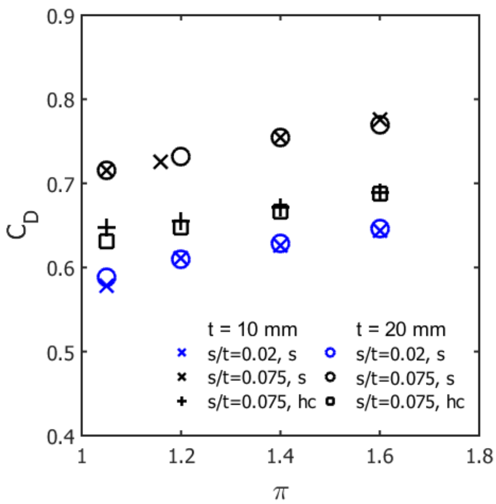

Fig. 6 Scaling effect on labyrinth seal with honeycomb discharge

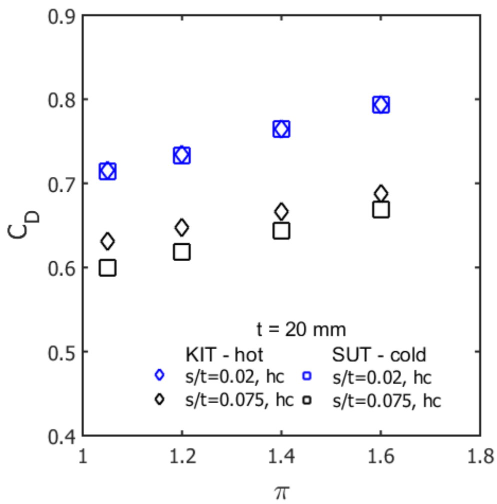

Fig. 7 Inlet parameters effect on labyrinth seal with honeycomb discharge

The comparison between C_D values obtained from the in-house tests and the data found in literature shows some discrepancy between the literature results and the results of measurements and CFD calculations for the configuration with a smooth wall, especially for the clearance of 0.4 mm and 0.9 mm, (cf. Fig. 8). Compared to the measurement data, the CFD calculation results show a tendency to overestimate the leakage value slightly. However, these differences are not significant, (cf. Fig. 8). Considering the configuration with the honeycomb structure, the CFD and the measurement results show significant agreement, in particular for clearance s = 0.4 mm – the maximum relative difference ΔC_D does not exceed 2%. (cf. Fig. 9). Satisfactory agreement is found between measurements using literature geometry and CFD results for the configuration with the honeycomb structure at clearances s = 0.9 and 1.5 mm (the maximum deviation does not exceed 5% in the entire measuring series) (cf. Fig. 9). Moreover, analysing the honeycomb case, a divergence was obtained between literature data and the SUT measurements and calculations at clearance s = 0.4 mm, while other gaps resulted in satisfactory convergence. In this case, good agreement of the SUT measurement and the CFD calculation results is revealed. The differences between literature data and the SUT estimations are included in the range of $\Delta C_D = 2 - 19.7\%$. This could be the effect of the Weinberger (2014) test rig potential deformation due to high temperature. The SUT test section, running on ambient air, was not deformed. The rig deformation and the effective clearance change could have some influence here, especially at low pressure ratios. The results were overestimated regarding the measurements and CFD calculations performed by the SUT team (cf. Fig. 9). It is worth mentioning that C_D is calculated in the same manner both in the KIT and the SUT. Comparing the effect of the honeycomb application, the outcome is the same in both works – C_D for relatively tight clearances (here s = 0.4mm) rises rapidly, while for larger ones (s = 1.5mm) leakage drops insignificantly, changing all trends in a particular manner. The discrepancies between the results are described in detail in Table 3, which shows the relative error between certain results related to the KIT experiment and the CFD calculation.

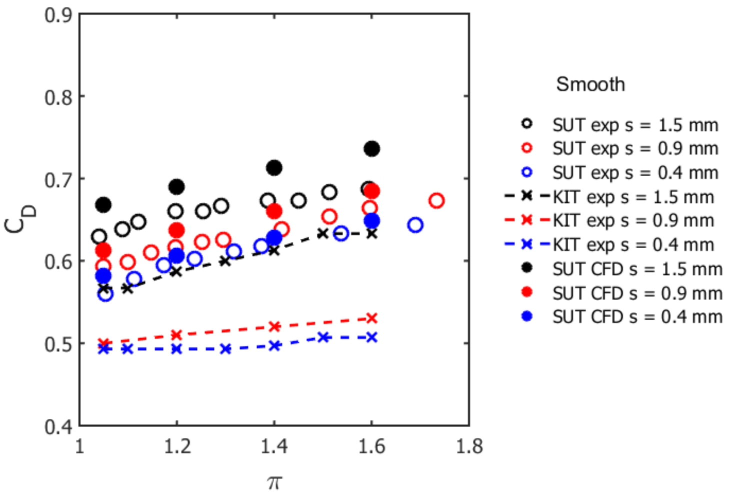

Fig. 8 Discharge characteristics of the KIT (Weinberger, 2014) labyrinth specimen – SUT measurement/ KIT measurement/ SUT CFD, case with smooth land

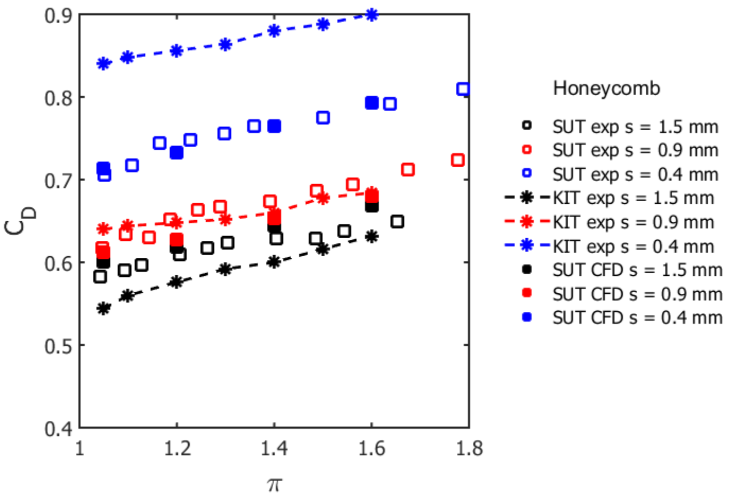

Fig. 9 Discharge characteristics of the KIT (Weinberger, 2014) labyrinth specimen – SUT measurement/ KIT measurement/ SUT CFD, case with honeycomb structure

It can be seen that the presented CFD methodology results show agreement with the experiment – up to 5.7 % of C_D. For this reason, they were used further for the research purpose. However, the considerable variations between the SUT and the KIT conclusions created the need to perform a deeper analysis – involving a comparison of the Reynolds number. The subject of the observation was the C_D variation depending on the Reynolds number and the clearance, for the case with the fin pitch t=20mm in a labyrinth seal with a honeycomb and a smooth land. The effect of the inlet air parameters (KIT – hot, 200 kPa; SUT – cold, 100 kPa) shows a characteristic shift towards higher Reynolds numbers when hot parameters are considered (cf. Fig. 10). The differences in the Reynolds number rise with the size of the clearance. Moreover, a hole-structure, if placed above the labyrinth, changes the sealing flow characteristics depending on the clearance size. Different Reynolds numbers may be a source of the presented difference, as reported by Al-Qutub (2000), despite keeping all relative dimensions constant. This evaluation issue will be investigated extensively in a future work.

Table 3 Discrepancies between SUT Test A case results and Weinberger (2014).

	Smooth land – SUT experiment to KIT			**Smooth land – SUT experiment to SUT CFD**		
s, mm	0.4	0.9	1.5	0.4	0.9	1.5
π	discrepancy, %			discrepancy, %		
1.05	14.4	16.2	11.2	1.1	2.7	4.7
1.2	16.7	17	10.1	2.4	3.7	5.6
1.4	19.1	18.5	8.8	2.3	3.6	5.9
1.6	20.3	19.9	8.5	2.1	3.4	6.4
avg	17.6	17.9	9.7	2	3.4	5.7
	Honeycomb land – SUT experiment to KIT			**Honeycomb land – SUT experiment to SUT CFD**		
	s = 0.4	s = 0.9	s = 1.5	s = 0.4	s = 0.9	s = 1.5
π	discrepancy, %			discrepancy, %		
1.05	16.9	2.1	7.7	0.6	2.4	1.8
1.2	16	0.1	4.8	0.7	3	2.2
1.4	15.2	2.2	4.1	0.2	3.2	3
1.6	14	2.6	2.2	0.5	3.2	3.6
avg	15.5	1.7	4.7	0.5	2.9	2.6

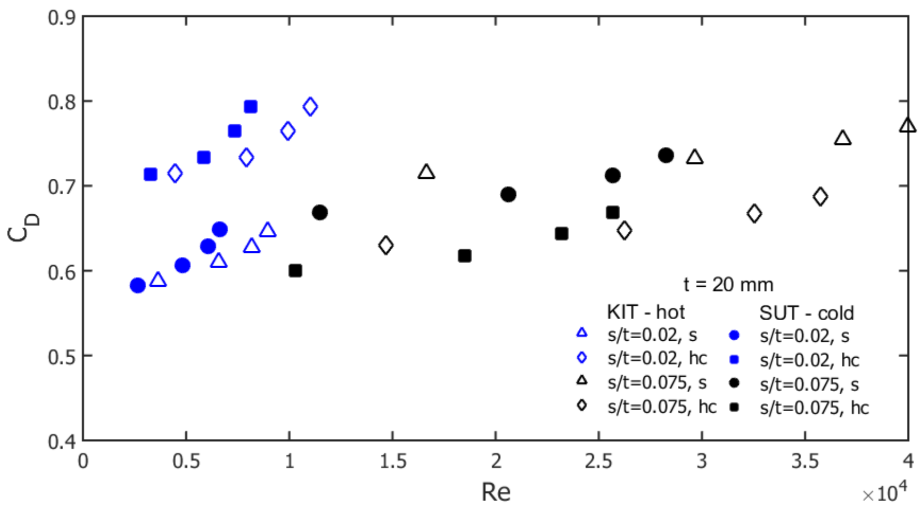

Fig. 10 Discharge characteristics depending on the Reynolds number and the clearance size, and inlet air parameters – (KIT and SUT approach).

LABYRINTH WITH THREE FINS – TEST B

This is a further study aiming to test a more complex geometry. For this purpose, the KIT labyrinth seal configuration with three straight fins, described by (Braun et al., 2012), is adopted. Cited studies focus on the labyrinth seal with three, five and six fins, in different configurations with a smooth and a honeycomb land. They were performed for a number of directly given clearances. However, other geometrical dimensions were presented in relation to pitch “t”, where the pitch is unknown. For the purpose of this work, a labyrinth seal with three fins against a smooth land is used (cf. Fig. 11). The literature study was originally performed on a test rig fed with air at high pressure (1000 kPa) with no information about the inlet total temperature. However, the presented diagram of the installation suggests that the air temperature may be elevated. These parameters are also different from the conditions in the works carried out by the IPET of the SUT (p_0=100 kPa, T_0=293K). Table 3 shows the dimensions of the indicated model, as well as the SUT model dimensions, assuming the fin pitch t = 7 mm, based on the preliminary CFD study.

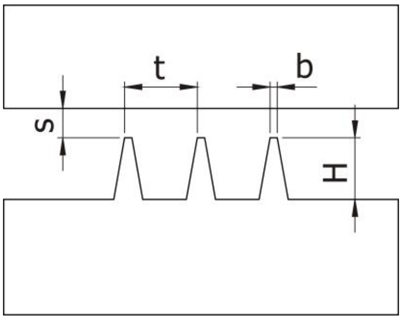

Fig. 11 Geometry of the three-finned labyrinth seal under consideration (Braun, 2012)

Table 3 Details of the KIT (Braun, 2012) and the SUT labyrinth seal geometries

Quantity	Value/pitch t, (KIT)	Value for t =7mm (KIT), mm	Value for t =7mm (SUT), mm
Clearance, s	-	1.55, 1.08, 0.79, 0.5	1.55 , 1.08 , 0.79 , 0.5
Fin height, h	0.85	5.95	5.95
Fin tip width, b	0.1	0.7	0.7

The comparison between the SUT experiment results, the CFD analysis using the previously described approach with ambient (SUT) parameters on boundary conditions and the literature data (Braun, 2012) shows agreement between the CFD and the SUT experiment results. The results are overestimated slightly for the 1.55 mm clearance, but the difference stands below 3%. The presented trends are identical in both methods (cf. Fig. 12). Despite keeping the same respective geometrical dimensions, as well as clearances, some discrepancies between the literature results and the SUT outcome are found, as the obtained trends are different (cf. Fig. 13). Considering the KIT results for large clearances (1.55 mm and higher), the C_D value drops with a rise in the pressure ratio; for gaps 1.1 and 0.8 mm, the C_D trend is almost constant as a function of the pressure ratio and, finally, for small clearances, the leakage value rises with an increase in output. In the SUT case, all plots rise with the pressure ratio (cf. Fig. 12). The trends obtained by the SUT tend to underestimate the results compared to the presented literature case, being by 10–15% lower, except for the histories for s = 1.55mm, where two different trends intersect each other (cf. Fig. 13). It should be noted that the SUT trends seem to be shifted down compared to the KIT, which may be the effect of the fin different height and pitch. According to Trutnovsky (1981), the fin height has a strong impact on the seal discharge, determining the depth of the cavity. The higher the fin, the lower the leakage. It should also be remembered that the differences in the upstream total pressure are significant – 1000 kPa in the KIT vs. 100 kPa in the SUT. As reported by Al-Qutub (2000), the inlet total pressure is a strong factor determining the leakage, apart from other thermodynamic and geometrical parameters.

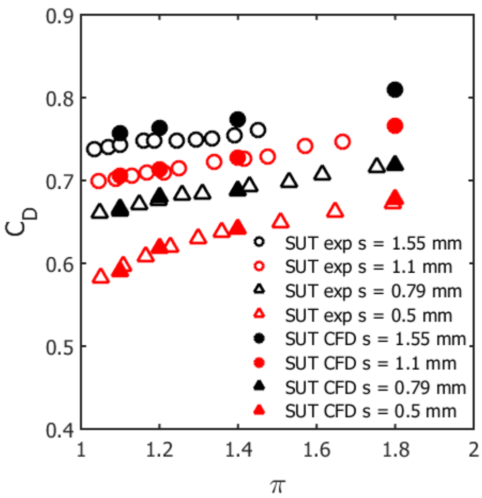

Fig. 12 Discharge characteristics of the KIT (Braun, 2012) labyrinth with three fins – SUT measurement/ CFD, smooth land case

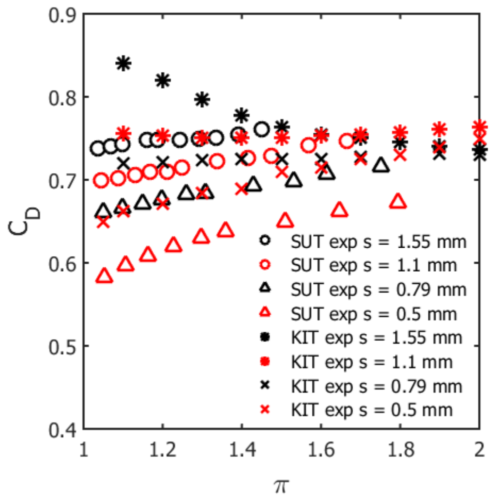

Fig. 13 Discharge characteristics of the KIT (Braun, 2012) labyrinth with three fins – SUT / KIT measurement, smooth land case

SUMMARY

This paper presents the methodology of experimental and CFD investigations of the labyrinth seal. Based on a literature survey, three different cases were adopted and examined. The presented study leads to the following conclusions:

- In all cases, the CFD results show good agreement with the in-house experiment results. The maximum deviation does not reach 6%. This means that the proposed method and the mesh and the turbulence model selection are appropriate to simulate this case.
- Despite satisfactory agreement between the results of the simulations and the experiment, it is only in the Test A geometry (labyrinth with two fins) with the honeycomb land that some agreement with the literature results is found. In other cases, especially if the smooth land is taken into account, discrepancies are observed.
- Both configurations (with two and three fins – Test A and B, respectively), with the smooth land, show significant differences between the results – reaching up to 15%. Moreover, the trends of the plots do not coincide.
- The explanation for such strong discrepancies has not been found yet. However, it should be remembered that the cited works do not provide full information about geometry – each and every case requires assumptions concerning the geometrical parameters. Nevertheless, this study shows how sensitive the flow through the labyrinth seal is – despite keeping all respective parameters the same, a little mistake in determining one of them can significantly change the flow overall characteristics.
- In literature studies, the method of operational pressure ratio evaluation was not presented. The place of the static pressure measurement for the pressure ratio and the discharge coefficient (1–3) can have a significant impact on overall trends. In the SUT tests, the methodology of operational pressure ratio determination is the same in both methods (CFD and experiment).
- Moreover, it should be remembered that the flow similitude due to the Reynolds number was not kept – upstream parameters in literature cases are elevated compared to the assumed ones (200 kPa – test A, 1000 kPa – test B, 100 kPa – SUT test rig).
- The flow behaviour shows reverse trends if the honeycomb structure is applied – the discharge coefficient drops with a rise in the clearance, which can be explained by the presence of the effective clearance rise phenomena. This shows some agreement with the findings of other research described in literature (Braun, 2012), (Alizadeh, 2014), (Weinberger, 2014).

- If a labyrinth seal with three fins is analysed, literature shows the possibility of the trends swap – a drop in leakage with a rise in the pressure ratio – at high values of the clearance. The SUT test did not predict this behaviour.
- Finally, this work shows that anticipation of the leakage behaviour in the labyrinth seal based on literature data only can be difficult, and underlines the need to conduct further research. Literature-based data cannot be the only source for the creation of a universal tool of the labyrinth seal discharge estimation, or optimization. Due to that, CFD or experimental studies become crucial.

ACKNOWLEDGEMENTS

This work was supported by the National Centre for Research and Development and Avio Polska within the Innolot Programme, Coopernik Project.

REFERENCES

Al-Qutub A. M., Elrod D., Coleman H. W., A new friction factor model and entrance loss coefficient for honeycomb annular gas seals. ASME J Tribol 200;122, pp. 622-627, 2000

Alizadeh M., Nikkhahi B., Farahani A. S., (2014). Numerical Study on the Effect of Geometrical Parameters on the Labyrinth-Honeycomb Seal Performance. Proceedings of ASME 2014

Bochon K., Wróblewski W., Dykas S., Rulik S. (2010). Optimization of tip seal with honeycomb land in LP counter rotating gas turbine engine. TASK QUARTERLY. 2010, vol. 14 No. 3, pp. 189-207

Braun E., Dullenkopf K., Bauer H. J., (2012). Optimization of Labyrinth Seal Performance Combining Experimental, Numerical and Data Mining Methods. Proceedings of ASME 2012

Denecke J., Dullenkopf K., Wittig S., Bauer H. J., (2005). Experimental Investigation of the Total Temperature Increase and Swirl Development in Rotating Labyrinth Seals, Proceedings of the ASME 2005

Doerr L., (1985). Modellmessungen und Berechnungen zum Durchflussverhalten von Durchblicklabyrinthen unter Ber¨ucksichtigung der ¨Ubertragbarkeit. PhD thesis, Universitat Karlsruhe (TH)

Gao J., Zheng K., Wang Z., (2013). Effect of Honeycomb Seals on Loss Characteristics in Shroud Cavities of an Axial Turbine. Chinese Journal of Mechanical Engineering, Vol 26, No. 1, pp. 69-77

Ha T. W., Childs D., (1992) "Friction Factor Data for Flat Plate Tests of Smooth and Honeycomb Surfaces", ASME Journal of Tribology, 114(4), p. 722-729.

Mahle I., (2010). Improving the interaction between leakage flows and main flow in a low pressure turbine. Proceedings of ASME 2010

Massini D., Facchini B.,Micio M., Bianchini C., Ceccherini A., Innocenti L.,(2014). Analysis of flat plate honeycomb seals aerodynamic losses: effects of clearance. 68th Conference of the Italian Thermal Machines Engineering Association, ATI2013, Energy Procedia 45

Paolio R., Moore S., Cloud D., Glahn J. A.,(2007). Impact of Rotational Speed on the Discharge Characteristic of Stepped Labyrinth Seals.

K. Trutnovsky i K. Komotori, „BerUhrungsfreie Dichtungen," *4. Auflage VDI-Verlag*, 1981.

Waschka W., Zum Einfluss der Rotation auf das Durchflussverhalten und Wärmeübertragungsverhalten in Labyrinthdichtungen und Wellendurchführungen, Dissertation, Institut für Thermische Strömungsmaschinen der Universität Karlsruhe, 1991.

Weinberger T., (2014). Einfluss geometrischer Labyrinth- und Honigwabenparameter auf das Durchfluss- und Wärmeübergangsverhalten von Labyrinthdichtungen. PhD thesis, Universitat Karlsruhe (TH)

Wittig S., (1987). Numerical Predictions and Measurements of Discharge. Coefficients in Labyrinth Seals. Proceedings of ASME 1987