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What-if analysis of the labyrinth seal of the gas turbine rotor tip

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Abstract

This paper presents a preliminary, numerical what-if analysis of selected geometrical parameters of the tip seal of the last stage of an aircraft engine turbine and the impact of the parameters on the leakage mass flow. The analysis is a part of the task of improving the rotor tip seal configuration in aircraft turbines. Calculations were carried out using the commercial computational fluid dynamics code. A straight-through seal with two leaning fins and a honeycomb land was analysed. The computational model was prepared based on some simplifications introduced to improve the efficiency of the calculations. The rotor entire blade-to-blade channel was analysed, while the seal pitch was reduced to the dimensions of two honeycomb cells. The geometry of the fins themselves was simplified too. In the original variant, the fin tips had caps to protect them from wear (shape deformation) due to rubbing. In the simplified model, the caps were omitted. The simplifications did not change the leakage mass flow significantly. Several variants of changes in the basic geometrical parameters of the seal were analysed to assess their effect on the leakage mass flow for altered flow conditions. Parameters such as the fin thickness, the fin inclination angle and the position of the fins and of the entire labyrinth were analysed. The best seal variant was selected, the flow phenomena were commented on and some points in the design of this type of the labyrinth seal were discussed.

Keywords: Gas turbine; Labyrinth seal; Honeycomb; CFD

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1 Introduction

Seals are components which offer a great potential for an improvement in the gas turbine efficiency. Owing to high reliability, thermal strength and no limitations concerning the pressure ratio, labyrinth seals are the most common solution in high-speed turbomachines. In order to improve efficiency, it is essential that the leakage mass flow be reduced as leakage is the major loss-generating factor.

In order to reduce leakage through the labyrinth seal, several fundamental conditions have to be met at the seal design stage. If possible, the diameters of subsequent gaps should be stepped or staggered to ensure a maximum reduction in the kinetic energy carry-over effect between the seal cavities. Moreover, it is important that the clearance in the seal be as small as possible. Song *et al.* [1] and Reichstein *et al.* [2] point out that the leakage mass flow through the seal increases linearly with the clearance size. It is also essential that the fins have sharp edges, which lessens the contraction coefficient and reduces the leakage itself.

These conditions, however, are not sufficient enough to achieve high efficiencies, and therefore labyrinth seals have to be developed further. The modifications introduced so far include, among others, curved or inclined fins or the application of abradable components which provide a better fit as operation progresses. A lot of attention is devoted in reference literature to the impact of the seal configuration on the leakage size [3,4]. Many works present an analysis of existing seals or attempt to work out their modification using a variant analysis. There are also studies that employ optimization methods to improve geometry [5,6,7].

One of the advancements in the labyrinth seal design that is gaining more and more importance is the introduction of a honeycomb land. The honeycomb land has a number of advantages. It resists hard working conditions in a range of high temperatures and high rotational speeds, allowing at the same time limited rubbing without the danger of the seal damage [8]. Compared to a full structure, at the same clearance the honeycomb land may increase leakage. This results from the free space that appears in the honeycomb cell above the seal fin [9,10]. Because of that, the effective clearance concept is used [11]. Despite increased leakage, the honeycomb land solution is applied more and more often, both in new seal designs and in the upgrade of seals already in use. The main reason for this is the possibility of a safe decrease in the tip clearance, which ultimately allows a reduction in the leakage mass flow.

The search for labyrinth seals with a honeycomb land has been going on for many years. Valuable research was performed and described in the late 1970's [12]. Numerical calculations aiming to resolve the flow structure inside labyrinth seals have been carried out since the late 1980's [13]. Initially, the calculations were performed using 2D models. Later on, 3D models were applied taking account of the geometry of peripheral honeycomb cells, e.g., [14–17].

Labyrinth seals with a honeycomb land are the most popular seal configurations in aero-engines. The seal performance depends both on the effective clearance and on the flow direction. A change in the shape of the fins affects kinetic energy dissipation and may change the flow direction. The effective clearance can be reduced by changing the position of the fins. It also depends on the relative thickness of the fin compared to the honeycomb cell size.

Two-fin labyrinths are used most often in the sealing of the turbine stages and in the turbine rotor cooling paths. The stepped and the straight-through designs are used depending on available space and on the rotor and stator platform shape design.

The selection of the seal type and of the seal geometrical parameters is based on the assumed acceptable leakage flow. Additionally, the seal design has to take account of other constraints such as the space for the seal location and the operating conditions. For this reason, the process of designing and selecting the appropriate seal design is often subject to optimization.

The main objective of the investigation was to identify the effect of selected geometrical parameters of the seal cavity and of the labyrinth seal to improve the sealing performance. The work was performed numerically through a computational fluid dynamics (CFD) approach to evaluate the impact of the modifications in a real configuration of a low-pressure turbine module. The study was performed for reference conditions which correspond to those of a real engine operation.

2 Numerical model

The last stage of an aircraft low-pressure turbine was selected for the flow analysis. The geometrical configuration of the main flow part consists of the vane row, the blade row the and turbine rear frame (TRF). The shape of the turbine flow channel changes significantly in the area of the blade rows. Due to that, the flow structure is three-dimensional and relatively complex.

The rotor has a straight-through labyrinth tip seal with a honeycomb land. The sealing area consists of an inlet chamber, a chamber between the fins and an outlet chamber. The definition of the computational model requires a definition of the domain, generation of a mesh with a number of nodes suitable for the calculations, a fluid flow model and formulation of boundary conditions for the fluid flow domain. For a what-if analysis, the seal geometrical parameters to be checked are defined with the objective function. CFD calculations are relatively time-consuming. For this reason, certain simplifications of the calculation domain are generally needed to lower computational costs. The comercial computational fluid dynamic software, Ansys CFX, was used to perform the simulations.

2.1 Computational domain and the rotor mesh

A simplified variant of the rotor computational domain omitting the vane row, the turbine rear frame and the outlet flow path was selected (Fig. 1). It is a domain with a one-blade pitch in the circumferential direction. The advantage of this concept was crucial for the consideration of certain seal geometries, especially those with honeycomb or honeycomb-like lands. The dashed lines in Fig. 1 show the interfaces and the bold lines – the inlet and outlet. The computational domain should have a simplified geometry in all locations which are of less importance for the fluid flow phenomena or the leakage mass flow rate. In the model, all tangential and axial gaps were closed except the inlet and the outlet of the seal cavities of the rotor shroud. The positions of the stator and rotor were defined for the hot case (cruise conditions) with the seal reference clearance of 0.76 mm.

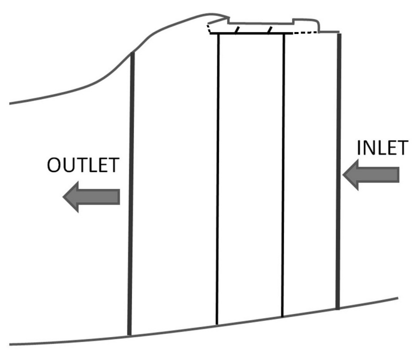

Figure 1. Computational domain concept for flow simulations through the rotor.

The calculation area adopted for further analysis (Fig. 1), apart from the main flow area, consists of the rotor tip sealing area. The inlet surface of the main flow area is moved away from the rotor inlet edge by a distance greater than the width of the inter-row gap. Such an inlet location is necessary to eliminate the influence of flow disturbances on the leading edge and in the inlet gap to the tip seal chamber on the distribution of parameters at the inlet. This ensures a stable computational process. The main flow area is connected to the tip seal area by two interfaces. The way of defining them and the method of the sealing area discretization will be discussed in more detail in Subsection 2.3.

The main flow channel area was discretized in the Ansys ICEM CFD program using a structured mesh of the total node size of about 10^6. The view of the main flow mesh with zoomed-in parts is presented in Fig. 2. The seal domain in the figure is presented only as a wireframe to offer a full view of the computational task.

The number of the nodes was selected so as not to lengthen the calculation time significantly on the one hand, and ensure that the inlet and outlet conditions of the rotor tip seal area were as close to reality as possible on the other. The boundary area in the main flow domain was prepared so that the dimensionless distance was less than $y^+ = 30$, which is sufficient for the wall function.

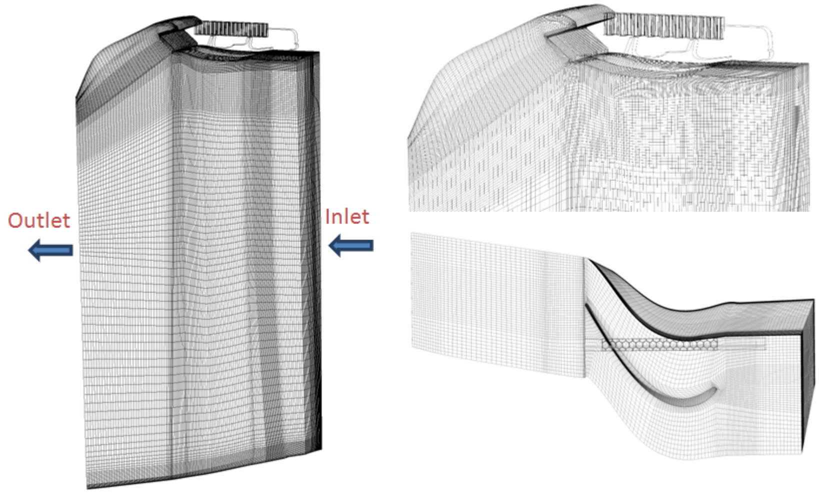

Figure 2. Computational mesh in the rotor passage.

2.2 Flow model and boundary conditions

The flow structure is modeled by governing equations for the compressible fluid flow: the continuity equation, the momentum equation, the conservation of energy equation and the equation of state. The unsteady Reynolds averaged Navier Stokes (URANS) form of the system of equations is solved, supported by the two-equation eddy-viscosity sheer stress transport (SST) turbulence model.

The high-resolution advection scheme was set up for continuity, energy and momentum equations, and also for kinetic turbulent energy and turbulent frequency transport equations to ensure better accuracy. The ideal gas was assumed with the total energy heat transfer option. The turbulence model with the Kato-Launder modification and the curvature correction was applied. Both molecular viscosity and conductivity were specified with the use of Sutherland's law as a function of static temperature.

Total pressure, total temperature and the flow angle distribution were applied at the rotor domain inlet (Fig. 1) as functions of the blade height. The static pressure averaged value was used as the boundary condition at the outlet with a possible pressure profile blend in the range of 3%. The flow conditions correspond to a pressure ratio of about 1.6. Parameter distributions at the inlet are defined from the parameter distributions obtained from the calculations performed for the flow path of the whole low pressure (LP) turbine. Turbulence intensity, Tu, at the main flow domain inlet was assumed at 5%. Periodic boundary conditions were applied to both sides of the computational domain. The rotational speed was applied for the rotating elements.

The numerical model was preliminary tested with the above-defined boundary conditions. The calculated mass flow rate of the main flow differed by 2% from the whole LP turbine computations without leakages, which was acceptable in terms of the analyses to be conducted.

2.3 Seal domain study

The reference configuration of the labyrinth seal has two leaned fins. The straight-through seal has a honeycomb land with the cell dimension of 3.175 mm. The honeycomb land is shaped as in the real turbine to ensure circumferential periodicity. This configuration is marked as RS-HC.

Labyrinth seal fins have protective caps. In consequence the lateral surfaces of capped fins have steps. It is assumed that the radius of the rounding of the fin tip is not taken into account. The geometric shape of a capped fin is marked with a a bright line in Fig. 3. Since caps are used in selected labyrinth seals only and their presence significantly hinders generation of a correct mesh in the boundary layer, the geometry of the fins was simplified and the steps were removed. At the base, the fin was enlarged by the size of the steps. The geometric shape of the modified fin is shown in Fig. 3 with a dark line. The results of the flow computations prove that such simplification does not affect the seal leakage value or the flow pattern. At the same time, the convergence of the computational process is improved. All further analyses were performed using the simplified version of the fin.

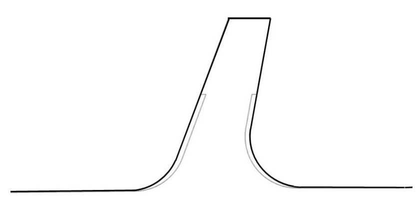

Figure 3. Capped fin geometry and simplified geometry.

The first step in the seal domain discretization is to decide how many details of the domain should be taken into account to model the interaction between the seal and the main stage flow. The assumed simplifications should enable an accurate assessment of the seal performance. The seal domain connected to the main flow domain via two interfaces may be defined with a pitch equal to the pitch of the blade-to-blade channel or with the minimal pitch equal to the honeycomb periodicity (about two honeycomb cells). If the stage model with vanes and blades had been used with the frozen rotor model, the circumferential distribution of parameters would have taken account of the wake behind the vane trailing edge, and that would have affected the seal cavity flow and the seal performance. Using only the rotor model, the circumferential distribution of parameters at the inlet was assumed constant, and the inflow into the cavity was influenced by the rotor blade leading edge only.

Two definitions of the labyrinth seal domain were considered to check the accuracy of the leakage flow modeling: with the minimal pitch and with the rotor channel pitch. The second variant pitch is ten times larger than the pitch in the first variant, which means that 20 honeycomb cells have to be discretized in the circumferential direction (overall 20 × 16 cells). A diagram of the two variants is presented in Fig. 4.

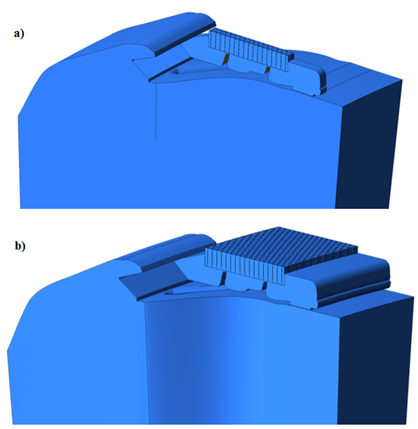

Figure 4. Seal domain concepts: a) two-cell honeycomb strip over the blade pitch, b) full honeycomb over the blade pitch.

The labyrinth seal mesh comprising the cavity inlet area, the cavity near the fins and the outlet area is of the hex-dominant type (Fig. 5). It is generated as a 2D mesh stretched in the circumferential direction. The labyrinth domain and the honeycomb domain are assumed as stationary. The cavity and labyrinth domain is connected to the honeycomb domain via an interface. The interface is placed at about a fifth of the height of the clearance under the honeycomb edges. In regions close to the rotor walls the maximum value of nondimensional distance

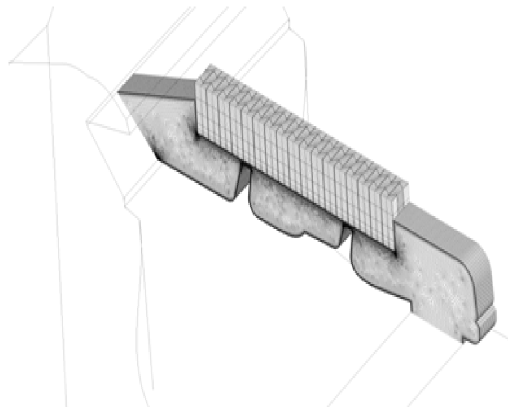

Figure 5. Overview of the numerical mesh in the seal region (two-cell pitch).

y^+ is less than 2.

A structured mesh is used in the honeycomb cells. The number of the mesh elements inside each cell of the honeycomb is identical. The near-wall region inside the cells is discretized moderately, assuming that the wall function will be used. The distribution of the mesh points in the radial direction was nonuniform and the nodes close to the upper part of the honeycomb cells were relatively coarse. The non-dimensional distance y^+ is less than 15.

The two concepts of the seal domain presented in Fig. 4 were studied. The computations were performed on meshes with the total number of 2.4×10^6 and 15.4×10^6 elements, respectively. The difference in the leakage was very small (about 0.12%). The flow structures below the honeycomb land for the two models are shown in Fig. 6. The wireframe of the honeycomb domain is visible in both cases. The flow structure calculated for the two-cell strip (Fig. 6b) is repeated 5 times in the circumferential direction to compare the same area. The picture of the overall structure of the flow is very similar. As expected, the periodicity of the structures is clearly visible (Fig. 6b). Some small discrepancies between the pictures can be noticed. The first one is in the Mach number variation at the inflow to the region with the honeycomb land. The strips in the inlet region are of a different strength on the left but of a uniform strength on the right. The strips show the leakage flow direction which is formed in the seal inlet chamber. The structures in the first fin region are very similar. They are not affected by the circumferential distribution of the flow at the honeycomb inlet. The direction of the flow tended to be more axial, but after the first fin region the flow turned back and the direction became more circumferential. This is a consequence of the rise in the axial component of the leakage stream velocity. A slightly different situation can be noticed in the second fin region. The structure at the second gap inlet is periodic and seems to be very similar, but after the gap the flow structures interact and a different periodicity is formed (with 3 cells in the circumferential direction). This may influence the mixing process when the leakage reaches the main flow but this is not the case in the problem considered herein. The honeycomb structure has an impact on the leakage flow structure. The leakage flow penetrates the land cells and the honeycomb makes the flow periodic in the gaps. The analysis results indicate that for the evaluation of the seal operation it is sufficient to use the seal area model which is reduced to the width of two honeycomb cells.

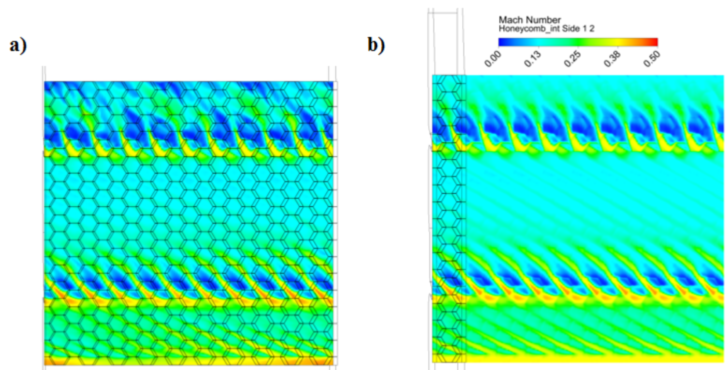

Figure 6. Flow structures beneath the honeycomb land: a) full honeycomb over the blade pitch, b) two-cell strip.

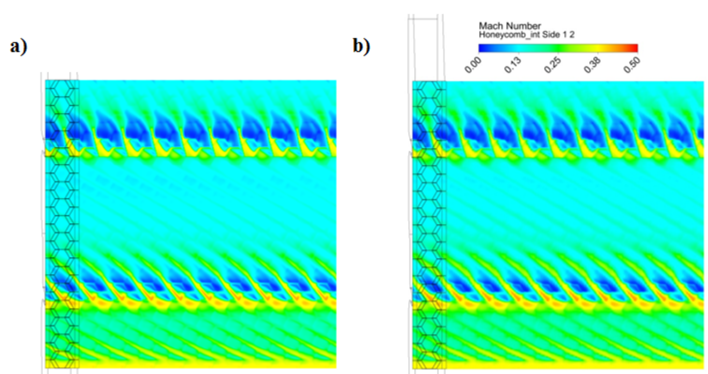

Figure 7. Flow structures beneath the honeycomb land: a) fine HC mesh, b) coarse HC mesh.

In the next step of the sealing area model selection, two methods of the land cells discretization were compared. For this purpose, an additional computational mesh was generated that had more nodes in the honeycomb cell area. The new mesh has 1.4×10^6 elements in the honeycomb domain. The difference between the coarse and the relatively fine meshes totals about 0.7%. The flow structures beneath the honeycomb land are compared in Fig. 7. The Mach number distributions are very similar. The structures on the fine mesh have better resolution in some regions.

In all the computations the predicted flow structure in the labyrinth domain and in the rotor domain was the same. The Mach number distribution in the seal region is presented in Fig. 8a. The Mach number range in the figure is adjusted to the flow in the seal. The streamlines present the vortices formed inside the seal cavities. Two vortices rotating in opposite directions are visible in the inlet cavity. The leakage jet is formed at the edge of the shroud platform and is headed directly towards the honeycomb edge, where it is split into the two streams. The leakage stream adheres to the bottom of the honeycomb land and flows directly into the first gap. The stream gets wider, the velocity at the gap inlet is relatively high and the situation is similar to the carry-over effect. Downstream the second fin, the stream adheres to the honeycomb land till the end and then flows towards the platform edge.

The stream in the internal cavity forms a jet which flows directly towards the second gap. In this part, the carry-over effect appears. A large vortex is formed in the internal cavity central part. At the outlet, a vortex is formed behind the second fin and the stream in the form of a relatively narrow jet leaves the seal outflow cavity. The mixing with the main flow takes place just behind the shroud platform.

The turbulence kinetic energy distribution in the seal cross section is presented in Fig. 8b. The highest values are observed in the region behind the gaps. The structure of the jets in the seal domain is well visible.

3 Computation results

The analysis was performed for the straight-through type of the labyrinth seal with two fins and a honeycomb land. The performance was calculated for different labyrinth configurations characterized by:

- different thickness of the fins,
- different inclination angle of the fins,

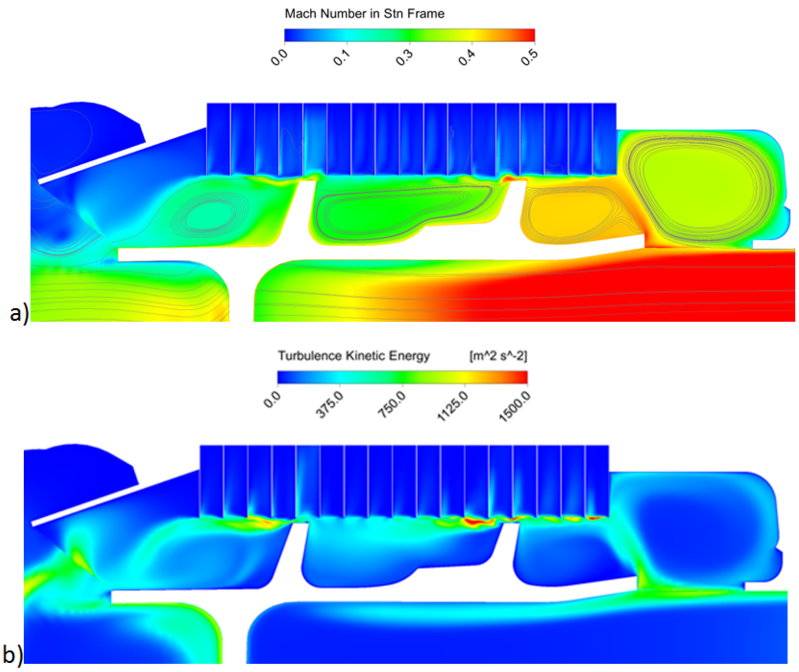

Figure 8. Flow structures in the seal: a) Mach number, b) turbulence kinetic energy.

- different positions of the fins on the shroud platform,
- shifting of the entire labyrinth (honeycomb land and fins).

None of these modifications needs adjustments in the main flow path. The analyses are aimed to determine the potential impact of a change in a single geometric parameter on the seal leakage value.

3.1 Fin thickness

In the new configuration, the fin thickness is reduced to about 0.38% of the initial value. The other geometrical parameters of the seal are the same. The fins are located in the same places as in the RS-HC configuration. The position of the fins is defined regarding the middle of the fin thickness. The new configuration is marked as RfO-HC-1.

The flow structure calculated for the RfO-HC-1 configuration is presented in Fig. 9. The leakage jet formed in the inlet cavity has the same shape as in the previous calculations. The leakage mass flow rate is by 21% lower compared to

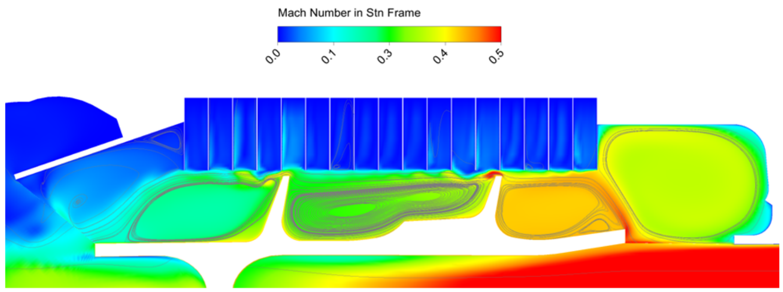

Figure 9. Flow structures and the Mach number distribution in the RfO-HC-1 seal.

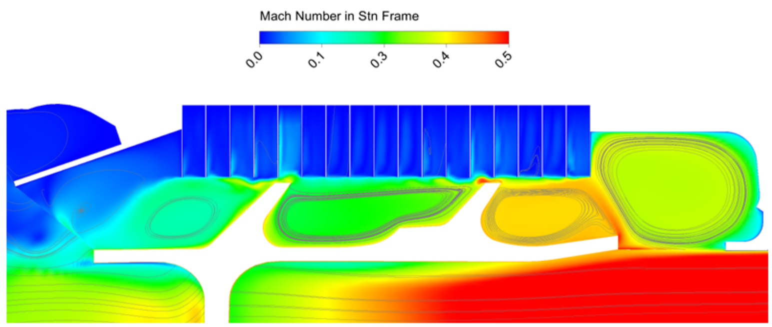

Figure 10. Flow structures and the Mach number distribution in the RSO-HC seal.

the RS-HC reference case. Although the flow structure in the seal is very similar, the seal performance became remarkably worse.

3.2 Fin inclination angle

In the next calculated case, marked as RSO-HC, the fins are located in the same positions as in the RS-HC configuration, but the fin inclination angles are reduced by 22° and 25° for the first and the second fin, respectively. The calculated Mach number distribution with streamlines and the turbulent kinetic energy distribution are shown in Fig. 10. The overall flow structure is very similar to the RS-HC case (Fig. 7). The leakage mass flow rate was 0.59% better than in the RS-HC seal. The results were very similar due to the same fin thickness, which is decisive in this kind of the labyrinth configuration. The flow angle of the first fin is of less importance in this case because the jet is located in the bottom part of the honeycomb, which limits the influence of the first fin shape on the flow in the gap.

3.3 Fin position

In the previous cases the fins were located in the same positions. In the next cases, their position is different assuming that movement is only possible by every cell dimension. The mutual position of the fins and of the honeycomb cells remains unchanged. The fin inclination and thickness were the same as in the RSO-HC case.

In the first case, the first fin was shifted upstream by a distance equal to 1 honeycomb cell (case RSO-HC-FP1U). In the second case, the second fin is shifted downstream by 1 honeycomb cell (case RSO-HC-FP1D). In both cases the distance between the fins is the same, but the location of the labyrinth on the shroud is different. In the next configuration, the first fin was shifted by 3 honeycomb cells upstream (case RSO-HC-FP3U). The position of the second fin remained unchanged. In the last case the first fin was shifted by 3 honeycomb cells downstream (case RSO-HC-FP3D). So was the second fin to maintain the reference fin distance.

The flow structure for the case with the first fin shifted upstream by one honeycomb cell (RSO-FP1U) is presented in Fig. 11. The flow structure is very similar to the RSO-HC case. By moving the first fin by one honeycomb cell it is possible to check if the reduction in the honeycomb length before the labyrinth is beneficial. In addition, the distance between the fins increases in this configuration. The increase in the distance between the fins should, according to literature, reduce the carry-over effect and improve the seal efficiency. The calculated mass flow through the seal is by 0.66% higher compared to the RSO-HC case. It can be seen that the reduction in the carry-over effect brought little benefit, which could not compensate for the deterioration caused by shifting the first fin.

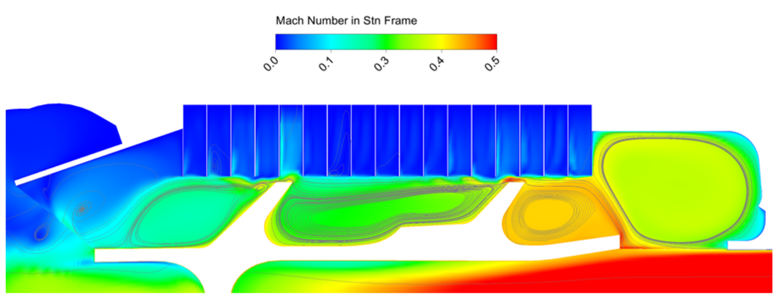

Figure 11. Flow structures and the Mach number distribution in the RSO-HC-FP1U case.

In the next configuration (RSO-FP1D), the second fin was shifted downstream by one honeycomb cell. The main details of the leakage flow in the seal are shown in Fig. 12. In this case, the obtained changes result from the decrease in the carry-over effect. This variant proved to be better than the previous one. A slight

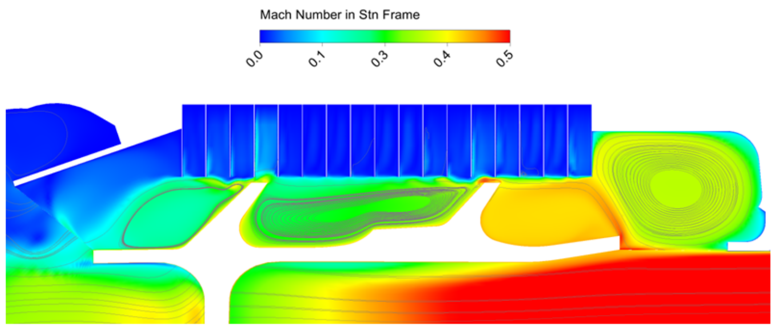

Figure 12. Flow structures and the Mach number distribution in the RSO-HC-FP1D case.

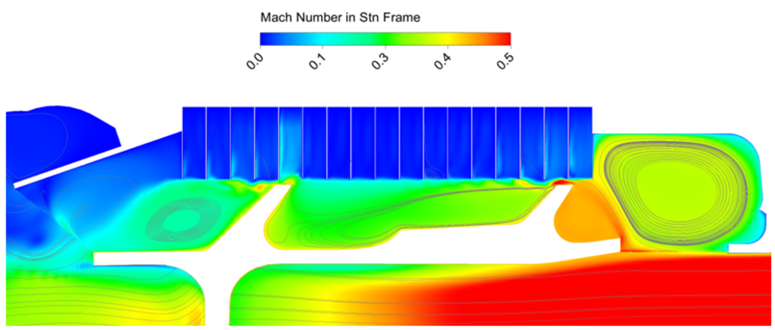

Figure 13. Flow structures and the Mach number distribution in the RSO-HC-FP3U case.

reduction in the mass flow of 0.4% was obtained compared the RSO-HC variant. Compared with the previous case, it can be seen that, for the same distance between the fins, the difference in the labyrinth location on the shroud of one honeycomb cell causes a relative change in the leakage flow of about 1 pp.

Another case under investigation was the RSO-HC-FP3U variant, in which the first fin is shifted upstream by three honeycomb cells. In this configuration, the first fin is placed in its limit position, it is the closest to the honeycomb land edge and to the place where the leakage jet changes its direction. The flow pattern through the seal is shown in Fig. 13. The jet inflow to the seal is very similar. After reaching the land structure, the jet flows into the clearance above the first fin. The inflow to the clearance takes place with a higher Mach number because the jet is not slowed down by the honeycomb cells, as can be seen in Fig. 10 for example. The distance between the fins is increased significantly. The jet has more space to get wider in the chamber between the fins. After flowing over the second fin, the jet adheres to the honeycomb structure till the end. Later on, it goes to the outlet edge of the platform. The calculated mass flow through the rotor seal is by 1.65% higher than the leakage mass flow for the RSO-HC case.

In the next case, RSO-HC-FP3D, both sealing fins of the RSO-HC configuration were shifted downstream by three honeycomb cells. The Mach number and the flow structure are shown in Fig. 14. The jet flowing onto the first fin at a longer distance before the fin gets wider. Before and over the fin, its Mach number is lower than in the previous cases. In the zone before the first fin a large vortex is developed with a high Mach number of 0.4. The zone behind the second fin is in this case different from the other cases. The jet is slowed down on the honeycomb cells less and therefore leaves the honeycomb land zone in the axial direction, reaches the deflector and along its wall goes towards the main flow.The mass flow through the rotor seal is by 1.58% less compared to the leakage mass flow for the RSO-HC case.

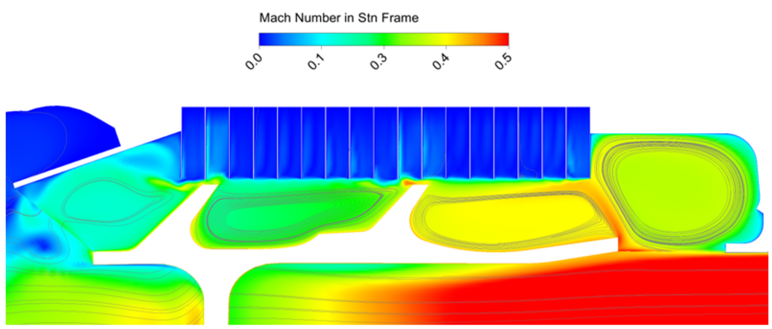

Figure 14. Flow structures and the Mach number distribution in the RSO-HC-FP3D case.

The leakage values obtained for the cases under consideration and their comparison with the reference values are summarized in Tab. 1. Changes in the labyrinth position on the shroud platforms produce small changes in the leakage mass flow, ranging from -1.6% to 1.58% compared the RSO-HC reference configuration. However, considering the possible limit configurations, the variation in mass flow is up to 3%.

Table 1. Comparison of the honeycomb seal performance for the cases with shifted fins.

Case	*vs.* RS-HC	*vs.* RSO-HC
RS-HC	0.00%	
RSO-HC	0.59%	0.00%
First fin shifted upstream (RSO-HC-FP1U)	-0.06%	-0.66%
Second fin shifted downstream (RSO-HC-FP1D)	0.99%	0.40%
First fin shifted upstream (RSO-HC-FP3U)	-1.05%	-1.65%
Fins shifted downstream (RSO-HC-FP3D)	2.16%	1.58%

3.4 Land and fin shift

The position of the seal in the seal domain can influence the flow structure in cavities and, consequently, the seal performance. Two cases are considered in this subsection. It is assumed that in both cases the land and the fins have the same relative position as in the RSO-HC option. In the first configuration, the labyrinth and the land were shifted downstream by the distance of two honeycomb cells, and in the second – the same shift is applied upstream. The symbols of the cases are given in Tab. 2.

Table 2. Description of the cases with a shift of the honeycomb and of the fins.

Case description	Symbol
Reference simplified optimal with land and fins shifted downstream	RSO-HC-L2D
Reference simplified optimal with land and fins shifted upstream	RSO-HC-L2U

The simulation results obtained for the RSO-HC-L2D configuration are presented in Fig. 15. If the land is shifted downstream, the inlet cavity becomes larger and the stream which is formed at the inlet platform edge flows radially and reaches the cavity upper wall, where it is split into two streams: the right one and the left one. The right stream forms a vortex which is similar to that observed in the other simulations. The left stream flows along the wall and is directed downwards by the honeycomb wall. The stream kinetic energy is high enough to reach the shroud platform, and the stream flows along the platform wall and the first fin wall. After that, the resulting flow structure is similar to the reference case. The value of the mass flow rate in the seal was by 5.57% lower compared to the RSO-HC reference case.

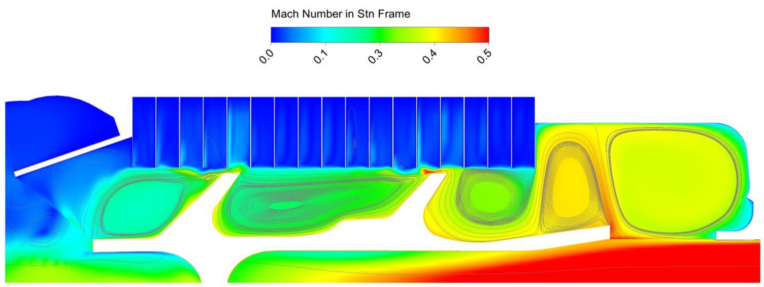

Figure 15. Land and fins shift – flow structures and the Mach number distribution in the RSO-HC-L2D case.

The second configuration with the labyrinth and the land shifted upstream is presented in Fig. 16. The stream in the inlet cavity gets to the bottom of the honeycomb at some distance from the edge of the land (of about one cell) and is divided into the left and the right stream. The right one forms a vortex which is smaller compared to the reference case. It also causes an additional weak vortex in the remaining part of the inlet cavity. The left stream flows directly to the gap. The stream behind the second fin has enough space to adhere to the platform before it leaves the outlet cavity.

Table 3. Comparison of the honeycomb seal performance for the cases with a shift of the honeycomb and of the fins.

Case	*vs.* RS-HC	*vs.* RfO-HC	*vs.* RSO-HC
Reference simplified (RS-HC)	0.00%	18.88%	
Reference for optimization (RfO-HC)	-23.27%	0.00%	
Reference simplified optimal (RSO-HC)	0.59%	19.36%	0.00%
Land and fins shifted downstream (RSO-HC-L2D)	6.12%	23.84%	5.57%
Land and fins shifted upstream (RSO-HC-L2U)	-1.10%	17.99%	-1.70%

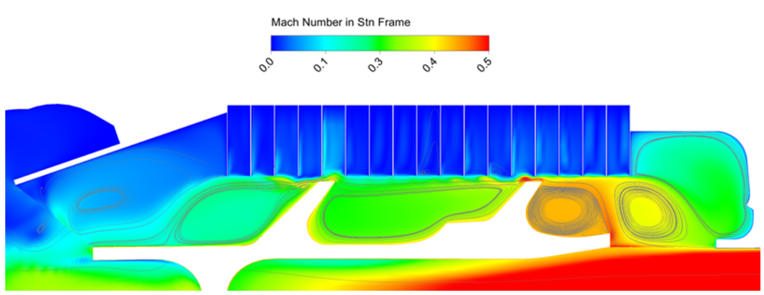

Figure 16. Land and fins shift – flow structures and the Mach number distribution in the RSO-HC-L2U case.

4 Conclusions

The aim of the presented analyses was to evaluate the impact of selected geometrical parameters of the labyrinth tip seal with a honeycomb land on the seal performance. A lot of attention was given to the preparation of the computational model, which enabled efficient and accurate computations.

The following parameters were considered in the what-if analysis: the fin thickness, the fin inclination and position on the shroud platform, as well as the position of the entire labyrinth (land and fins). The parameters were analysed separately to observe the effect of each.

The thinning of the fins caused a significant increase in the leakage mass flow, which is mainly due to an increase in the effective clearance. A slight reduction in the leakage mass flow was obtained due to changes in the fin inclination angle. The angle of the first fin is of less importance in the considered case because before the first fin the jet flows horizontally close to the honeycomb land. Such horizontal flow, directly under the honeycomb, causes additional energy dissipation, as indicated by all the cases related to the analysis of the position of the fins. It follows that with such organization of the flow, the longer the distance from the beginning of the honeycomb to the first fin, the better. In addition, it is preferable to increase the distance between the fins, due to the limitation of the carry-over effect. However, the effect of such operation is of less importance compared to the impact of the position of the first fin.

Changing the position of the entire labyrinth (fins and land) was aimed to assess the effect of the labyrinth position with respect to the seal inlet. Such a change affects the organization of the leakage flow into the seal significantly. While the shifting of the labyrinth towards the inlet did not have a beneficial impact on the leakage, the shifting towards the outlet reduced the leakage significantly. This is due to the fact that the leakage jet changed its way completely. After flowing into the inlet chamber, it reaches the chamber top wall and then, on the side wall of the honeycomb, the jet flows downwards until it reaches the shroud platform. Further along the fin wall, it enters the clearance above the first fin. It is mainly the change in the inflow onto the first fin that is responsible for the obtained significant reduction in the leakage mass flow, which was the highest among the presented cases and totalled almost 6%.

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