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Numerical Study of Labyrinth Seal with Dimple Pattern Using Open Source CFD Software

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Abstract—The secondary flow path in gas turbines is responsible for supply of cooling air to hot sections. Labyrinth seal acts as sealing for the gaps between rotating and stationary components. It minimize the leakage flow and prevent hot flow ingress. Labyrinth seals works with controlled pressured drop, along a series of cavities having small clearance, which are separated by narrow teeth. The secondary air system can account for significant impact on the thermodynamic efficiency. The precise control of mass flow is mandatory in order to avoid overheating or excessive cooling of main stream flow. Manufacturing cost, maintenance and reliability are additional parameters to be considered in seal design[1]. The present analysis aims at the evaluation of a new genre labyrinth seal configuration which has dimples on the stator surface that serves as an alternative to honeycomb cells on the stator.

Index Terms—Dimple pattern, Discharge co-efficient, Labyrinth seal, Leakage behavior, Numerical Simulation, OpenFOAM, Windage Heating

1 Introduction

THElabyrinth seal works by throttling flow through small successive openings in series, each one of which converts pressure into velocity which ideally is dissipated in the intervening chambers to reduce leakage flows in turbo machines, tight operational clearances between stator and rotor parts are desirable. With reduced clearances, the risk of rub contact increases. In such situations, the stator is fitted with an abradable structure or coating that minimizes damage to the rotor when such rub contact occurs. A popular abradable structure is metallic honeycomb, which derives its abradability from a low structural density, typically in the range of 8 to 20% of the bulk alloy density[2]. Seal fins on the rotor together with the stator wall form cavities. A gas flow is accelerated as it enters into the labyrinth from the high-pressure side through an annular gap. Subsequently, the flow area cross section increases dramatically as the flow enters the cavity causing it to dissipate flow energy through a reduction of speed and pressure in a turbulent flow. A series of such events, creating a tortuous path for the gas flow, allows it to maintain a sizable pressure difference across the labyrinth seal, although a certain amount of leak-age flow cannot be avoided. The amount of leakage flow, however, depends on the size of the clearance. Small operational clearances can only be designed if the stator wall is lined with a structure that can easily be cut by the rotating seal teeth without damaging or overheating them Rotation of a labyrinth seal is also known to raise the temperature through a Windage effect that is primarily dependent upon rotational velocity and surface roughness.

Traditional honeycomb seals prone to failure due to delamination of rub strips, fatigue cracking at brazing, increased clearance due to wear. The study presents the alternative design pattern to overcome these problems[2].

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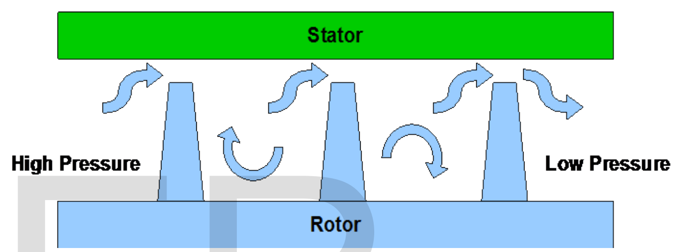

Figure 1: Flow through labyrinth seal

2 Methodology

The simulations presented here were performed using OpenFoam, an open source C++ library for computational volume scheme. The turbulent stress terms were closed using a two equation turbulence model based on the Boussinesq turbulent viscosity hypothesis.

2.1 Flow Equations

The governing equations solved by OpenFOAM and the turbulence models used for this simulation. The flow is governed by the continuity equation, the energy equation and Navier-Stokes momentum equations. Transport of mass, energy and momentum occur through convective flow and diffusion of molecules and turbulent eddies. All equations are set up over a control volume.

2.2 Turbulence Modeling

The most popular turbulence model, the two equation k-ε model is used in the current study, includes the turbulent kinetic energy k and a turbulence dissipation rate ε. The model solves two additional equations, allowing the turbulent velocity and length scales to be independently determined. Essentially energy is cascaded from largest to the smallest scales where it is dissipated.

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2.3 Wall Function

Using wall functions "nutkWallFunction" the viscous sub-layer is modelled by relying on the logarithmic region in the velocity profile outside of the viscosity dominated region.

Often for practical engineering purposes (high Reynolds number flows) the wall function approach is used for robustness and speed.

2.4 Numerical Method

The solution methodology is based on a segregated, compressible version, pressure based PISO algorithm with Euler temporal integration. For pressure and velocity an algebraic multigrid solver with preconditioning is used and for the turbulent quantities and the energy equation a preconditioned, bi-conjugate gradient solver is used. The vector field is interpolated using a combination of Gauss linear scheme and first order Gauss upwind scheme[3].

5 Leakage Performance Parameters

The following parameters are commonly used in the literature to describe the primary characteristics of labyrinth seals and are adopted in this study[4].

There are several parameters related to the leakage behavior. The corresponding dimensionless number, discharge coefficient C_D , is given by

$$C_D = \frac{\dot{m}}{\dot{m}_{id}}$$

Where $\dot{m}$ denotes mass flow, the ideal mass flow $\dot{m}_{id}$ is derived from the non-choked isentropic flow of ideal gases through an annular.

$$\dot{m}_{id} = \dot{Q}_{id} \frac{P_{tot} A}{\sqrt{T_{tot}}}$$

Where A the cross–sectional area is over the tooth tips, P_{tot} and T_{tot} designate the inlet total pressure and temperature respectively.

$$\dot{Q}_{id} = \sqrt{\frac{2\kappa}{\Re(\kappa-1)}\left[1-\left(\frac{1}{\Pi}\right)^{\frac{\kappa-1}{\kappa}}\right]\left(\frac{1}{\Pi}\right)^{\frac{1}{\kappa}}}$$

$$\Pi = \frac{P_{tot}}{P_{out}}$$

The expansion function $\dot{Q}_{id}$ is defined by the pressure ratio Π, ratio of specific heats κ, and specific gas constant $\Re$.

The flow factor φ is also commonly used to represent the leakage rate,

$$\varphi = \frac{\dot{m}\sqrt{T_{tot}}}{A P_{tot}}$$

Choked flow occurs when C_D or φ remains constant regardless of a further increase in P_{tot}. The effect of total temperature increase due to internal losses is called windage heating and is measured by the dimensionless number, windage heating coefficient σ,

$$\sigma = \frac{2 c_p \Delta T_{tot}}{U^2}$$

Where ΔT_{tot} is taken as the difference of the average total temperature between the inlet and the outlet, ω is the rotational speed, and c_p is the fluid specific heat capacity at constant pressure[5].

The swirl development across the seal is defined by the outlet swirl ratio K with the average circumferential velocity at the outlet $u_{\tan}$.

$$K = \frac{u_{\tan}}{U}$$

Various operating conditions are written as dimensionless numbers as well. The pressure ratio π and the circumferential Mach number $M_{\tan}$ are defined as with the outlet static pressure P_{out} and the speed of sound a.

$$M_{\tan} = \frac{U}{a}$$

$$a = \sqrt{\kappa \Re T_{stat}}$$

Rotor rotational velocity is given as below, where R is the radius of the rotor surface from centre of rotation. $U = \omega R$

3 Geometry Details

The labyrinth reference geometry is considered has been studied with smooth land and honey comb seal configurations in the literature by Denecke, et al.[4] and Xin Yan et al.[5]

The similar geometry dimensions are consider for the study except the changes are with the smooth stator which has been modified to dimple pattern with honeycomb base.

The dimple pattern shows improved flow friction behavior in other heat transfer application[6].

The diameter of the base honey comb for the study is equivalent to extruded honey comb size which is 1/16", the depth of the dimple is 0.35 mm and less than half of the cell diameter so as to maintain continuous wavy surfaces. The dimples are intended to create air pockets and thus the main stream flow smoothly glides on the cavity.

The rotor is at average radius 253 mm from the center of rotation, three geometric variations of clearance at tooth tip are considered with gap ranging from 1.3mm, 1.5 mm and 1.7 mm.

In order to cut down the computational resource sector of the geometry is solved with periodic boundary condition to replicate the full model behavior. The sector has 2 dimple cells included.

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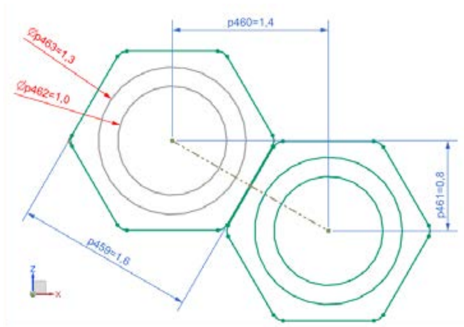

Figure 2: Pattern layout

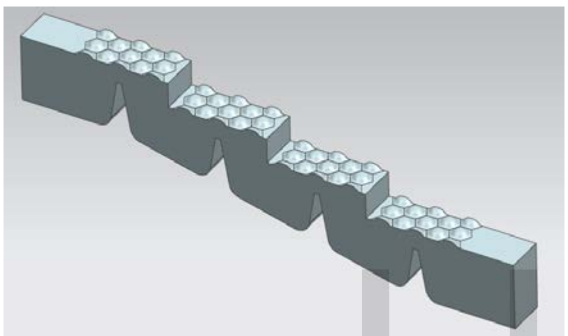

Figure 3: 3D CAD model with dimple pattern

4 Mesh Details

A grid refinement study was done in order to assure that the results are grid independent. Table 1 presents the mass flow parameter for the flow on the labyrinth seal with a pressure ratio PR = 1:1 for three different mesh sizes. The table shows that the results do not change by more than <1%. All computations presented in the following section where performed using simpler one tooth geometry with axisymmetric model without accounting for the rotor rotational speed.

TABLE 1
Grid Independence Study

Case	Mesh count Y-Z plane (2D)	Global length (mm)	Mass flow outlet (kg/s)
1X	424	0.56	0.00101
2X	1874	0.27	0.00103
4X	7864	0.13	0.00104
8X	25600	0.065	0.00105

The global average length is chosen 0.3 mm and first cell height is 0.0001 m for targeted yplus of 150. The total cell count in the actual model is about 0.32 million mesh.

6 Boundary Conditions

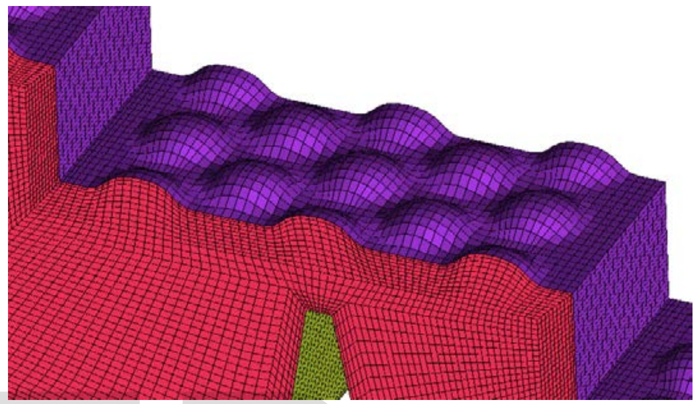

Figure 5: Hexahedral block mesh

The rotational speed of the rotor is kept constant 10000 rpm, the outlet pressure at low pressure side is maintained 200000 Pa. The inlet side pressure is varied for different pressure ratios[4].
The temperature at the inlet is 300 K. All the walls i.e., stator is imposed with no slip condition. Only a sector of the geometry is sufficient to replicate the full 360 degree model thus sector consisting of two dimples are considered and periodic boundary condition is assumed, with all the nodes matching on periodic planes.

TABLE 1
Boundary Conditions

Boundary Conditions	Fields	Value	Units
Inlet	Total Pressure	Variable Based on π=1.1,1.5,1.9	Pa
	Temperature	$T_{tot,in}$=300	K
Outlet	Pressure	P_{out}=200000	Pa
Stator	Velocity	No slip	m/s

Pa = Pascal, K =Kelvin, m = meter, s=second

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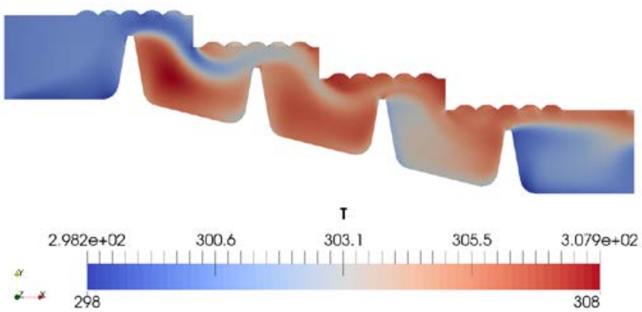


Figure 9: Temperature contour, π=1.1, C=1.3mm

7 Results

7.1 Flow structure

The flow in the labyrinth seal is mainly dominated by the pressure difference in axial direction. At the rotor surface the tangential velocity is maximum due to the rotational speed of the rotor.In the lower part of the cavities the flow recirculates and forms the swirl all along the circumference of the seal cavity. The upper portion of the cavity the flow is straight taking a staircase path.The dimples at the stator help to have a fluid layer for the main flow to simply glide over it. At the outlet there is backflow and stagnation in lower portion of the cavity.

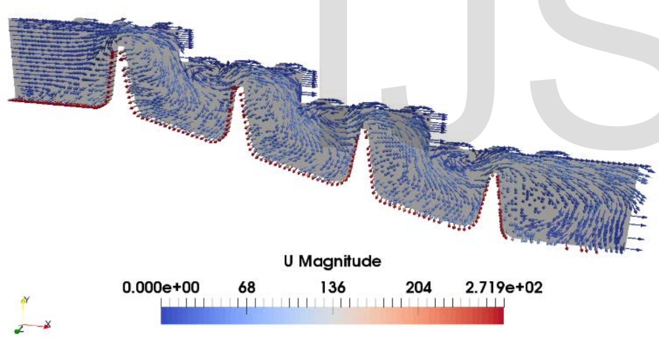


Figure 6: Velocity vectors, π=1.1, C=1.3mm

7.2 Velocity, Pressure and Temperature contours

From the velocity contour it is observed that the flow is stagnant at the dimple cavities. Pressure drops in the seal as it encounters small tip passage in series of steps. The Temperature at the outlet upper portion i.e., close to stator is more compare to rotor region.

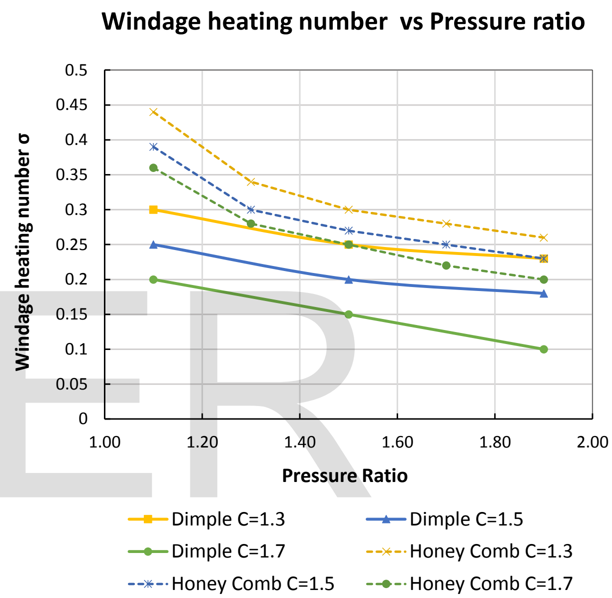
7.3 Comparison

The Dimple pattern seal with different clearance ratio is compared with seal with honey comb cells with different clearance.

The honey comb data is obtained from CFD study done by Xin Yan et al.[5]For clearance 1.3 mm case the results is closely matching for both the seal designs for all pressure ratio.In case of clearance 1.5 mm and 1.7 mm at lower pressure ratio show similar leakage flow, whereas in case of higher pressure ratio dimple pattern leakage flow is more than honey comb design by ~10% to 25 %.

Windage heating number for different pressure ratio is plotted as below, the graph shows similar downward trend as pressure ratio increases windage number decrease. Windage number increases as clearance of gap decreases. The comparison between dimple pattern seal and honey comb seal there is ~30% to 40% difference because of the reason that inlet pre swirl effect is not consider in current study whereasXin Yan et al.[6]

Had included the effect of per swirl.



8 Conclusion

Geometric modifications to a proposed labyrinth seal stator configuration were investigated aiming to deliver similar performance as that of honeycomb cells. From the current study it is seen that it is possible to arrive at discharge coefficients slightly higher than the discharge coefficients of the honey comb cell design but for clearance 1.3 mm it closely match the performance of the honey comb seal, also for lower pressure ratio the flow performance is same as honey comb seal. Thus it dimple pattern is recommended as an option to simply have this pattern instead of smooth land seal. In case of seal space where there is lesser room for installing honey comb cells this can be implemented.

REFERENCES

[1] P. D. I. G.Winterfeld, "Seal Technology in Gas Turbine engines," in *AGARD Conference Proceedings No.237* , France, 1978.

[2] R.C. Hendricks, B.M. Steinetz and M.J. Braun, "Turbomachine Sealing and Secondary Flows, Part 1—Review of Sealing Performance, Customer,Engine Designer, and Research Issues," National Aeronautics and, Ohio, Glenn Research Center 2004.

[3] L. M. F. a. M. T. M. Romulo B. Freitas, "Computational Evaluation of Labyrinth Seal," *50th AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition,* January 2012.

[4] J. Denecke, K. Dullenkopf, S. Wittig and H.-J. Bauer, "Experimental Investigation of the Total Temperature Increase and Swirl Development in Rotating Labyrinth Seals," in *ASME Turbo Expo 2005: Power for Land, Sea and Air*, Reno-Tahoe, Nevada, USA, June 2005.

[5] Xin Yan, Jun Li and Zhenping Feng, "Effects of Inlet Preswirl and Cell Diameter and Depth on Honeycomb Seal Characteristics," *ASME-Journal of Engineering for Gas Turbines and Power,* vol. 132, no. 122506, pp. 1-13, December 2010.

[6] Y. Rao, Y. Feng, B. Li and B. Weigand, "Experimental and Numerical Study of Heat Transfer and Flow Friction in Channels with Dimples of Different Shapes," *ASME-Journal of Heat Transfer,* vol. 137, no. 031901, pp. 1-12, March 2015.

[7] Xin Yan, Jun Li, Liming Song and Zhenping Feng, "Investigations on the Discharge and Total Temperature Increase Characteristics of the Labyrinth Seals With Honeycomb and Smooth Lands," *ASME-Journal of Turbomachinery,* vol. 131, no. 041009, pp. 1-8, October 2009.