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ANALYTICAL AND NUMERICAL INVESTIGATION OF FLOW THROUGH A LABYRINTH SEAL

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Recent rapid improvements in the efficiency and power output of gas turbines require enhanced design of every flow component inside the engine. Labyrinth seals are commonly found in rotating machines such as turbines, pumps, and compressors. The purpose of the labyrinth seals is to control the leakages from high-pressure areas to low-pressure areas which are reflected in engine efficiency and stability. The air mass flow through a labyrinth seal designed for a low-pressure turbine has been determined both through analytical calculus and CFD modelling. The labyrinth seal teeth height, pitch, inclination, and number have been kept constant while varying the radial clearance. The results will be validated through experiments. If the experimental data does not match with the numerical results, improvements will be made to the numerical model.

Keywords: labyrinth seal, leakage flow, turbomachinery, Computational Fluid Dynamics (CFD)

1. Introduction

Increasing performance requirements on gas turbines have led to ever-increasing gas temperatures and pressure ratios. Together with the resulting increase in cooling flows, this requires internal gas leakages to be minimized and controlled even further. The application of a new seal design and improved understanding of leakage flow characteristics are of particular importance in order to meet future performance goals. Understanding the flow in labyrinth seals is fundamentally important in developing improved seal concepts to enhance and predict component performance in gas turbines engines.

Labyrinth seals are commonly found in rotating machines such as turbines, pumps, and compressors. Considerable research was made to investigate the fluid flow through the labyrinth seals which are placed between the casing and the shaft. The purpose of the labyrinth seals is to control the leakages from high-

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pressure areas to low-pressure areas which are reflected in engine efficiency and stability.

Two aspects determine the seal performance: leakage and rotor stability. Leakage, the lapsed fluid between the steady and rotating regions, is the primary source of loss in an aero-engine, whereas rotor stability and relative stable flow are essential as this can greatly increase excitation force on the rotor [1].

There are many forms of dynamic sealing. Labyrinth sealing is efficient and relatively easy to manufacture. There is no mechanical contact, so wear is low or non-existent and does not require special maintenance. Labyrinth sealing is more efficient as the speed of the rotating component is higher. However, labyrinth seals do not completely eliminate fluid leaks. In general, the design of a labyrinth seal takes into account the working speed, the degree of sealing required, the space available for sealing, the temperature and pressure of the working fluid, the radial clearance in the labyrinths, the precision of the components, and others [1][2].

The labyrinth is presented as a succession of chambers delimited by the ribs of the labyrinth, in which the fluid jet expands and forms swirling areas that consume the energy of the jet. A fraction of the jet continues to pass through the radial clearance and accelerates, the process being repeated in the next chamber, as presented in Fig. 1.

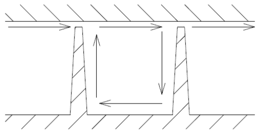


Fig. 1. The flow through labyrinth seals

There are many constructive forms of labyrinths. Fig.2 illustrates some configurations used in seals in gas turbine engines. Labyrinth seals are used in all sections of an engine, in compressors, turbines, etc., and to achieve sealing to most working fluids: air, flue gases, and oils. Their configuration is also chosen according to the fluid that seals it [1].

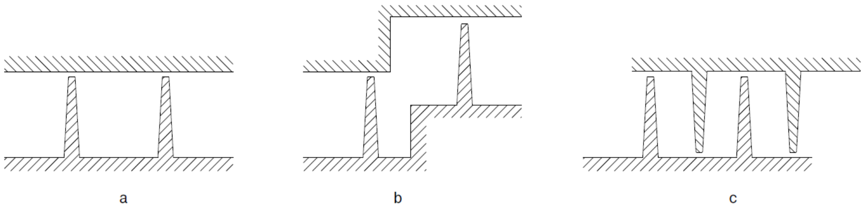


Fig. 2. Typical labyrinth types a) simple through type b) stepped type c) staggered

Numerous calculation models are taking into consideration flow coefficients which enable leakage estimation. One of the pioneers who modelled the fluid flow through the labyrinth seals was Becker [3]. Shortly, Martin [4] presented the first empirical leakage equation for the labyrinth seal. Using his research Egli [5], Kearton and Keh [6], and Vermes [7] continued the investigations, improving and proposing new relations for: the flow coefficient, the kinetic energy carry-over coefficient, and an expansion coefficient. Using computed fluid dynamics (CFD), a significant number of numerical studies were performed. Research about the influence of seal geometric size on the leakage, including radius clearance, tooth pitch, tooth height, inclination, and tooth number were approached [8,9,10,11]. Labyrinth seals configurations for reducing leakage were investigated [12], [13], analyses include parameters such as clearance, pressure ratio, number of teeth, and rotor speed. Effects of pressure ratio and rotational speed on the leakage flow and cavity pressure characteristics of the rotating labyrinth seal were investigated by means of experimental measurements and numerical simulations in [14]. A calculation model enabling determination of the leakage rate in a labyrinth seal is presented in [15]. The results were compared with experimental data. They indicated that the value of the kinetic energy carry-over coefficient depends not only on the seal geometry but also on the pressure decrease.

The scope of the investigations presented in this article is to determine the air mass flow through the proposed labyrinth seal, using analytical calculus and CFD modelling. Over the years CFD techniques have proven useful in designing different component parts of a gas turbine, including labyrinth seals [16,17,18,19,20]. At this stage, the proposed labyrinth seal teeth height, pitch, inclination, and number have been maintained constant, only the radial clearance has been varied, 4 values being taken into consideration.

These results will be validated later through experiments, using the test bench (Fig. 3) manufactured during the AIRSEAL project from CLEAN SKY program. The test bench will be used to perform experiments regarding leakage in labyrinth seals for a low-pressure turbine.

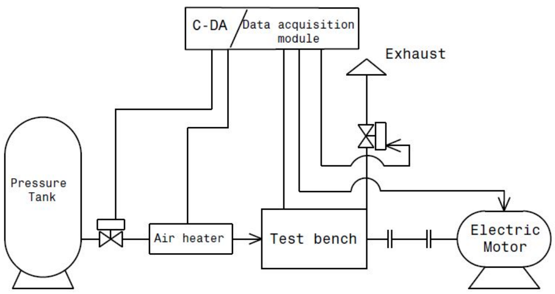


Fig. 3. AIRSEAL test bench

The objective is to optimize the low-pressure turbine by minimizing the leakage flow of burning gases between the casing and the rotor. While the total elimination of these leakages is not possible, reducing tip clearances between the tip of the rotor blade and casing by finding new labyrinth geometries leads to minimum leakage flow.

2. Analytical calculus

To calculate the mass flow through the labyrinth seal the following relation (eq. 1) has been used [21]:

$$\dot{m} = 0.685 \cdot \mu \cdot A \cdot \sqrt{\frac{p_0}{v_0}} \cdot \sqrt{\frac{1-\varepsilon_z^2}{z \cdot (1-\varepsilon_*)} - \frac{\varepsilon_* \cdot (1-\varepsilon_z)^2}{z^2 \cdot (1-\varepsilon_*)^2}} \quad (1)$$

where: μ - flow coefficient, A – minimum section area, P_0 – pressure before the minimum section, $v0$ – specific volume before the minimum section, ε_z - pressure ratio, ε_*= 0.13 [21], z – number of teeth. If the edges of the labyrinth seal teeth are well rounded then ε_*= 0.546 [21].

For the given labyrinth seal, the values presented in Table 1 have been used for determining the air mass flow.

Table 1

Labyrinth seal input data

Parameter	Value	Unit
P_0 (pressure before the labyrinth)	400000	Pa
P_1 (pressure after the labyrinth)	100000	Pa
T_0 (air temperature)	423	K
v_0 (specific volume)	0.303503	
ε_z (pressure ratio)	0.25	
ε_*	0.546	
z (number of teeth)	2	
RC (radial clearance)	0.3	mm
	0.5	
	0.8	
	1.5	
μ (flow coefficient)	0.6-1	

The critical mass flow through the labyrinth seal is calculated using eq.1 in which ε_z is substituted with $(\varepsilon_*)_z$. $(\varepsilon_*)_z$ is calculated using eq. 2 [21]:

$$(\varepsilon_*)_z = \frac{\varepsilon_*}{z \cdot (1-\varepsilon_*) + \varepsilon_*} \quad (2)$$

If $\varepsilon_z \geq (\varepsilon_*)_z$, the air mass flow through the labyrinth seal is calculated using eq. 1. Otherwise, the mass flow through the labyrinth seal stays constant and is equal to the critical mass flow. For the proposed labyrinth seal it was obtained $(\varepsilon_*)_z = 0.069519$. Thus $\varepsilon_z > (\varepsilon_*)_z$.

In Fig. 4 the analytical calculated results regarding the air mass flow through the proposed labyrinth seal, for different flow coefficient values are presented.

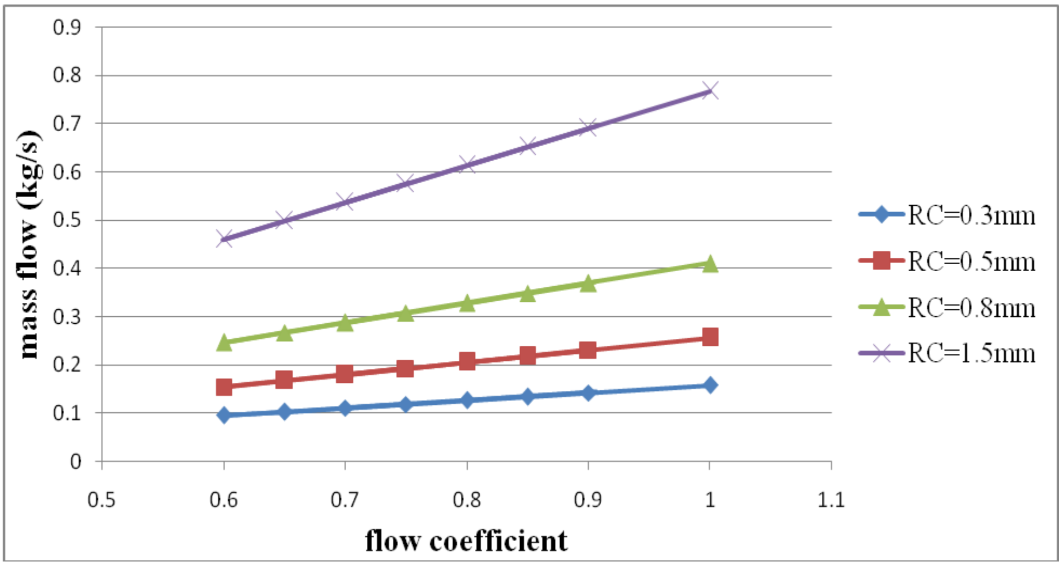


Fig. 4 Air mass flow through the labyrinth

As it was expected, the mass flow increases with the increase of the flow coefficient. Also, the mass flow increases with the increase of the labyrinth radial clearance.

3. CFD modelling

In Fig. 5 the geometry of the test bench on which the labyrinth module will be tested is presented. The geometry of the labyrinth module is copyright protected, thus more details can not be provided.

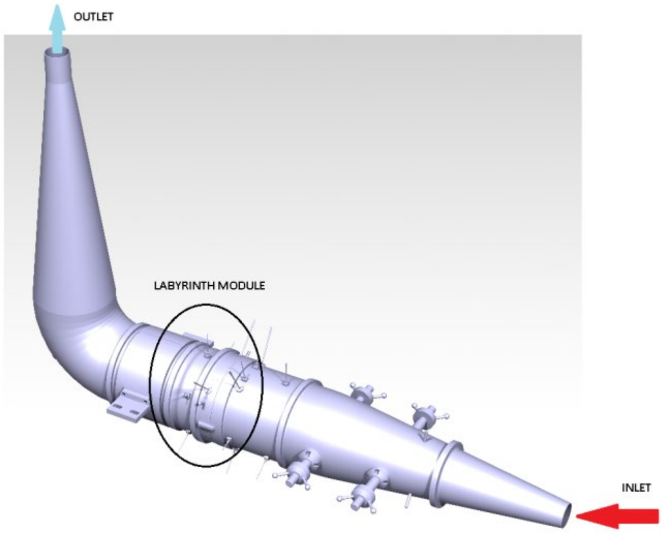


Fig. 5. Geometry

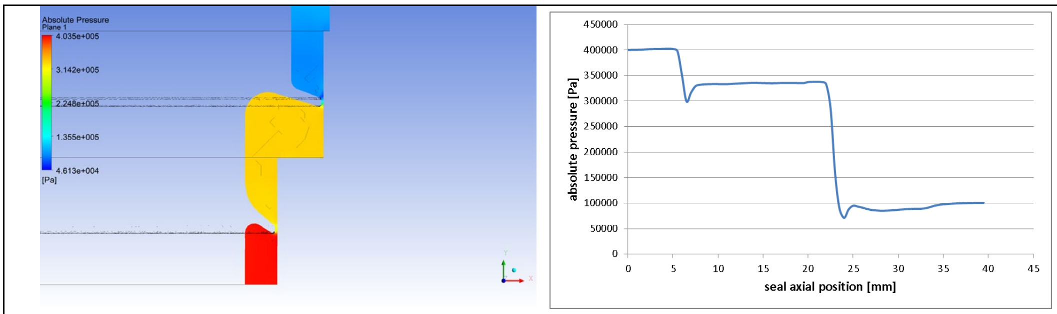
Based on the geometry presented in Fig.5, the computational mesh has been generated using ICEM CFD. The geometry being symmetric, only half of it has been considered in the numerical simulations, thus shortening the computational time. The mesh is of unstructured type. The domain is divided into 4 sub-domain. To better capture the flow through the labyrinth module a boundary layer has been generated. The grid area-averaged y+ value for wall regions of importance, the labyrinth module walls, is 18 and for less important walls is 52.

A RANS type turbulence model has been chosen, namely, the k-ε model, which is a numerically stable and robust model and very popular in the realization of technical applications numerical simulations. Together with this turbulence model, the scalable wall function formulation developed by ANSYS CFX has been used. The reference pressure has been set to 1 bar. Sub-domains 1, 2, and 4 are stationary. Sub-domain 3 is rotational. The rotational speed has been set at 15000 rev/min. The walls are considered adiabatic and smooth.

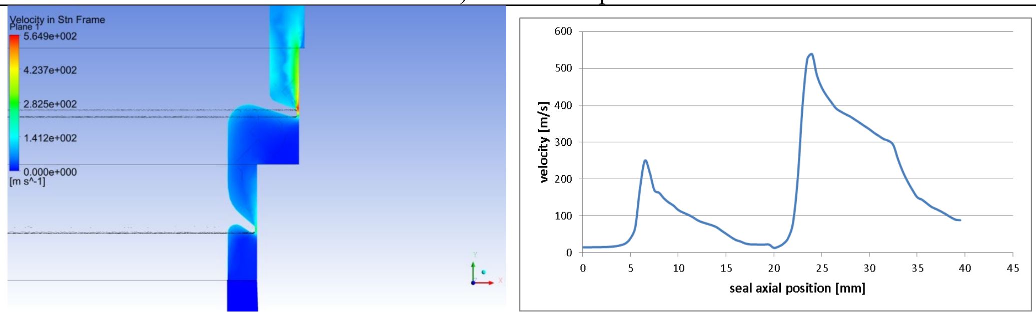
The following boundary conditions have been set: at inlet the total relative pressure of 3 bars and the total temperature of 150 °C and at the outlet the static relative pressure of 0 bar.

4. Results

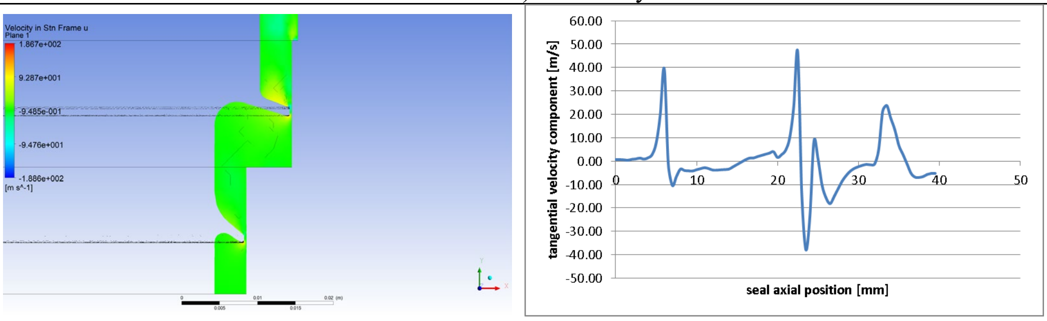
In figures 6-9 the numerical simulations results for the considered radial clearance values are presented. The pressure and velocity fields have been monitored.



a) Absolute pressure

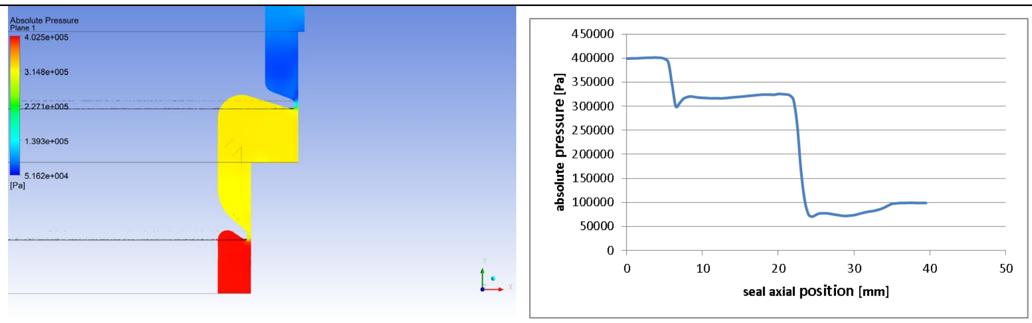


b) Velocity

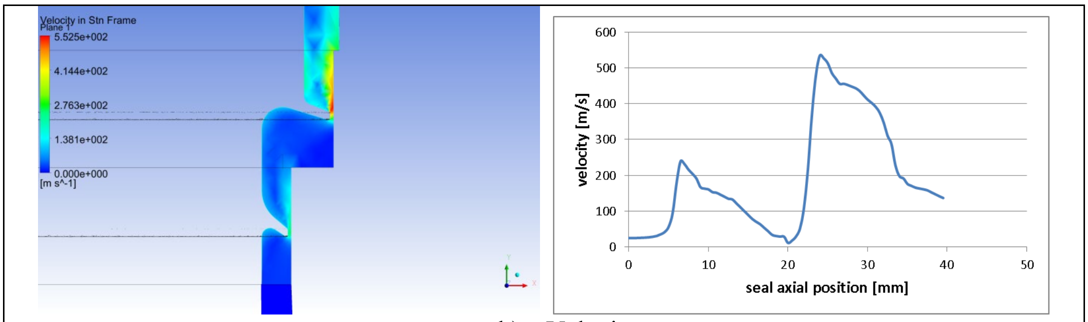


c) Tangential velocity

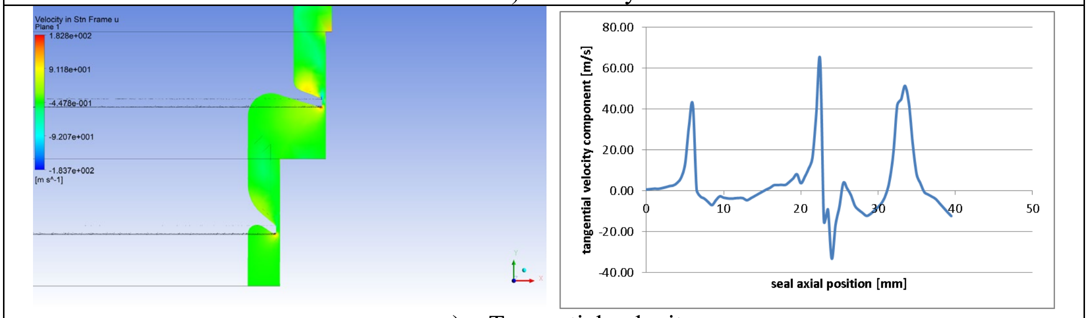
Fig. 6. Radial clearance 0.3 mm



a) Absolute pressure

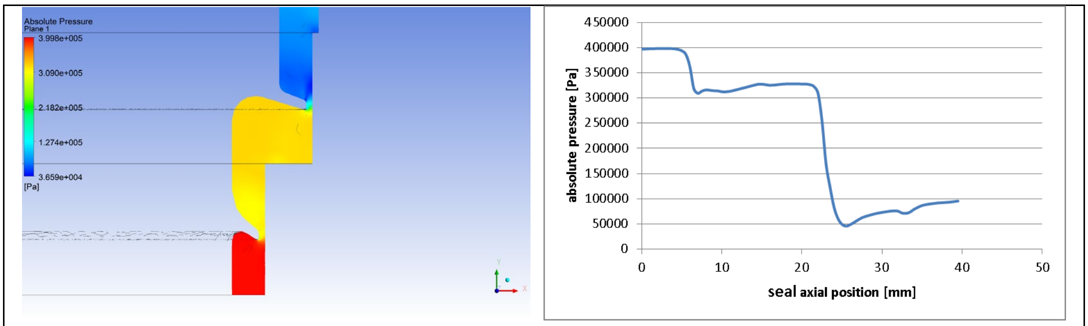


b) Velocity

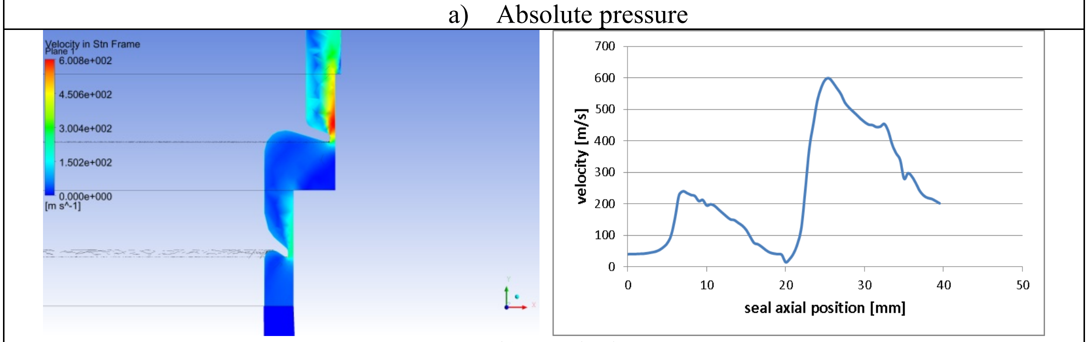


c) Tangential velocity

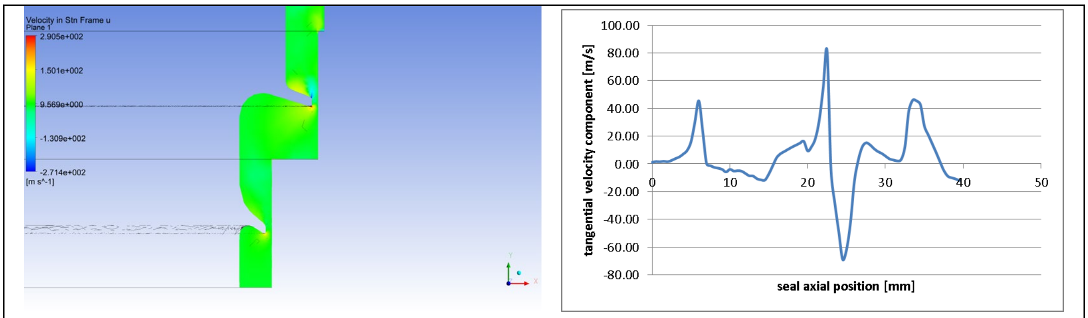
Fig. 7. Radial clearance 0.5 mm



a) Absolute pressure

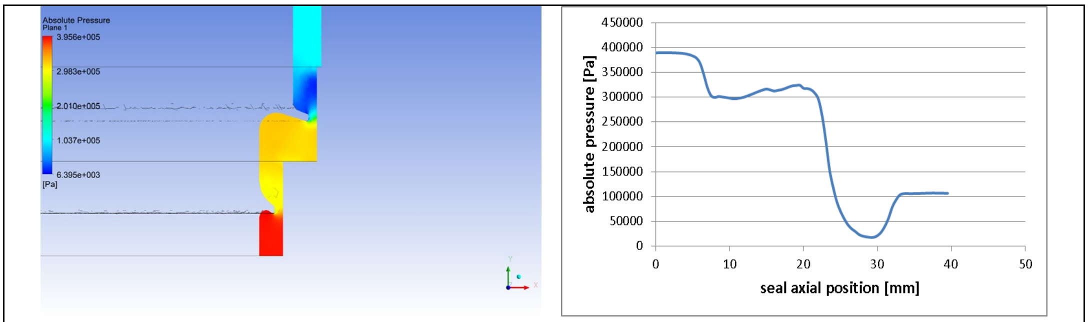


b) Velocity

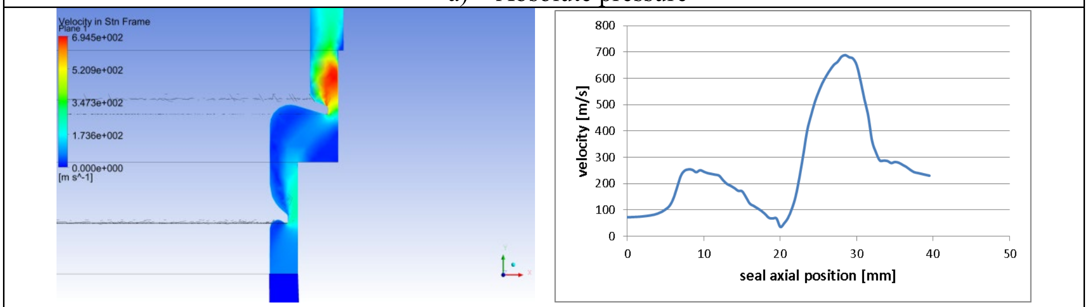


c) Tangential velocity

Fig. 8. Radial clearance 0.8 mm



a) Absolute pressure



b) Velocity

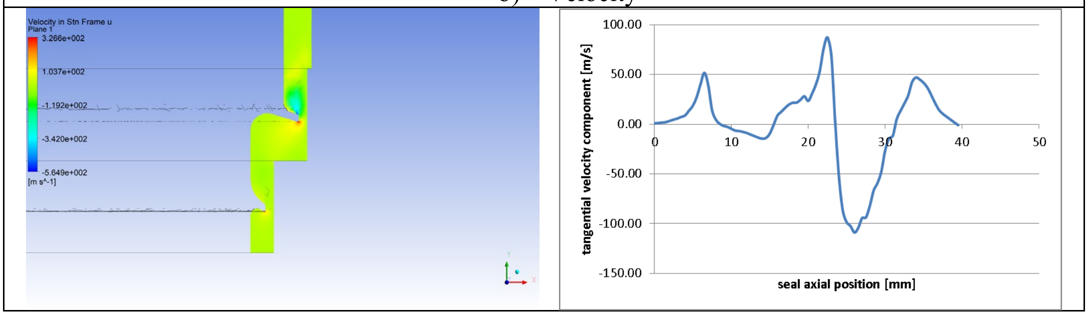


Fig. 9. Radial clearance 1.5 mm

At the entrance of the first labyrinth interstice the air flow is contracted. The air vein is then directed to the labyrinth step, where it is deflected by 90° and flows straight to the lower wall of the labyrinth seal chamber. The air vein flows along the second canal, heading for the second interstice. In the labyrinth seal chamber, the surrounding fluid masses are entrained by the flowing vein, thus forming swirling zones. The existence of labyrinth steps leads to the prolonging of the flowing vein path, which favours the complete dissipation of its energy.

The mass flow, obtained through numerical simulation, for each of the considered radial clearance is presented in Table 2. The walls being considered smooth, the numerically obtained results are compared with the analytical results obtained for $\mu=1$.

Table 2

Air mass flow through the labyrinth

Parameter	Value				Unit
Radial clearance	0.3	0.5	0.8	1.5	mm
numerical mass flow	0.1698	0.2736	0.4428	0.816	kg/s
analytical mass flow	0.1831	0.2909	0.4747	0.8699	kg/s
difference	7.2	5.9	6.7	6.2	%

As can be seen, from Table 2, there is a difference of 6-7% between the mass flow values obtained through the 2 methods. This difference can be explained by the fact that in the numerical simulations the rotational speed has been taken into consideration. The turbulence induced by high speed's tangential component led to the increase of the labyrinth seal's efficiency, thus decreasing the air mass flow rate that can pass through the labyrinth seal. Based on these results it is taken into consideration finding an analytical formula for calculating the leakage through a labyrinth which includes the influence of the rotational speed also.

5. Conclusions

The air mass flow through a labyrinth seal designed for a low-pressure turbine has been determined using both analytical calculus and numerical modelling. The labyrinth seal teeth height, pitch, inclination, and number have been kept constant while varying the radial clearance. Comparing the results obtained through the 2 methods, a difference of 6-7% has been obtained. This may be due to the fact that in the numerical simulations the rotational speed has been taken into consideration. Thus, because of the induced turbulence, the numerical simulation obtained mass flow is lower than the analytical calculus one. For future work, the rotational speed, air temperature, and air pressure ratio will be varied also to observe their influence on the air mass flow through the labyrinth. The results will be validated through experiments.

Acknowledgments

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