Aerospace Science and Technology ••• (••••) •••–•••

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Aerospace Science and Technology

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# Experimental testing for the influences of rotation and tip clearance on the labyrinth seal in a compressor stator well

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ARTICLE INFO

*Article history:*
Received 7 December 2016
Received in revised form 18 September 2017
Accepted 2 October 2017
Available online xxxx

*Keywords:*
Compressor stator well
Labyrinth seal
Rotating cavity
Leakage behavior
Windage heating
Swirl flow
Rotation
Tip clearance

ABSTRACT

The design of the inter-stage seal in an axial compressor is an important topic because the leakage flow across the stator well would lead to aerodynamic mixing losses with the main flow, which will consequently impact the efficiency of the compressor. In this region, the leakage flow is normally controlled by a labyrinth seal with upstream and downstream rotating cavities. In addition, the long rotating wall results in substantial temperature rise and swirl flow development. In particular, the swirl flow in the compressor stator well has a great influence on the leakage behavior of the labyrinth seal. Therefore, it is essential to understand the leakage characteristic, windage heating characteristic and swirl flow characteristic of the stator well.

A test rig capable of running at rotational speed 8100 rpm and pressure ratio 1.3 was built according to the simplified model of the labyrinth seal in a compressor stator well (one stage). Labyrinth rings with different rotor tip radii were manufactured to investigate the effect of tip clearance. Leakage flow rate, windage heating and swirl ratios in the outlet cavity were measured at different rotating speeds and different labyrinth rings. As the working tip clearance was very important for the analysis of the leakage behavior, the set up tip clearance was measured with plug gauges, while the radial displacements of rotating disc and stator casing were measured separately with two laser distance sensors. Since the tip clearance was varying with rotating speed and airflow temperature, the data interpolation method was used to find the pure influences of rotation and tip clearance.

Numerical simulations were performed to analyze the flow characteristic, variation of total temperature and development of swirl flow in the stator well. Besides, CFD results could provide more detailed insight into the flow mechanisms that are responsible for the influences of rotation and tip clearance.




## 1. Introduction

Gaps between stationary and rotating parts are unavoidable in turbomachinery. Large gaps can lead to flow instability and decreasing efficiency while very small gaps can result in rotor–stator collision. The sealing system in turbomachinery is very important because it has many benefits such as increasing the output power and efficiency and improving the life [1]. Labyrinth seals are non-contacting, rotating and widely used throughout the modern engines. Since aero-engines are characterized by high temperatures, pressures and rotational speeds, they are the most available technology that allows the current standards in terms of reliability and durability to be met. In a labyrinth seal, flow occurs between two relatively moving components, namely, teeth and a seal land. When the air flows through the constriction between the tooth tip and land, a part of pressure energy is converted into kinetic energy. Cavities are formed between adjacent teeth such that the kinetic energy is dissipated through uncontrolled expansion, turbulence and viscous before entering the next tooth tip restriction. Therefore, this increases the resistance of flow and controls the leakage flow rate [2]. Another characteristic of labyrinth seals is that there are many performance-influencing parameters, e.g. pressure ratio, rotational speed, tip clearance and tooth shape. The leakage behavior of labyrinth seals has often been the subject of investigations in the past through numerical and experimental methods. However, much less attention had been paid to the windage heating and swirl development.

The stator well in a compressor is the space between the rotor and stator inside the mainstream annulus flow (see Fig. 1). As the mainstream pressure rises, it is necessary to establish the labyrinth seals in a compressor stator well in order to prevent too much leakage flow through the clearance. Compared to normal labyrinth seals, there are rotor–stator cavities at the upstream and downstream of labyrinth seals. Due to the long rotating wall, the windage heating and the swirl development are remarkable in this

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https://doi.org/10.1016/j.ast.2017.10.003
1270-9638/

**Nomenclature**

| | | |
|---|---|---|
| $A$ | Area | $m^2$ |
| $A_R$ | Surface area of the seal | $m^2$ |
| $b$ | Axial clearance between rotor and stator in the cavity | m |
| $B$ | Tooth pitch | m |
| $C_D$ | Discharge coefficient | |
| $C_M$ | Seal moment coefficient | |
| $c_p$ | Specific heat capacity | J/kg K |
| $c$ | Working tip clearance | m |
| $c_0$ | Set up tip clearance | m |
| $\Delta c_1$ | The radial displacement of labyrinth ring | m |
| $\Delta c_2$ | The radial displacement of stator casing | m |
| $H$ | Tooth height | m |
| $m$ | Mass flow rate | kg/s |
| $N$ | Teeth number | |
| $p^*$ | Total pressure | $N/m^2$ |
| $p$ | Static pressure | $N/m^2$ |
| $Q$ | Rotor power loss | W |
| $R$ | Rotor radius | m |
| $R_0$ | Initial rotor radius | m |
| $R_g$ | Specific gas constant | J/kg K |
| $Re = m/\pi R\mu$ | Axial Reynolds number | |
| $t$ | Tooth tip thickness | m |
| $T^*$ | Total temperature | K |
| $\Delta T$ | Windage heating | K |
| $Ta = \frac{2c \times U}{\nu}\sqrt{\frac{c}{R}}$ | Taylor number | |
| $U$ | Linear velocity of rotor | m/s |
| $x$ | Axial coordinate | m |
| $V$ | Velocity of fluid | m/s |
| $\alpha$ | Tooth front inclined angle | ° |
| $\beta$ | Swirl ratio | |
| $\gamma$ | The angle between $V$ and $V_a$ | ° |
| $\kappa$ | Ratio of specific heats | |
| $\pi$ | Pressure ratio | |
| $\rho$ | Density | $kg/m^3$ |
| $\mu$ | Dynamic viscosity | kg/m s |
| $\nu$ | Kinematic viscosity | $m^2/s$ |
| $\theta$ | Tooth rear inclined angle | ° |
| $\omega$ | Rotational speed | rpm |
| $\Theta$ | Windage heating coefficient | |

*Subscripts*

| | |
|---|---|
| *ideal* | Ideal |
| *labyrinth* | Labyrinth seal segment |
| *SYS* | System parameter |
| *ave* | Average value |
| *a* | Axial direction |
| $\varphi$ | Circumferential direction |
| *r* | Radial direction |
| 0 | Initial value |
| 1, 2..., 6 | Measurement station |

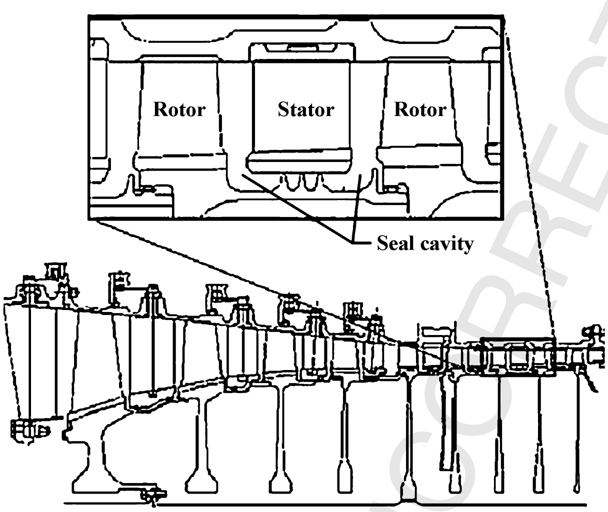


**Fig. 1.** A straight-through labyrinth seal in a compressor stator well [3].

region, which can have a great influence on the leakage characteristic. This inter-stage leakage flow is expected to further impact the aerodynamic performance of mainstream. In addition, the windage heating and swirl flow can affect the structural strength and vibration of rotor roots, as well as the accuracy of thermal analysis.

In the earlier analytic and experimental attempts, very few researchers considered the rotational effects of labyrinth seals. Moreover, the centrifugal growth and the thermal expansion were not measured in most cases. Therefore, it is not suprising that some of the results are not in good agreement. For example, the leakage increased by 13% in Morrison's and Chi's [4] stepped seal but decreased by 9% in Stockers [5] seal toward higher rotational speeds. Then, an experimental study was presented by Waschka et al. [6], where the leakage rate was measured on a high speed straight-through labyrinth seal. The rotation reduced the leakage flow rate beyond a certain Ta/Re ration of 0.2. Paolillo et al. [7] conducted the experiments for various stepped labyrinth seal designs and focused in particular on the effect of rotational speeds on the discharge characteristic. Leakage reduction was characterized in terms of $C_D/C_{D,0}$ (the ratio of leakage rate with rotation over leakage rate without rotation) as a function of circumferential flow velocity to axial velocity. For large velocity ratios of $V_\varphi/V_a > 5$, leakage reductions of more than 20% were observed.

As a rotating component, the labyrinth seal would cause the windage heating and swirl velocity of flow, which become more and more important for an optimized engine design. For example, the total temperature and swirl development after the labyrinth seal in pre-swirl chamber directly influence the blade cooling air temperature. McGreehan et al. [8] published the experimental results of windage heating for different labyrinth seal geometries and a tooth to tooth calculation algorithm was derived from shrouded-disk correlations. Millward et al. [9] provided a simple correlation to calculate seal moment coefficient based on McGreehan's data in order to get the windage heating characteristic of the rotating labyrinth seal. In the current study, the measurement data of total temperature increase would be compared to the correlation developed by Millward. Denecke et al. [10] investigated the total temperature and swirl development across stepped labyrinth seals experimentally and numerically. The influences of inlet swirl ratio, circumferential Mach number and honeycomb on the windage heating were considered. In addition, Scherer et al. [11] found that the discharge behavior also affected the windage heating and swirl flow with CFD.

Only few publications deal with the rotating labyrinth seal in a compressor stator well. An experimental study was presented by Wellborn [12], where the velocity and pressure parameters within the stator well at low speeds were investigated. Bayley and Childs [13] used previously published correlations for rotor disc moment coefficients to predict the windage heating, but this