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AN IMPROVED CONTROL METHOD OF RIM SEAL BASED ON AUXILIARY SEALING HOLES

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ABSTRACT

Purge flow is of great importance in cooling the rotor-stator disc cavity and reducing hot gas ingestion in gas turbines. The amount of cooling air extracted from the compressor is crucial to engine efficiency. In order to simplify rim seal structure while ensuring high sealing efficiency, the current paper optimises the flow path of the secondary air system and present a new rim seal structure with auxiliary sealing holes transporting secondary sealing flow. The new structure is compared with the traditional one using CFD methods, showing that the sealing efficiency is improved by using inclined sealing holes. The depth of hot gas ingestion and the maximum pressure difference along circumference has been reduced. The current paper investigates the sealing efficiency under different inclined angle of auxiliary sealing hole (0 °, 45 °) and flow distribution of sealing air (main sealing flow rate versus secondary sealing flow rate=1:1, 2:1, 3:1), found that these two parameters both have important impacts on sealing efficiency. The relationship between these two factors and sealing efficiency has obtained, and it provides a new idea for the design of rim seal in gas turbines and aero engines.

INTRODUCTION

The mainstream hot gas may get into disk cavity through turbine rim in gas turbines. Hot gas ingestion may cause a lot of bad effects such as disk temperature increasing, disk core overheating and bearing damaging. Previous studies have shown that the life of the turbine disk can be reduced by 50% as long as the concentration of ingested gas has a certain increase in the disk cavity. In addition, the efficiency of the engine will increase by 0.5% and the fuel consumption will be reduced by 0.5% when the amount of cooling air cut in half (Scobie 2016). Therefore, the optimization goal of the rim seal is to achieve effective sealing with less sealing air in order to reduce the loss of thermal-power conversion and mixing between sealing flow and mainstream flow.

In order to improve the sealing efficiency, the widely used method is to provide a rim seal structure on the outer edge of the turbine disk to increase the flow resistance of hot gas and weaken the effect of tangential velocity of the mainstream. Sangan (Sangan 2012) used CO_2 as a tracer gas to compare the sealing efficiencies of different rim seal structures, found that complex structure can improve sealing efficiency.

With the in-depth understanding of the flow mechanism of hot gas ingestion and the improvement of design and manufacture level, the current rim seal structure tends to be complicated. For example, Sangan (Sangan 2014) proposed a method by increasing the fin structure in the circumferential direction of the rim in order to increase the pressure of the external chamber near the rim, which can suppress hot gas ingestion. Scobie (Scobie 2016) proposed a rim seal structure with fins on the static disc side, and the minimum sealing mass flow rate Φ_{min} can be reduced from 0.036 to 0.024. Li (Li

2016) designed a hexagonal honeycomb along circumferential direction in the inner ring of the radial rim seal structure, which increases the turbulent dissipation of the axial velocity component, resulting in an increase in sealing efficiency of about 9%~14%.

Although the complex structure can improve the sealing efficiency, too complicated structure will cause problems such as difficulty in manufacture and scratch between components, which will reduce reliability and increase difficulty of maintenance. It may also cause thermal deformation and creep in some conditions.

Different from conventional optimization in structure, the current paper optimizes the flow path of the secondary air system and present a new rim seal method with auxiliary sealing holes transporting secondary sealing flow. The structure is shown in Fig. 1. By adding holes with an inclined angle in circumferential direction at a high radius of the static disk, the secondary flow of the combustion chamber（燃烧室二股气流） are introduced through these holes to make cooling and sealing better at disc rim. The flow path of this new rim seal method are shown in Fig. 2.
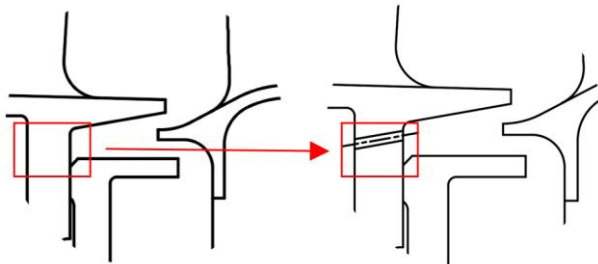

Fig. 1 rim seal with auxiliary sealing hole
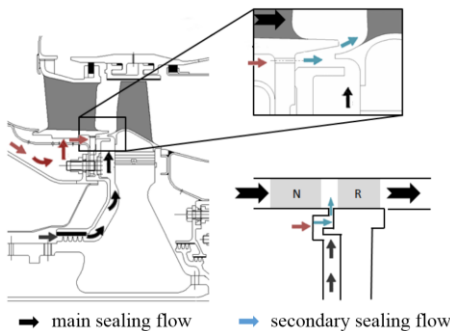

→ main sealing flow   → secondary sealing flow

Fig. 2 flow path of rim seal with auxiliary sealing hole

This optimization idea comes from the real flow condition that exists in gas turbines. Clarks (Clarks 2016a, 2016b) investigated the leakage flow called Chordal Hindge Leakage (CHL) near the inner ring of the first turbine guide vane in a real engine shown in Fig. 3. Bunker (Bunker 2005) and Patinios (Patinios 2018) studied the similar flow structure. However, the leakage flow here only accounted for 10% of the total air flow bleed into the disk cavity, and have no tangential velocity component. The results of these studies show that this leakage air flow has no significant effect on engine efficiency, sometimes there are even bad effects.
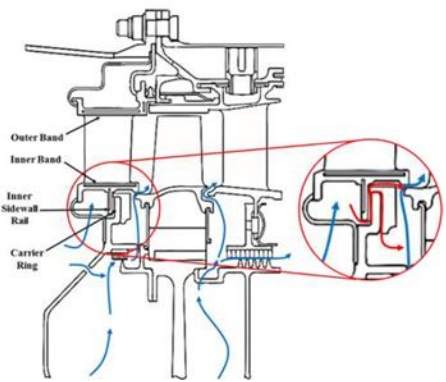

Fig. 3 CHL in real engine

In the past two years, turbine designers has realized that this leakage flow (CHL) has the potential to improve the sealing efficiency of rim seal. Both Clarks (Clarks 2018) and Patinios (Patinios 2018) found that when the sealing air flow rate is constant, the excessive CHL flow will cause the "toroidal vortex" in disk cavity, which has negative effect on sealing efficiency. But under certain CHL flow rate, the Batchelor flow pattern inside the cavity can be maintained, and the sealing efficiency can be improved.

In a patent of PW (Durocher 2006) shown in Fig. 4, an inclined hole at high radial position is presented (No. 59). However, the inventor intended to use the impingement effect of cooling jet to cool the end wall of inner ring, and did not mention the effect of this inclined hole on the rim seal of this structure.
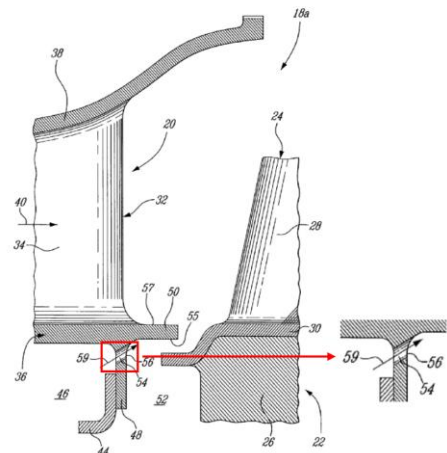

Fig. 4 a patent of PW

As is known to the author, the investigation of new control method and the use of inclined hole in high radial position to improve the rim seal efficiency is completely absent.
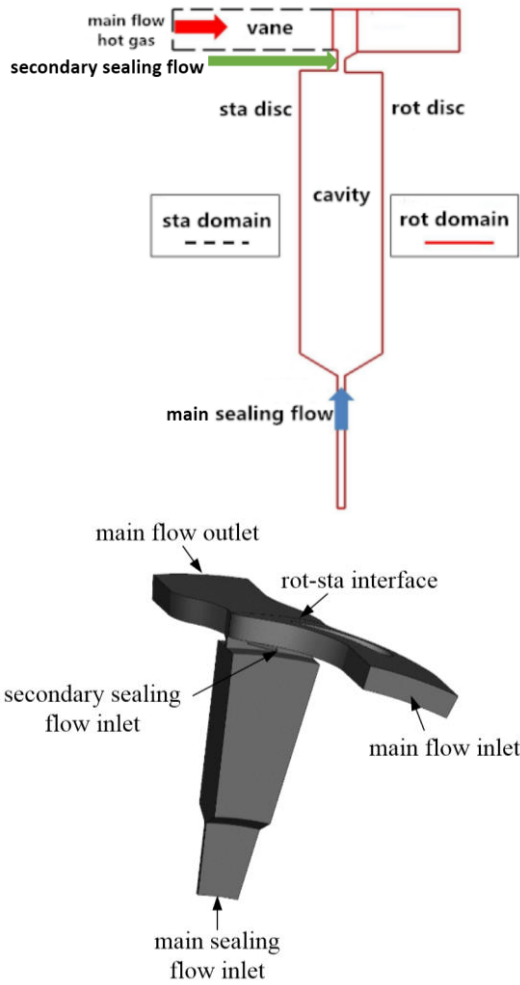
CFD MODEL AND METHOD
CFD domain

Based on the simple axial rim seal geometry, the CFD model are shown in Fig. 5. The model includes main flow and cavity flow, which can simulate the External Induced (EI) ingress and Rotational Induced (RI) ingress simultaneously.

The geometric parameters of the rim seal structure include:

Table 1 domain geometry

rim seal inner radius (b)	190 mm
height of mainstream channel (h)	10 mm
axial clearance of gap ($S_{c,x}$)	2 mm
axial clearance of cavity (S)	20 mm

The axial clearance ratio of the sealing gap $G_{c,x}=S_{c,x}/b=0.0105$, axial clearance ratio of cavity $G=S/b=0.105$. The vane is in stationary domain and the disc cavity is in rotational domain. The guide vane profile of high load and small aspect ratio (Sangan 2011) is selected. Due to symmetry, only a 11.25 deg sector (1/32 of whole ring) is simulated.


Fig. 5 CFD model

CFD method and validation

The ANSYS CFX 19.0 was used in the CFD process. The tracer gas concentration method was used in the study, and the trace gas concentration was used to indicate the degree of hot gas ingestion and the effect of rim seal. The CFD results are compared with experiment results by Kang Wu (Wu 2014).

The non-dimensional coefficient of static pressure (c_p) is the main factor driving hot gas ingestion. The swirl ratio (β) reflects the flow pattern in the disk cavity. The CFD results of c_p and β agree well with the existing experiment results (Fig. 6, 7), and the reliability of the method of model building, mesh generating and numerical scheme are verified.

$$c_p = \frac{p_a - p_{ref}}{0.5\rho\omega^2 b^2} \quad (1)$$

$$\beta = \frac{v_\varphi}{\omega\, r} \quad (2)$$
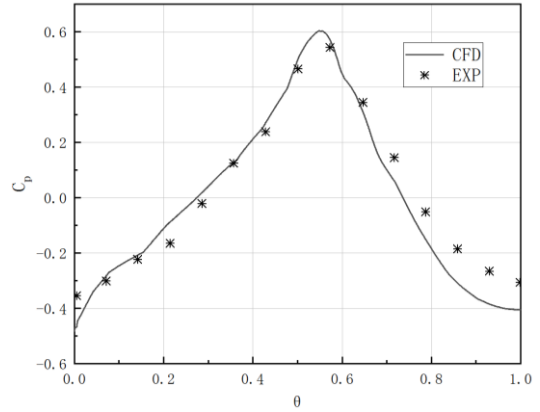

Fig.6 compare c_p between CFD and EXP
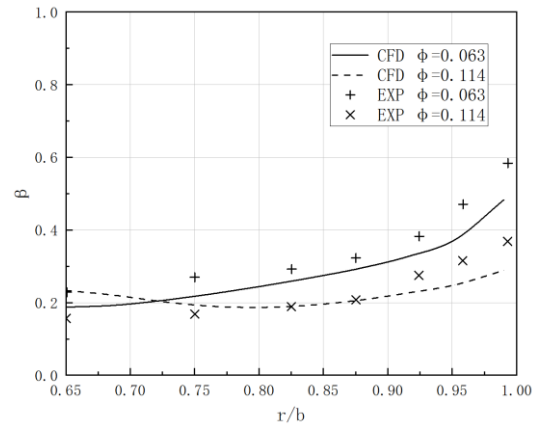
Fig. 7 compare β between CFD and EXP

Mesh and boundary condition

The mesh was generated by ANSYS ICEM CFD 19.0. Fig. 8 shows the mesh detail near the disk rim. The mesh nodes in mainstream channel and cavity are perfectly matched to ensure the accuracy of the solution. Three geometries of different inclined angle (IA) of auxiliary sealing hole are shown in Fig. 9, and the mesh elements of these three geometries are between 3~3.5 million.
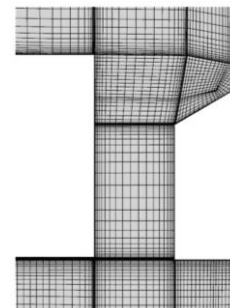
Fig. 8 mesh detail at disk rim
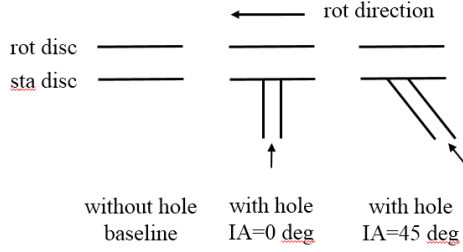
Fig. 9 three different geometries

In order to investigate the influence of inclined angle of auxiliary sealing hole and flow distribution of sealing flow, seven cases are calculated as below (IA=inclined angle of auxiliary sealing hole, m_1=main sealing flow from cavity entrance, m_2=secondary sealing flow from auxiliary sealing hole), the total sealing flow rate is remained equal for all cases, which account for 2.2% of the main flow rate. The baseline is case without the secondary sealing flow.

Table 2 CFD cases

	IA (deg)	m_1:m_2
without hole (baseline)	-	-
with hole	0	1:1, 2:1, 3:1
	45	1:1, 2:1, 3:1

Table 3 CFD boundary conditions

rotating speed (N, rpm)	3000
non-dimensional sealing flow rate (Φ_0)	0.063
Reynolds number of mainstream (Re_x)	$4.4*10^5$
Reynolds number of rotation (Re_ϕ)	$8.17*10^5$

$$\Phi_0 = \frac{m}{\mu b 2\pi G_c \, Re_\phi} \quad (3)$$

$$Re_x = \frac{\rho \omega b}{\mu} \quad (4)$$

$$Re_\phi = \frac{\rho \omega b^2}{\mu} \quad (5)$$

RESULTS AND DISCUSSION
The effect of auxiliary sealing hole and inclined angle

In previous studies, the aim of rim seal design is to prevent hot gas ingest into cavity completely. It requires a large amount of sealing air, which will result in a significant drop in engine efficiency. Full-sealing is too consuming and not necessary, what important is to make sure that the temperature of key parts of disk cavity under the limitation. Therefore, the current paper investigate the sealing efficiency instead of minimum sealing flow rate.

The sealing efficiency is defined by concentration of a tracer gas added to the sealing air. It is accomplished by adding an additional variable and solving the transport equation of it in ANSYS CFX.

$$\eta_c = \frac{c}{c_a} \quad (6)$$

where c is the concentration of the tracer gas, and c_α is the concentration of it in sealing air.

Figure 10 shows the sealing efficiency along radial direction on the stationary disk surface. The auxiliary sealing hole of 45 deg is effective to improve sealing efficiency by 10% compared to the case without auxiliary sealing hole. However, the straight auxiliary sealing hole has a negative effect on sealing efficiency by 4% compared to the case without hole. These results can be confirmed by the sealing efficiency contour of the meridional plane in the disk cavity in Fig. 11.

When m_1:m_2=2:1, the inclined hole of 45 deg have a positive effect on sealing efficiency. As the inclined direction of the hole is same to the rotational direction, the total temperature of the cooling air relative to the disk can be reduced by pre-swirl, which is also beneficial to cooling.
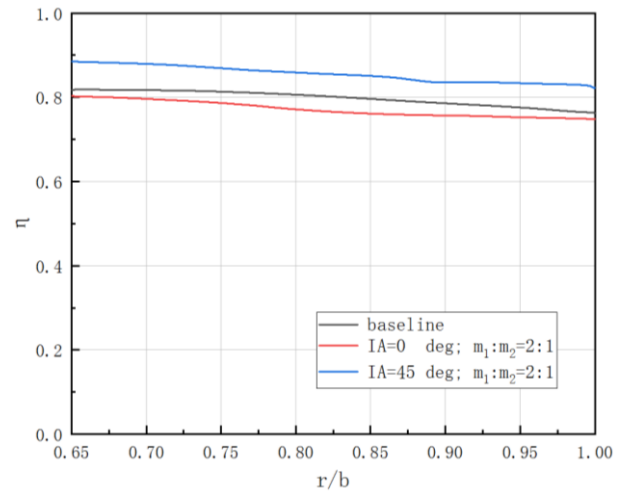
Fig. 10 sealing efficiency on sta disk of different IA
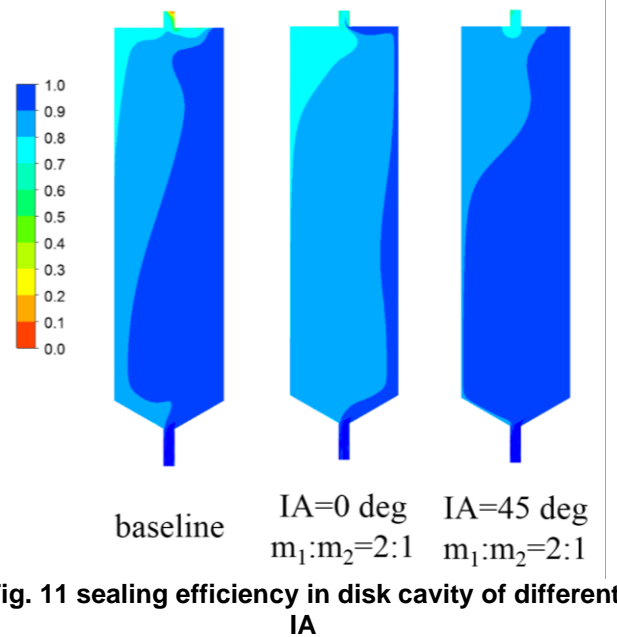
Fig. 11 sealing efficiency in disk cavity of different IA

Campbell's study (Campbell 1979) shows that the nonuniformity of pressure along the circumferential direction at disk rim helps to increase hot gas ingestion. The non-

dimensional coefficient of static pressure is shown in Fig. 12. Hot gas will ingest into cavity at high pressure zone where $c_p>0$, and low pressure zone where $c_p<0$ is safe without the danger of hot gas ingestion. The inclined hole of 45 deg has a minimum Δc_p, which is 8.15% less than the baseline, which can account for the trend of sealing efficiency.
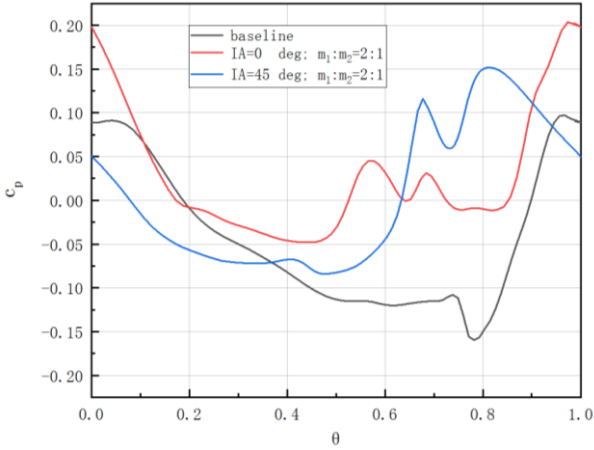

Fig. 12 c_p along circumference of disk rim

The effect of flow distribution

The whole sealing flow rate stay unchanged, and the secondary sealing flow rate account for 1/2, 1/3 and 1/4 respectively.

The investigation of sealing flow distribution has done on the optimized model with auxiliary sealing hole of 45 deg. Three cases (m_1:m_2=1:1, 2:1, 3:1) are calculated, showing that sealing flow distribution is also an important factor to sealing efficiency. The sealing efficiency is low when the mass flow of main sealing flow and secondary sealing flow are equal. When the ratio is increased to 2:1 and 3:1, the sealing efficiency is about 11% higher, and the difference between these two cases are much smaller.
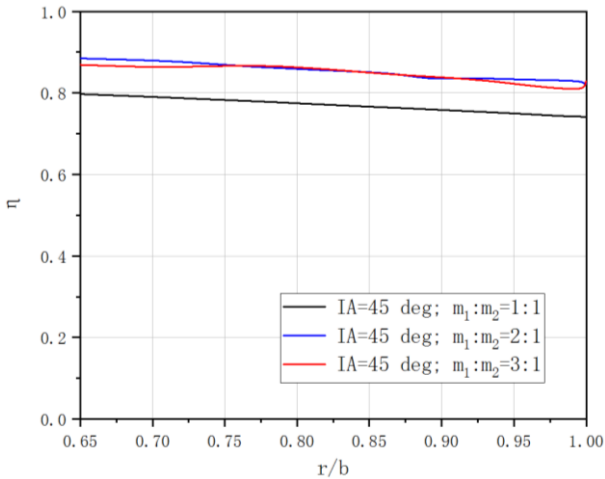

Fig. 13 sealing efficiency on sta disk of different sealing flow distribution
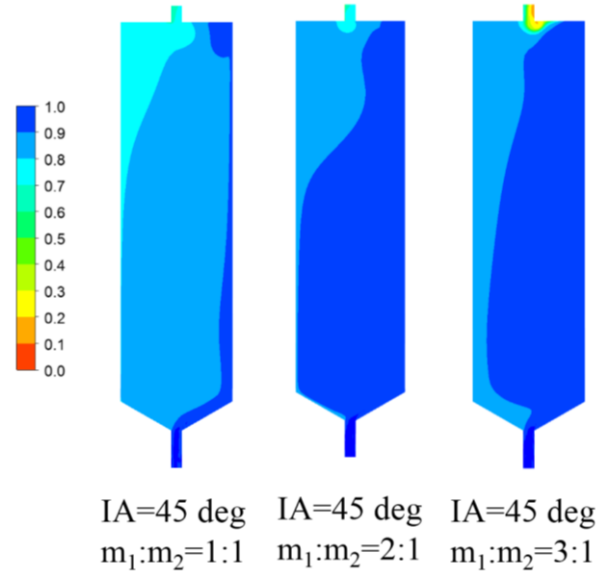

Fig. 14 sealing efficiency in disk cavity of different sealing flow distribution

CONCLUSIONS

The inclined auxiliary sealing air can improve the sealing efficiency, so that the air used for sealing from the secondary air system can be appropriately reduced to achieve the same sealing efficiency, which is beneficial to the aerodynamic efficiency of the turbine.

The new rim seal structure with auxiliary sealing hole is effective to improve sealing efficiency under certain conditions. Both inclined angle of auxiliary sealing hole and flow distribution of sealing flow have important impacts on rim seal efficiency.

1. The inclined sealing hole with the same direction of disc rotation has a positive effect on sealing efficiency, while the straight hole has a negative effect on it.

2. For inclined sealing hole, the sealing efficiency increases first and then remain almost unchanged as the flow distribution ratio m_1/m_2 increases.

3. The secondary sealing air from auxiliary sealing hole reduces hot gas ingestion by reducing the nonuniformity of pressure along circumferential direction.

The new structure of rim seal is easy to processing and manufacturing, which can acquire high rim seal efficiency without using complex structure. It provides a new idea to rim seal design in gas turbines.

NOMENCLATURE

b = inner radius of disc
c = concentration of the tracer gas
η = sealing efficiency
m = mass flow rate
ω = rotating speed of the disc (rad/s)
p = pressure
c_p = non-dimensional coefficient of pressure
r = radius
v_φ = velocity in tangential direction
ρ = density
β = swirl ratio

μ = dynamic viscosity
G_c = axial clearance of rim seal gap
Re_x = Reynolds number of axial direction in mainstream
Re_φ = Reynolds number of rotation

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