# Gas Ingestion Under Unsteady Rotor-Stator Interaction of Turbine Blade

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**Abstract.** Unsteady simulation of a 1.5 stage turbine with an axial cavity was conducted to illustrate the ingress mechanism under the blade-rotor unsteady interaction. The numerical approach was fist be validated by the experiment data. The pressure potential caused by the rotor blade plays a major role in externally induced ingress. The ingress area in the circumstance direction is rotated with the rotor blade, and the most serious ingestion would happen as the rotor leading edge and stator wake are close to each other. It is worth noting that a vortex would form in the situation that the ingress gas and sealing flow were both exit in the rim seal clearance. The rim seal vortex rotates from rotor wheel space to the stator side, as the result makes the ingress deeper near the rotor wheel space in rim clearance, which can be proved from the lower sealing efficiency near the rotor wheel space in the rim gap. Moreover, the rim seal vortex is mainly caused by shear in the gap. In addition to the tangential velocity gradient, the radial gradient also promotes the formation of rim seal vortex.

**Keywords:** Gas ingestion · Rotor-stator interaction · Seal efficiency · Rim seal vortex

## 1 Introduction

The operating life of a turbine can be shortened owing to hot gas ingestion into cavities. High-pressure air, known as purge flow (sealing flow), from a compressor, is introduced to cool the metal configuration as well as to suppress the ingress of cavities. In previous studies, the research by Bayley and Owen exhibited that gas ingress is mainly affected by the seal structure and the rotating Reynolds number, without considering the annulus flow effect [1, 2]. For a considerable time, researchers have considered that gas ingress is caused by the effects of rotationally-induced ingestion (RI) and externally-induced ingestion (EI) and the latter plays a major role in gas ingesting [3, 4]. Due to the interaction between rotor and stator, the non-axisymmetric pressure field is mainly generated. Ingress occurs where the pressure in the annulus is higher than that in the cavity; in the opposite situation egress would be happen.

Many studies have further focused on the contribution of the rotor and stator to the circumferential non-uniform pressure of the annulus channel. Green and Turner et al. [5]


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believe that the existence of rotor blade weakens the non-uniform pressure field caused by the wake of vane blades; therefore, the sealing efficiency is improved. However, hills et al. [6] pointed out that the rotating high-pressure area caused by the leading edge of the rotor blade would increase the degree of gas intrusion. Chew et al. [7] studied the relationship between gas ingestion and axial position of vane blade separately, without rotor blade. The ingress was weakened with the increase of the distance between the guide and the wheel space. Bohn et al. [8, 9] reached a similar conclusion on the influence of vane blade position on gas ingestion; Further research showed that both the rotor blade and guide vane have a very important impact on gas ingestion, although the degree of impact is related to the sealing structure. Hualca and Horwood et al. [10] studied the effect of guide vane position and rotor blade on gas ingestion. The result showed that compared with the rotating blade, the axial distance had a significant effect on the range between maximum and minimum pressure which would be decreased with the increasing distance from the trailing edge of the blade. However, in the absence of rotor blades, the guide vane position has little effect on gas ingestion.

As the rotating blade, the interactions between the stator wake and the pressure potential field at the leading edge of the rotor are unsteady. It is still of practical significance to explore the gas ingestion mechanism and sealing degree, in this actual unsteady environment.

## 2 Computational Models and Numerical Approach

### 2.1 Geometries and Models

The section numerically invested include a 1.5 stage turbine with a vane-blade-vane configuration was show in Fig. 1. For more detailed instructions referred to [11]. The number of blades in the numerical simulation was molded as 2:3:2 since the number of blades in the whole annulus was 36, 54, 36 respectively. Therefore, 1/18 sector was adopted in the unsteady calculation.

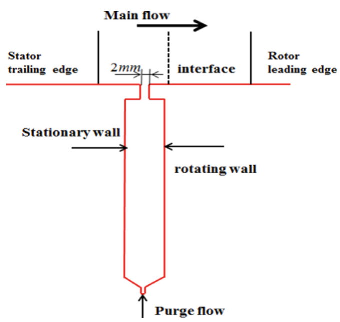



**Fig. 1.** Cross section of calculated model

### 2.2 Numerical Approach and Boundary Condition

Numerical simulations were performed in ANSYS CFX software. Reynolds-averaged Navier–Stokes equations for fully three-dimensional (3D), unsteady flow were solved. Structured grid generation was undertaken using NUMECA AutoGrid5 and ICEM as displayed in Fig. 2. For minimizing the interpolation error, a matching grid interface was defined between the stator and cavity domains. The total number of nodes was 8.0 million.The circumferential grid resolution was set as 0.34°/cell, Grids near the wall were characterized by a boundary layer grid with the first cell height of approximately $y^+ < 1$.

A total pressure (140 kPa) and total temperature (328 K) boundary condition was used at the main path inlet, whereas an average static pressure condition was set at the main path outlet. The cooling air mass flow (purge flow) and total temperature were applied at the cavity inlet. The cooling air mass flow rate (IR = 0.5%) and the rotational periodicity in the circumferential direction were assumed at appropriate boundary. The unsteady solution was obtained at 42 time steps per blade passing event. The CO2 tracer gas was employed, which was be set to o in the mainstream inlet, while 1 in the cavity inlet.

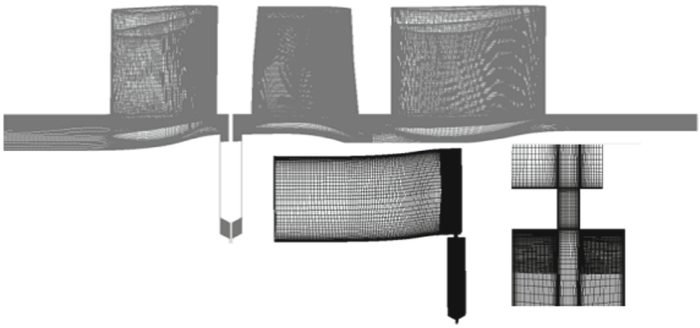


**Fig. 2.** Computation mesh of 1.5-stage turbine with seal cavities

### 2.3 Validation of Numerical Model

To verify the reliability of the numerical approach, the relative total pressure coefficient and flow angle at rotor exit were choose to compare with the experimental data, as show in Figs. 3 and 4. The relative total pressure coefficient was defined as follows.

$$c_{pt} = (p_t - p_{s,exit})/(p_{t,inlet} - p_{s,exit}) \tag{1}$$

The figure from flow angle indicates that the experimental and numerical predictions agree well in a wide range of span.Furthermore compared with the experimental results, the numerical simulation accurately captures the high loss area of the rotor exit. Therefore, it can be considered that the numerical simulation method in this paper satisfy the calculation requirements.

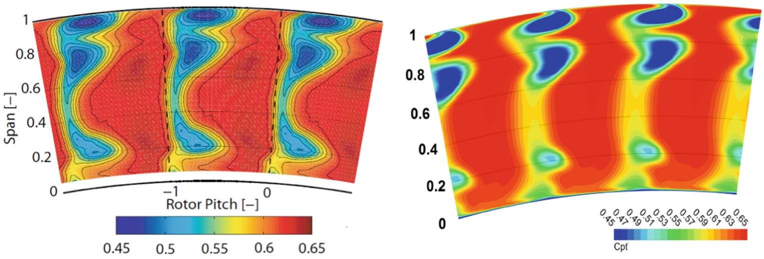



**Fig. 3.** Relative total pressure coefficient at rotor exit

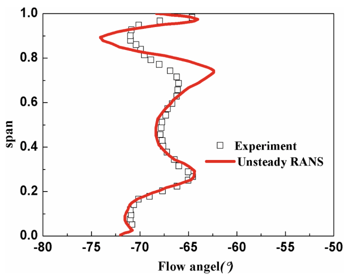
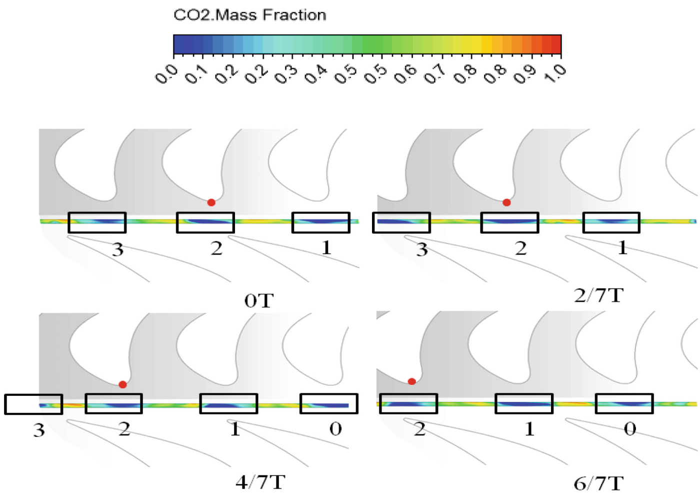



**Fig. 4.** Flow angle at rotor exit

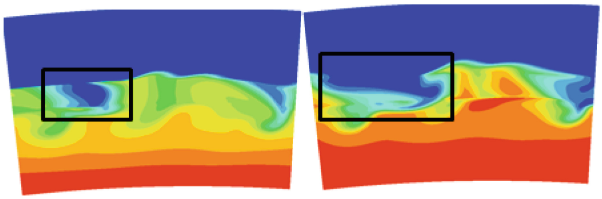
## 3 Research and Discuss

TO study the influence of the relative position of rotor and stator on gas ingestion, the time of rotor seeped per stator sector was divided into seven equal parts and the unsteady analysis was carried out at four times: 0T, 2 / 7T, 4 / 7T, and 7T. Furthermore, the two circumferential surfaces close to the stationary wheel space and the rotor disc in the cavity seal are defined as S_Cavity, R_Cavity. The CO2 fraction contour on above surfaces and cavity exit was shown in Fig. 5.

At time t = 0T, the circumferential position of gas ingestion is 1, 2 and 3 areas as shown in the black wireframe in Fig. 5a, of which area 1 and 3 are located near the leading edge of the rotor, and area 2 is located at the intersection of the leading edge of the rotor and the trailing edge of the stator. At 2/7T, the gas ingestion area rotates along the circumferential position. Areas 1 and 2 are near the leading edge of the rotor, and area 3 is located at the junction area of rotor leading edge and stator trailing edge, while, the circumferential ingestion degree is deepened compared to 0T moment. The same conclusion can be obtained from 4/7T and 6/7T. It can be summarized as that the circumferential position of gas ingestion is mainly affected by the pressure potential field of the leading edge of the rotor, while the stator wake will increase the depth of gas ingestion when it is close to the leading edge of the rotor. It also can be see that the intrusion area rotates with the rotor blade, Meanwhile, as the rotating ingress area matched the rotating blade, therefore the pressure potential field at the leading edge of the rotor is the dominant factor of EI (externally-induced ingestion). The Circumferential location of gas intrusion near the stator and rotor is almost consistent however the ingested area neighboring rotor wheel space is larger than the stator side, which can be seen from Fig. 5b.




(a) CO2 concentration contour at the outlet of cavity



(b) CO2 concentration contour(left: S_Cavity;right:R_Cavity)

**Fig. 5.** **a** $CO_2$ concentration contour at the outlet of cavity. **b** $CO_2$ concentration contour (left: S_Cavity; right: R_Cavity)

The stator channel was divided into 5 equal sections along the circumferential direction, and 5 dimensionless circumferential angles: $\theta = 0.1, 0.3, 0.5, 0.7$, and 0.9 sections were taken into analysis. The CO2 fraction contour at each location was displayed in Fig. 6. The circumferential position and radial depth of gas ingestion change with the relative position change of rotor and stator. The gas ingest into the whole rim clearance at the location of $\theta = 0.3$(0T), $\theta = 0.5$(2/7T), $\theta = 0.7$ (4/7T), $\theta = 0.1$ (4/7T). Combined with Fig. 5a, the above areas mentioned are located near or at the intersection of the leading edge of the rotor and the trailing edge of the stator. The high pressure induced by the rotor leading edge and wake make the pressure in the main annulus is higher than that in the cavity, as the result the gas-filled the rim clearance. While the Circumferential position sited only adjacent to the leading edge, the ingress was mainly happened at rotor wheel space, such as $\theta = 0.9$(0T), $\theta = 0.1, 0.9$(2/7T), $\theta = 0.3$(4/7T), $\theta = 0.1,0.3$(6/7T). In other positions, affected by the effect of rotor pumping, the purge flow was flowed out through rotor wheel space. In Conclusion: when the leading edge of the rotor approaches, the circumferential pressure of the main flow dominates ingress, and the gas ingested from the rotor side. When the leading edge of the rotor is far away, the pump effect is dominating, the sealing flow egress form rotor side. Rotor blade has significantly affected both gas ingress and sealing flow egress.

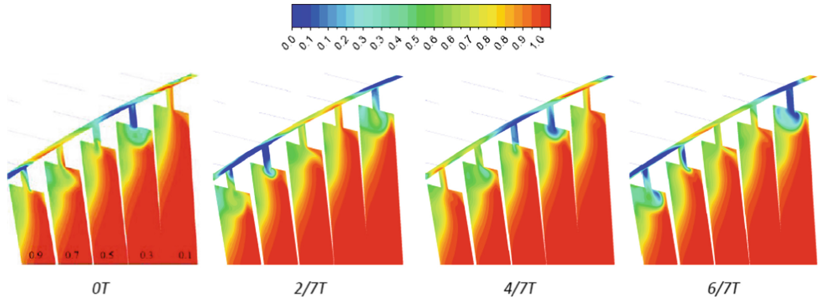



**Fig. 6.** $CO_2$ fraction contour at different time

At different times, there may be gas, sealing flow, or their mixture in the rim gap. To analyze the flow details in the cavity gap and the influence of its flow characteristics on gas ingestion, the streamline and axial vorticity at three circumferential positions ($\theta$ = 0.1, 0.5, 0.9) on four moments were taken into consideration, displayed in Fig. 7. The gap vortex structure is not likely formed when the gap is dominated by gas ingress or purge flow egress such as the positon $\theta = 0.1$ (egress) on 0T or 6/ 7T (ingress). The same conclusion is reached in another similar case. However, when the annulus gas and purged flow are both exist in the gap, a vortex structure occurred. It can be considered that the high-temperature gas ingested through rotor wheel space meets the sealing flow purged out through the stator side shape of the vortex structure which can be found through the positive axial vorticity value.

The above changes can be revealed as follows: when the gas ingestion occurs, the corresponding mainstream pressure on the rotating side is greater which could suppresses the rotor pump effect and makes the gas-driven the gas ingested from the rotor side. In another world, the pressure potential field generated by the rotation of the leading edge of the rotor blade is the dominant factor causing the gas ingestion.

Moreover, the gap(rim seal clearance) vortex should be caused by radial or tangential velocity shear in the gap, which is considered be K-H instability by much research. However, its unsteady characteristics are worth studying, because the causes include radial velocity gradient, while the K-H instability was thought to have been induced by tangential velocity gradient. It is certain the vortex structure certainly made the ingress deeper along the rotor side.

Figures 8 and 9 shows the sealing efficiency, radial velocity coefficient, and tangential velocity coefficient in the turbine cavity, the axial location is defined as: cavity Stator, Seal middle and cavity Rotor. The velocity coefficient is dimensionless with rotor hub rotation speed. In the middle section of the cavity, the radial velocity is small and remains

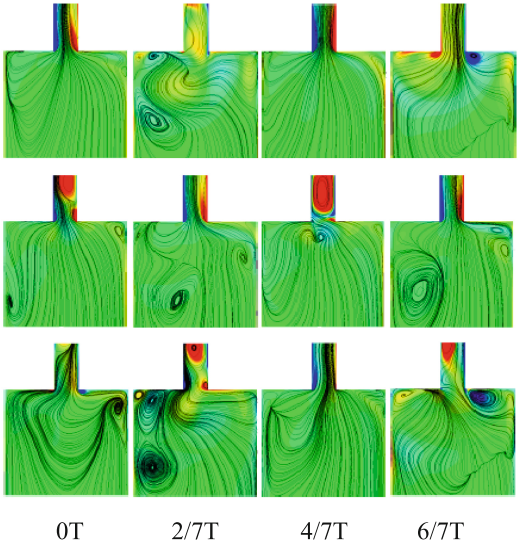



**Fig. 7.** **a** Streamline and axial vorticity ($\theta = 0.1, 0.5, 0.9$ from top to bottom)

unchanged when r/R is less than 0.8, which is coincident with the inviscid flow theory in the vortex core region.

At the high radius close to the rim, the radial velocity coefficient is greatly difference between the rotor wall and the stator wall due to the influence of gas ingestion and vortex structure in the gap. It can be concluded from the above analysis that the gas ingestion is affected by the unsteady pressure wave of the rotating blade, and most of the high-temperature gas enters the cavity along the rotor side. Therefore, the time average radial velocity coefficient on the rotor side decreases with the increase of radius, when r/R is greater than 0.8. Due to the above ingress mechanism, the sealing efficiency near the rotor wall is lower than that near the stator wall in the gap, although the sealing efficiency is higher near the stator wall for the most regions in the inner cavity.

As for tangential velocity: in most areas of the disk cavity, the tangential velocity of the stationary wall and the rotating wall is mainly affected by the wall friction, that is, the tangential velocity close to the stator wall is almost 0, for the same reason the tangential velocity near the rotor wall increase with the radius. In the high radius and gap of the cavity, the dominant factors affecting the tangential distribution include gas ingestion, sealing flow egress, and their interaction. The tangential velocity is increasing rapidly as a consequence of the ingested gas with higher circumferential velocity caused by the guide vane upstream, What's more, exaggerated is the tangential speed at the rotating wall will exceed the rotation speed of rotor hub. Unlike the rotor, the tangential velocity is still relatively small even at the cavity outlet. What needs more attention is that fluid near the stator wall flows out of the cavity into the mainstream, which could cause the K-H inability for the tangential velocity gradient of mainstream and purged flow. The vortex structure is located at the rim, as shown in the continuous blue surface vortex mechanism in Fig. 10.

In addition to the rim, the shear vortex structure induced by gas intrusion in the gap can also be seen from the figure, as shown in the elliptical wireframe in the figure. The vortex is not only related to the tangential velocity in the gap, but also related to the radial velocity gradient.

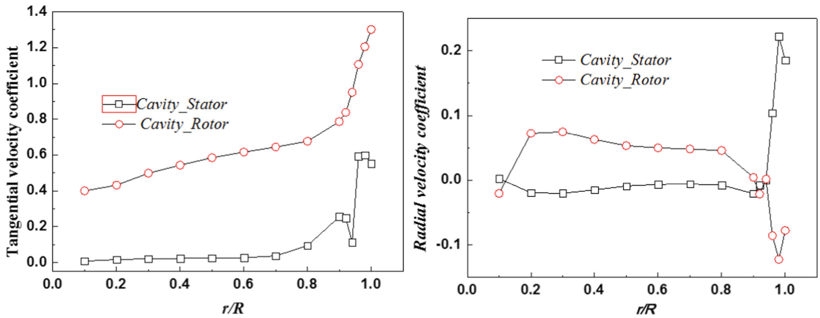



**Fig. 8.** Tangential velocity coefficient and Radial velocity coefficient in cavity

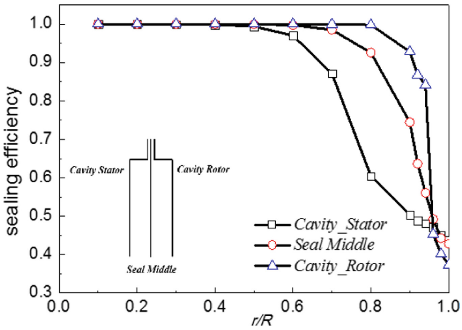



**Fig. 9.** Sealing efficiency in cavity

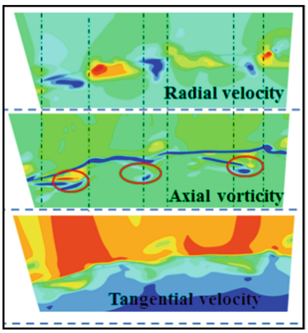



**Fig. 10.** Vortex in cavity wheel space

## 4 Conclusions

In order to carefully analyze the gas ingestion mechanism and the generation mechanism of rim seal vortex under rotor-stator interaction, an unsteady numerical calculation of a 1.5-stage turbine is carried out, and the following conclusions are obtained.

(1) The pressure potential field at the leading edge of the rotor dominates the gas ingestion and makes the ingested area rotates in the circumferential direction with the rotation of the rotor blade. The degree of gas intrusion near the leading edge of the rotor is aggravated when the leading edge of the rotor is close to the stator wake. Affected by the pump effect of the rotor, the purged flow egress still occurs near the rotor side when it is far from the leading edge of the rotor. That is to say, rotor is the key factor for both ingress and egress.
(2) Vortex in rim seal will form as the interaction of the radially inward ingestion flow and radially outward sealing flow. Which make the gas intrusion depth near the rotor wheel space, and the sealing efficiency in the cavity gap is reduced and lower than that of the stationary wall.
(3) Because the large radial velocity gradient in the gap promotes the formation of the gap vortex, it is worth discussing whether the gap vortex is the same as the K-H vortex proposed in the previous literature.

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