A Study on the Leakage Characteristics of a Stepped Labyrinth Seal with a Ribbed Casing

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Abstract: A new type of stepped seal with a ribbed casing is proposed to efficiently reduce the leakage at the tips of turbine blades. The leakage characteristics of two different types of labyrinth seals (conventional seal vs. ribbed seal) were compared and analyzed through computational fluid dynamics (CFD) in a wide operating range of pressure ratios and clearances. The analysis showed that the ribbed seal has superior leakage performance to the conventional seal at all clearance sizes. With the same clearance size (S/H = 1.0), the flow function of the ribbed seal was approximately 21.5–42.6% less than that of the conventional seal. Also, different trends of variation in the flow function according to the increase of the clearance were found between the conventional and ribbed seals. The leakage flow inside the labyrinth seal was analyzed to explain the cause of this difference in tendency, and it was confirmed that the added ribs cause collision between the leakage flow and the tooth wall, even with the increase of the clearance. Also, the ribbed seal enables operation at a larger clearance with the same leakage performance when comparing the absolute leakage flow rate of the two seals. In addition, a parametric study on the influence of the rib height and rib inclination angle revealed that the flow function generally decreases as both parameters increase.

Keywords: stepped labyrinth seal; turbine; rib; clearance; leakage; flow function

1. Introduction

As the performance requirements for gas turbines steadily increase, sealing technology is becoming essential for efficiency enhancement of turbomachinery such as compressors and turbines. Among the various loss sources of a gas turbine, tip leakage between the rotor and stator directly affects the aerodynamic performance of the turbine, overall engine performance, and operational stability. Despite the development of other sealing technologies, labyrinth seals are still widely used to prevent leakage at the blade tips because of their dominant advantages, such as heat resistance at high temperatures and availability at wide pressure ratios.

Clearance is the design parameter that most directly affects leakage flow rate. Since the clearance changes according to the operating conditions and thermal load of the turbine blades, accurate predictions of leakage characteristics according to the change of clearance are required. In addition, clearance needs to be designed and controlled more tightly than before to reduce leakage flow and improve the efficiency of turbines and compressors with the technological development of gas turbines. However, all clearances between stationary and rotating parts have a minimum required size to avoid rubbing. Therefore, it is necessary to improve seal geometries to reduce leakage flow without reducing the clearance size too much.

Fundamental experiments and model development have been pursued to analyze complex flow phenomena inside a labyrinth seal. Vermes [1] developed an analytical model capable of predicting leakage flow according to a design parameter through experiments with straight, stepped, and combination seals. Wittig et al. [2–4] conducted experimental
and computational studies on the leakage flow characteristics and heat transfer of straight and stepped seals. Also, they conducted experiments with scale variations to analyze the effect of the scale of the experiment on the flow coefficient and the friction factor. Waschka et al. [5] analyzed the effect of rotational effects on leakage through experiments reflecting rotational effects and conducted a study on the heat transfer and leakage rate of a straight seal.

With the development of computational fluid dynamics (CFD), research has been conducted on the internal flow phenomena inside a labyrinth seal according to the change of design parameters. Zimmermann et al. [6,7] analyzed the effect of the design variables of straight and stepped seals on leakage and suggested a correlation that can be applied in practice. Also, they investigated the impact of wear of the tooth tip. Schramm et al. [8,9] optimized the geometry of labyrinth seals and compared the leakage characteristics of honeycomb and solid land seals using CFD.

Michaud et al. [10] observed the flow phenomena inside a labyrinth seal using flow visualization and PIV techniques and experimented with changing some design variables. Kim et al. [11–13] conducted experimental and numerical studies on various pressure ratios and clearance sizes for straight and stepped seals. Kang et al. [14] conducted an experiment and numerical analysis on a stepped seal with changes in the number of teeth and clearance. They also compared the leakage characteristics of solid and honeycomb seals. Hur et al. [15] analyzed the leakage characteristics of a stepped labyrinth seal according to clearance size and confirmed that there is a clearance size with a minimum leakage performance parameter.

Recently, research has been conducted on advanced seals made available by advances in computational and experimental techniques. Stocker et al. [16–18] presented nine unique labyrinth seal configurations with some variations of a conventional seal and found that the leakage performance of the proposed seals was 10–25% better than that of a conventional seal. Rhode et al. [19,20] researched labyrinth seals with added grooves and observed variations in the flow field inside the seals using a flow visualization technique. Vakili et al. [21] performed experiments and computational analysis on stepped seals with inclined teeth and verified a leakage reduction effect through comparison with reference values.

Soemarwoto et al. [22] presented the geometry of a canted-knife seal and compared the leakage performance with those of a conventional solid and honeycomb land seal through both experimental and computational analyses. Chougule et al. [23] presented a staggered honeycomb and a notched tooth with a modified tooth tip. Leakage performance was analyzed through computational analysis, and it was confirmed that leakage was reduced by up to 17% compared to a conventional seal.

Zhang et al. [24] presented a mixed labyrinth seal (MLS) in which lateral teeth were added to the teeth of a conventional staggered seal (SLS). It was confirmed that the MLS had about 30% less leakage performance than an SLS. Wroblewski et al. [25] suggested an optimal geometry of four labyrinth seals with different geometrical land configurations (solid land, honeycomb, squeezed honeycomb, and rhomboid). Jia et al. [26] proposed a staggered seal using T-shaped teeth (TLS) and compared the leakage with those of conventional straight and staggered seals through computational analysis. Compared to the straight seal, leakage decreased by 23–25%, but compared to the staggered seal, leakage increased by 7–8%.

As described above, research is being actively conducted on advances in seal geometries to minimize leakage flow without reducing operating clearance too much. This study presents a method of maximizing the reduction of leakage flow of stepped labyrinth seals through a relatively simple geometry change. The key is adding ribs to the casing of the stepped seal. The effect of reducing leakage by the added rib was confirmed, and the leakage characteristics were investigated according to the variation of the clearance. In addition, parametric studies were conducted on the main design parameters of the rib (rib height and rib inclination angle), and the effect of each design parameter on leakage was analyzed.
2. Analysis

2.1. Seal Geometry

Since a gas turbine is a rotating power engine, the effect of rotation should be considered in its analysis. However, it is acknowledged that the rotation effect is only important when the rotational speed is very high (to be exact, when the ratio of the rotational speed of the blade to the axial speed of the flow is larger than 1) [5,27–29]. In addition, if the rotation effect is neglected, a stationary two-dimensional (2D) rig can provide almost the same sealing performance results as an axisymmetric three-dimensional (3D) rig [18]. Therefore, a 2D stepped seal geometry [15], which represents an actual turbine tip seal, was selected as a reference seal configuration. The basic leakage performance characteristics of the reference configuration were investigated through both experimental and computational methods [15].

A stepped labyrinth seal is most commonly applied to prevent leakage at turbine blade tips and consists of a rotating part with teeth and a stationary part covering the top. The geometry of the reference stepped seal [15] is shown in Figure 1. In the revised seal, ribs are added to the casing of the reference stepped seal, as shown in Figure 2. The leakage flow path is a diverging flow path, which means that the leakage flow moves from small to large diameters (i.e., from left to right in the figures).

![Figure 1. Schematic of the conventional stepped seal.](image1)

![Figure 2. Schematic of the ribbed seal.](image2)

The main design variables of the stepped seal are the clearance (S), tooth-tip thickness (b), tooth height (K), pitch (D), step height (H), and tooth angle (θ). The additional geometric parameters due to the inclusion of the rib are the thickness (e), height (t), and inclination...
angle ($\beta$) of the rib. Each design parameter is represented by non-dimensionalized expressions. For example, the clearance is expressed as a ratio to the step height (S/H), and the rib height is expressed as a ratio to the tooth height (t/K). In this study, numerical analysis was conducted by setting the range of S/H as 0.2 to 1.2. Also, to conduct a parametric study on the geometric parameters of the rib, t/K and $\beta$ were set in the ranges of 0.05 to 0.3 and 60 to 120°, respectively. Table 1 provides the details of the symbols, values, and variation ranges of design parameters.

### Table 1. Design parameters of the conventional and ribbed seal.

| Parameter | Description | Reference Value | Variation Range |
|-----------|-------------|-----------------|-----------------|
| N         | Number of teeth | 3               | -               |
| D/H       | Pitch/step height | 4               | -               |
| K/H       | Tooth height/step height | 4               | -               |
| $\theta$  | Tooth angle     | 15°             | -               |
| S/H       | Clearance/step height | 0.6             | 0.2–1.2         |
| e/b       | Rib thickness/tooth-tip thickness | 1               | -               |
| t/K       | Rib height/tooth height | 0.1             | 0.05–0.3        |
| $\beta$   | Rib inclination angle | 90°             | 60–120°         |

The leakage performance is expressed in terms of the flow function defined as follows:

$$
\phi = \frac{m \sqrt{T_{o, in}}}{A_C P_{o, in}}
$$

(1)

where $m$ is the flow rate, $A_C$ is the throat area at the clearance, $P_{o, in}$ is the inlet total pressure, and $T_{o, in}$ is the inlet total temperature. The flow function is a performance variable excluding the gas constant ($R$) from the expression of flow capacity, which is a dimensionless variable that can be applied to compressible flow. Therefore, the flow function is a semi-dimensionless number that facilitates the prediction of the real leakage flow rate for any arbitrary operating condition as long as the working fluid does not change. It should be noted that the flow function does not represent the actual leakage flow rate but indicates relative leakage performance. The performance of the labyrinth seal is evaluated by its relation to the flow function and the pressure ratio (PR), which is defined as the ratio of total pressure at the inlet to the static pressure at the outlet of the seal. The lower the value of the flow function at the same pressure ratio, the better the leakage performance of the labyrinth seal will be.

### 2.2. Numerical Approach

The commercial software ANSYS CFX ver. 19.0 [30] was used to analyze the flow phenomena inside the labyrinth seal. The 3D calculation domain was set as follows. The depth of the domain (i.e., the thickness of the domain perpendicular to the direction of the main flow) was set to be thin (approximately 1/8 of the largest clearance size), and one element was created in the depth-wise direction. Symmetry conditions were applied at the lateral faces. Practically, this analysis method is close to a 2D calculation and is in accordance with ANSYS CFX’s recommendations [31].

For grid generation, ANSYS ICEM ver. 19.0 was used. Grids of leakage flow paths were constructed using an unstructured tetra mesh in most of the flow area, while a structured mesh (prism layer) was adopted in the near-wall region to maintain $y^+ \approx 1$ (the maximum $y^+$ value is 1.2). In the case of the conventional seal without the rib, the grids of the clearance area were densely constructed to accurately predict the separated flow from the tooth tip. In the case of the ribbed seal, the grids of the entire leakage flow path were densely formed except at the inlet and outlet because the leakage flow collides with the ribs and creates additional vortices. Figure 3 shows the analysis domain of the ribbed seal and an example of the generated meshes.
For grid generation, ANSYS ICEM ver. 19.0 was used. Grids of leakage flow paths were constructed using an unstructured tetra mesh in most of the flow area, while a structured mesh (primarily hexa meshes) was adopted in the near-wall region to maintain $y^+$ below 1.2. In the case of the conventional seal without the rib, the grids of the entire leakage flow path were densely constructed to accurately predict the separated flow from the tooth tip, whereas the grids of the ribbed seal were more sparsely formed except at the inlet and outlet of the clearance area. In the case of the ribbed seal, the grids of the entire leakage flow path were densely constructed to accurately predict the separated flow from the tooth tip. In Figure 3, an example of the computational domain and meshes (S/H = 0.6) is shown. (a) Entire domain. (b) Enlarged view of the rib & clearance area.

Based on the grid configuration, grid dependence tests were conducted to select the number of grids that did not affect the numerical analysis results. Figure 4 shows an example of the results of the grid dependence test of the ribbed seal. The flow function became constant at about 120,000 mesh elements for the conventional seal and about 340,000 mesh elements for the ribbed seal. The influence of the number of grids on other flow properties such as velocities also showed the same trends as Figure 4. Accordingly, the number of meshes adopted for parametric analyses was between 120,000 and 180,000 for the conventional seal and between 350,000 and 420,000 for the ribbed seal. The lower and upper numbers correspond to the smallest and largest clearance values shown in Table 1.

The boundary condition settings for steady-state CFD analysis were as follows. The outlet was given atmospheric conditions ($p = 101.325 \text{ kPa}$), and the inlet total pressure was varied, resulting in various pressure ratios of 1.1 to 3.0. The total inlet temperature was constant at 295 K. Adiabatic and no-slip conditions were used for the solid surface, and symmetry conditions were applied to the lateral faces. In addition, compressible ideal gas was used as the working fluid. To accurately predict the separation of the flow occurring at the tooth tip, we applied the SST turbulence model with automatic wall function, which has an advantage in the prediction of vortex size and separation points [32,33]. The validity of the SST model has also been confirmed for the conventional seal of this study [15]. It showed slightly better agreement with experiments in comparison to other turbulence models such as $k-\varepsilon$ and $k-\omega$ models. A high-resolution advection scheme was selected, which adequately uses first- and second-order schemes depending on the situation and provides both numerical stability and accuracy in the analysis. The first-order upwind scheme was used for the turbulence numerics, and the convergence criteria for residual
were set to less than $10^{-4}$ of RMS. Table 2 summarizes the information about the numerical analysis methods and boundary conditions.

**Table 2.** Numerical methods and boundary conditions.

| Turbulence Model | Shear Stress Transport (SST) |
|------------------|-----------------------------|
| Advection scheme | High resolution             |
| Fluid            | Air (ideal gas)             |
| Pressure ratio   | 1.1~3.0                     |
| Inlet total temperature | 295 K                  |
| Outlet static pressure | 101.325 kPa          |
| Wall             | Adiabatic, no slip          |
| Lateral faces    | Symmetry                    |

The CFD calculation was validated through comparison with test results for a conventional seal without the rib [15]. The experimental results and CFD analysis results showed a deviation of about 3% and were found to be similar. Details of the validation can be found in the literature [15]. Accordingly, the comparison of the results confirms that the CFD model has sufficient accuracy in predicting the leakage performance of the labyrinth seal. Therefore, the analysis of various geometries was carried out using the validated CFD tool to understand the leakage characteristics of the ribbed seal.

One more point that was checked prior to the main parametric simulation was the scaling effect. The actual seal sizes could be different from those used in the test or simulation. If the actual seal sizes were smaller than those of the simulation, the Reynolds number would be lower, and thus the flow conditions would not exactly be the same as in the simulation. This is the so-called scaling effect or Reynolds number effect. Accordingly, we conducted additional simulations to check the scaling effect. The result was that the flow function changed by only up to 1.6% in the range of fourfold variation in the scale. As a result, it was concluded that the results of this study could be used in a relatively wide size range.

3. Results and Discussion

3.1. Comparison of Leakage Characteristics of Conventional and Ribbed Seal

The leakage characteristics of the ribbed seal and conventional seals are compared in Figure 5. The variation in the flow function with PR is displayed at a fixed clearance size $(S/H = 0.6)$. It is clear that the addition of the rib reduces the leakage flow. For example, at PR of 2.5, where the flow is nearly choked, the flow function of the ribbed seal is 17.8% lower in comparison to that of the conventional seal. To see the causes of the improved leakage performance, the detailed flow inside the seal was analyzed.

![Figure 5](https://example.com/figure5.png)

*Figure 5.** Variation in flow function of the conventional and ribbed seal with PR $(S/H = 0.6, t/K = 0.1, \beta = 90^\circ)$. 
Figures 6 and 7 show the total pressure and Mach number distribution inside the seal at \( PR = 2.5 \). In the case of the conventional seal, there are two main reasons for the leakage reduction effect [15]. The first is that the leakage flow hits the teeth, and the kinetic energy of the flow is dissipated, and the second is that the high-velocity flow layer traps the rotating flow inside the cavity. In the ribbed seal, the high-velocity flow layer hits the walls twice, resulting in a larger dissipation of dynamic energy of the flow, which hits the rib first and then the next tooth. Moreover, the point of collision with the next tooth moves downward because the added rib moves the flow layer in the downward direction (radial inward direction in an actual engine). This leads to greater flow separation at the tooth tip as shown in Figures 6 and 7. Accordingly, in comparison to the case of the conventional seal, where the flow layer naturally passes the clearance, the added rib increases the flow resistance inside the seal cavity and thus reduces the leakage flow at a fixed pressure ratio.

**Figure 6.** Total pressure plots for the conventional and ribbed seal (\( PR = 2.5, S/H = 0.6, t/K = 0.1, \beta = 90^\circ \)). (a) Conventional seal. (b) Ribbed seal.

**Figure 7.** Mach number contour plots for the conventional and ribbed seal (\( PR = 2.5, S/H = 0.6, t/K = 0.1, \beta = 90^\circ \)). (a) Conventional seal. (b) Ribbed seal.
After confirming the substantial leakage reduction effect at the reference clearance size, we extended the investigation to a wider S/H range and identified a significant difference in the trend of the flow function change with clearance between the ribbed and conventional seals. Figure 8 shows a comparison of the flow function variations between the two seals at PR = 2.5. The flow function of the conventional seal decreases as S/H increases, but it tends to increase after a certain clearance size (S/H = 0.6). On the other hand, in the ribbed seal, the flow function decreases continuously up to a very large clearance (S/H = 1.2).

![Figure 8](image)

**Figure 8.** Variation in the flow function with S/H (PR = 2.5, t/K = 0.1, β = 90°).

To analyze the change in the tendency of the seals according to the change of S/H, the total pressure and static pressure distributions inside the seal cavity were compared, as shown in Figures 9 and 10. In the case of the conventional stepped seal, the existence of a minimum flow function was demonstrated in [15]. If the size of the clearance increases to more than half the step height (S/H > 0.5), the leakage performance begins to decrease (i.e., the flow function begins to increase) because the flow layer is directed to the next clearance space almost without hitting the next tooth (see Figure 9a).

![Figure 9](image)

**Figure 9.** Total pressure plots for conventional seal and ribbed seal (PR = 2.5, S/H = 1.0, t/K = 0.1, β = 90°). (a) Conventional seal. (b) Ribbed seal.

However, in the case of the ribbed seal, the rib diverts the flow layer in the downward direction, so even if the size of the clearance increases, the high-velocity flow layer still hits the next tooth (see Figure 9b). Accordingly, the static pressure locally increases at the tooth wall, where the dynamic energy of the flow layer is largely dissipated, unlike in the conventional seal (compare Figure 10a,b). Therefore, the flow function of the ribbed seal decreases as clearance increases and the flow function difference between the ribbed and conventional seals gradually increases, as demonstrated in Figure 8. The difference in the flow function is as large as 36.2% when S/H is 1.0.
With the confirmation of a significant leakage reduction effect using the basic rib geometry \((t/K = 0.1, \beta = 90^\circ)\), we performed parametric analyses of the influences of the two rib geometric factors on the leakage performance. First, the impact of the rib height \((t)\) was investigated. Figure 11 shows the variation in the flow function with \(S/H\) for various rib heights at \(PR = 2.5\). It was confirmed that the flow function of the ribbed seal is smaller than that of the conventional seal at all design and operating conditions. Even with a very small rib height, the leakage reduction effect is considerable. When compared with \(S/H = 1.0\), the flow function decreases from 21.5\% \((t/K = 0.05)\) to 42.6\% \((t/K = 0.3)\) compared to the flow function of a conventional seal.

![Total Pressure plots for conventional seal and ribbed seal (PR = 2.5, S/H = 1.0, t/K = 0.1, \(\beta = 90^\circ\)). (a) Conventional seal. (b) Ribbed seal.](image)

**Figure 10.** Static pressure plots for conventional seal and ribbed seal \((PR = 2.5, S/H = 1.0, t/K = 0.1, \beta = 90^\circ)\). (a) Conventional seal. (b) Ribbed seal.

### 3.2. Parametric Study on the Effect of Rib Geometries

#### 3.2.1. Rib Height

Also, the change in the tendency of the leakage performance according to the size of \(t/K\) changed according to the range of \(S/H\). Below \(S/H = 0.6\), the change in the tendency of the flow function according to the increase of \(t/K\) is not apparent. In contrast, above \(S/H = 0.6\), the flow function decreases as \(t/K\) becomes larger, resulting in a considerable difference in the flow function at a sufficiently large \(S/H\). For example, at \(S/H = 1.0\), the flow function is 23.1\% higher at \(t/K = 0.05\) and 10\% lower at \(t/K = 0.3\) compared to that at \(t/K = 0.1\), which is the reference case.

![Variation in the flow function with \(S/H\) and \(t/K\) \((PR = 2.5)\).](image)

**Figure 11.** Variation in the flow function with \(S/H\) and \(t/K\) \((PR = 2.5)\).

Figure 12 compares the velocity contours for the cases at three rib heights. As \(t/K\) increases, the deflection of the high-velocity flow layer out of the precedent tip clearance to the downward direction becomes stronger due to the larger rib height. Accordingly, the impingement points at which the flow layer hits the next tooth gradually move downward. This action creates stronger flow separation around the rib and the tooth tip, reducing the
effective area through which the flow can pass. Overall, increasing the rib height provides greater flow resistance inside the seal, which results in smaller leakage flow at a fixed pressure ratio.

![Velocity contour plots for various t/K (PR = 2.5, S/H = 1.0, β = 90°).](image)

(a) t/K = 0.05. (b) t/K = 0.1. (c) t/K = 0.2.

Figure 12. Velocity contour plots for various t/K (PR = 2.5, S/H = 1.0, β = 90°). (a) t/K = 0.05. (b) t/K = 0.1. (c) t/K = 0.2.

Also, the flow function continuously decreases as S/H increases except in the case of very small rib height (t/K = 0.05), which is a different trend compared to that of the conventional seal, as explained in Section 3.1. The minimum flow function point moves toward a very large S/H value. For example, in the cases of t/K = 0.2 and 0.3, the minimum point is located beyond the limit of the figure (over 1.2). But as the rib height decreases, the minimum point moves to a lower S/H value. We can see the existence of a minimum point for t/K = 0.05 and 0.1 in the figure. This happens because the effect of the rib gradually diminishes, and the flow phenomena inside the seal tend to return to those of the conventional seal, as the rib height becomes smaller.

The advantage of the ribbed seal is that even when the size of S/H is large (i.e., when the clearance size is greater than half of the step height), the flow function is reduced remarkably. However, the comparison of the flow function only shows the difference in the fundamental sealing performance of the labyrinth seal, not the actual leakage mass flow rate. Comparing the actual mass flow rate might be more important in terms of observing changes in the performance of the gas turbine (i.e., power and efficiency).

Therefore, the values of the actual mass flow rate are shown in Figure 13 for various rib heights at PR = 2.5. For the convenience of comparison of the actual mass flow rate of different labyrinth seals, the mass flow rate is expressed as a normalized mass flow rate relative to the highest mass flow rate. The change of the actual mass flow rate with the increase of S/H differs from the flow function change (compare Figures 11 and 13). According to the definition of the flow function (Equation (1)), when the inlet total temperature \(T_{o,in}\) and pressure \(P_{o,in}\) are constant, the actual mass flow rate (iii) of each t/K case is proportional to the accumulated area under each curve in Figure 11. Thus, both the conventional and ribbed seals show that the actual mass flow rate continuously increases in proportion to the size of S/H.

Assuming that a certain amount of leakage occurs, the required clearance size (S/H) increases as the size of the rib height increases. Let’s consider an example of a specific target leakage mass flow rate, indicated by the dotted horizontal line in the figure. In the case of the conventional seal, the target leakage mass flow is achieved with S/H = 0.7. However, the required clearance size increases with increasing rib height: S/H = 1.0 for t/K = 0.1 and S/H = 1.2 for t/K = 0.3 (42% and 71% larger operating clearance sizes, respectively). This means that when the design leakage flow rate requirement is given, the operating clearance of the turbine can be greatly increased by adding rib geometries to the casing. In addition,
the mass flow rate of the ribbed seals is less sensitive to variations in S/H compared to the conventional seals. Since the clearance can change with operating conditions or thermal expansion, lower sensitivity to clearance change must be a significant advantage.

3.2.2. Rib Inclination Angle

The influence of the rib inclination angle (β) was investigated. Figure 14 shows the variation in the flow function with S/H for various rib angles at t/K = 0.1. As in the results of the rib height, it was confirmed that the flow function of the ribbed seal is smaller than that of the conventional seal in all cases. When compared with S/H = 1.0, the flow function decreases from 33.6% (β = 60°) to 36.6% (β = 120°) compared to the flow function of the conventional seal. Also, the flow function decreases as β increases. But unlike the case of rib height, there was no significant difference in the flow function. For example, at S/H = 1.0, the flow function is 4.1% higher at β = 60° and 0.6% lower at β = 120° compared to the reference value β = 90° at t/K = 0.1.

Despite the change in β, the difference between the flow function was not large because the rib height was not large, so we changed the reference rib height (from t/K = 0.1 to 0.2) and compared the rib inclination angle. Figure 15 shows the variation in the flow function with S/H for various rib inclination angles at t/K = 0.2. When compared with S/H = 1.0, the flow function decreases from 38.9% (β = 60°) to 43.7% (β = 120°) compared to the flow function of the conventional seal. As the size of β increases, the flow function decreases. At
S/H = 1.0, the flow function is 4.3% higher at $\beta = 60^\circ$ and 4% lower at $\beta = 120^\circ$ compared to the reference value $\beta = 90^\circ$ at $t/K = 0.2$.

![Figure 15. Variation in the flow function with S/H and $\beta$ (PR = 2.5, t/K = 0.2).](image)

Figures 16 and 17 show the velocity contour and static pressure when $\beta = 60^\circ$ and $120^\circ$ at $t/K = 0.2$. In the case of $\beta = 60^\circ$, the kinetic energy of the flow is dissipated as the flow layer hits the ribs, and the static pressure partially increases. However, due to the dissipation of kinetic energy, the velocity of the flow layer decreases, and the pressure loss decreases due to collision with the tooth. In the case of $\beta = 120^\circ$, the increment in static pressure due to collision with the rib is less than at $\beta = 60^\circ$. However, the higher-velocity flow layer hits the tooth, and the kinetic energy of the flow is significantly reduced than in the case of $\beta = 60^\circ$.

![Figure 16. Velocity contour plots for various $\beta$ (PR = 2.5, S/H = 1.0, t/K = 2.0). (a) $\beta = 60^\circ$. (b) $\beta = 120^\circ$.](image)
conducted on several major design parameters of the rib. The main conclusions of this analysis for a wide range of pressure ratios and clearances, and a parametric study was proposed by partially modifying the geometry of a conventional stepped labyrinth seal. The leakage characteristics of the proposed ribbed seal were analyzed through CFD analysis for a wide range of pressure ratios and clearances, and a parametric study was conducted on several major design parameters of the rib. The main conclusions of this study are summarized as follows.

1. It was confirmed that the leakage performance of the ribbed seal is better than that of the conventional seal at all clearance sizes (when S/H = 1.0, the flow function is up to 42.6% lower in comparison to the conventional seal). Also, unlike the conventional seal, in which the tendency of the flow function changes as the clearance increases, the flow function of the ribbed seal continuously decreases as the clearance increases. This happens because the added rib changes the flow layer direction, causing a continuous collision between the flow layer and the tooth as clearance increases.

2. The flow function of the ribbed seal is affected by the rib height (t/K) and rib inclination angle (β), and at almost all S/H, the leakage performance improves as both design parameters increase (when S/H = 1.0, the flow function is 10% lower at t/K = 0.3 and 0.6% lower at β = 120° in comparison to the reference value t/K = 0.1, β = 90°). Also, the larger the size of the rib height and rib inclination angle, the larger the difference in the flow function is between the conventional seal and the ribbed seal. Both design parameters have little effect on the flow function when S/H is very small, but as S/H gradually increases, changes in the flow function occur. Also, it was confirmed that the change in the rib height had a much greater influence on the leakage characteristics than the rib inclination angle. The influence of the rib inclination angle becomes larger when the size of the rib height is large.

3. The most important advantage of the ribbed seal is that the leakage flow can be greatly reduced by adding very small ribs to the casing when a target seal clearance is kept the same as in the conventional seal. Reduction of leakage flow not only improves the sealing performance but also contributes to the improvement of the performance of the entire gas turbine. Another important point is that the actual operating clearance could be much larger while maintaining the same leakage flow rate compared to the conventional seal. This is a definite advantage in the viewpoint of the turbine design, which could lessen the possibility of tip/casing rubbing while maintaining high turbine performance. One possible practical concern could be the...
increase of manufacturing complexities due to the addition of the ribs. However, because labyrinth seals with more complex geometries such as interlocking seals with staggered teeth have already been used, it would be quite possible to realize the ribbed seal.

Author Contributions: Conceptualization, M.-S.H. and T.-S.K., methodology, M.-S.H. and S.-W.M., software, M.-S.H. and S.-W.M., formal analysis, M.-S.H., investigation, M.-S.H. and S.-W.M., resources, T.-S.K., data curation, M.-S.H., writing—original draft, M.-S.H., writing—review and editing, M.-S.H. and T.-S.K., supervision, T.-S.K., project administration, T.-S.K., and funding acquisition, T.-S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Inha University Research Grant.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

- $A_c$: Throat area (m$^2$)
- $b$: Tooth-tip thickness (mm)
- $D$: Pitch (mm)
- $e$: Rib thickness (mm)
- $H$: Step height (mm)
- $K$: Tooth height (mm)
- $k$: Specific heat ratio
- $m$: Mass flow rate (kg/s)
- $N$: Number of teeth
- $P_o$: Total pressure (kPa)
- $P$: Static pressure (kPa)
- $PR$: Pressure ratio
- $R$: Gas constant (kJ/kg·K)
- $S$: Clearance (mm)
- $t$: Rib height (mm)
- $T_o$: Total temperature (K)

Greek letters

- $\beta$: Rib inclination angle (degree)
- $\theta$: Tooth angle (degree)
- $\phi$: Flow function (kgK$^{0.5}$/kNs)

Subscripts

- $c$: Contraction
- $in$: Inlet
- $out$: Outlet

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