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Original Paper

Investigation of Leakage Characteristics of Straight and Stepped Labyrinth Seals

Tong Seop Kim, Soo Young Kang

Department of Mechanical Engineering, Inha University
253 Yonghyun-Dong, Nam-Gu, Incheon 402-751, Korea

Abstract

Leakage characteristics of two labyrinth seals with different configurations (straight vs stepped) were investigated. Leakage flows were predicted by computational fluid dynamics (CFD) for the two configurations and compared with test data. A semi-analytical leakage prediction tool was also tried to predict the leakage. It was confirmed that the CFD gives quite good agreements with test data. The analytical tool also yielded similar leakage behaviors with test results, but the overall agreement with test data was not as good as that of the CFD. The effect of flow direction in the stepped seal on leakage flow was examined. The dependence of leakage performance, in terms of flow function, on the seal clearance size was investigated. Flow function decreased with decreasing clearance in the straight seal, while the trend was reversed in the stepped seal.

Keywords: labyrinth seal, straight seal, stepped seal, leakage, flow function, clearance.

1. Introduction

Rotating machines need sealing of fluid leakage between rotating and stationary parts. Despite many other advanced sealing techniques, labyrinth seals are still widely used because of their various advantages such as structural simplicity, reliability, high temperature resistance, and wide operating range in terms of pressure difference. The secondary airflow system of gas turbines is the most important application of labyrinth seals. They are used to reduce leakage loss at blade shrouds, prevent hot gas ingress or minimize cooling air leakage at rotating disk spaces. The combination of sudden contraction, flow through narrow channel, sudden expansion and strong flow circulation makes the flow structure inside a labyrinth seal highly complicated. Thus, accurate prediction of its leakage flow is quite challenging.

Even though there have been various efforts to suggest semi-analytical leakage prediction tools, no simple analytical models to satisfactorily predict performances of wide variants of labyrinth seals have been available. Vermes [1] conducted systematic investigations on sealing performance and suggested analytic prediction models. Stocker's works [2,3] are typical examples of test results for various configurations. Tipton et al. [4] summarized previous efforts to predict seal performance and proposed a prediction method of their own. Zimmerman and Wolff [5] provided an insight into the seal performance behavior, and discussed main design parameters and their effect on leakage flow. With the development of computational fluid dynamics (CFD), its use in investigating flows inside labyrinth seals and predicting their leakage performance has also been increased [6-8].

A labyrinth seal consists of two sides facing each other, with teeth (or knives) on one of the two sides. The gap between the teeth tip and the face of the other side (seal land) is usually called clearance. If the teeth side has steps and thus the teeth diameter varies along the axial flow direction, the seal is called a stepped seal. On the other hand, if there are no steps and thus the diameters of all the teeth tips are the same, the seal is called a straight seal. Providing additional flow resistance and thus reducing the leakage flow due to the existence of steps is the main purpose of using a stepped seal. In recent researches [9,10], comparisons of leakage characteristics between the straight and stepped seals, have been made. In particular, the performance dependence on key design parameters such as clearance size was compared between the two configurations.

This study aimed to investigate the leakage characteristics difference between straight and stepped labyrinth seals. Two labyrinth seals were selected and their leakage flows were predicted by both the computational fluid dynamics (CFD) and a semi-analytical leakage prediction tool. The prediction accuracy was validated with test data. Then, leakage performance was investigated with varying major design parameters: pressure ratio, clearance, number of teeth, and flow direction (for the stepped seal only). Leakage performance characteristics of the two configurations were compared.

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Corresponding author: Tong Seop Kim, Professor, kts@inha.ac.kr

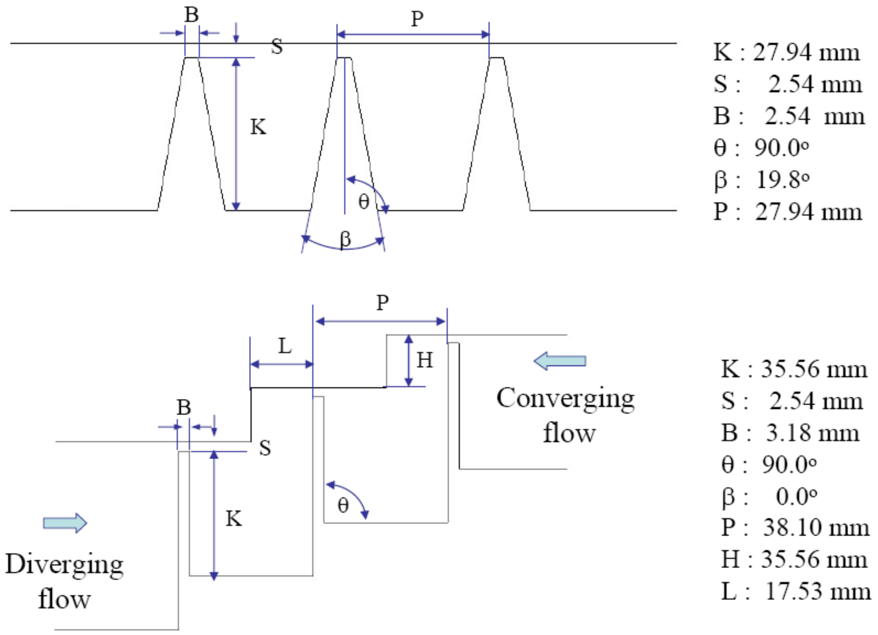


Fig. 1 Seal geometries (upper: straight, lower: stepped)

2. Seals

Test data for straight and stepped seals with similar dimensions [4] were selected. Fig. 1 shows the configurations of the two seals. Both tests were done with static two dimensional (linear) rigs. It has been acknowledged that the effect of rotation is important only when the rotating speed is very high (more exactly, when the ratio between the circumferential speed of the seal arm and the flow speed is very large) [11]. Therefore, two dimensional rigs are sufficient to compare sealing performances of different configurations. All the geometric dimensions of the two seals are also shown in the figure. The two seals have three teeth, but the case with single tooth was also tested for each seal. In the stepped seal, two flow directions were tested. The flow from the left is a diverging flow and the reversed is a converged flow. The two flow arrangements correspond to a flow from small to large diameters (STLD) and a flow from large to small diameters (LTSD), respectively, in practical axisymetric annular situation. Performance of a seal can be described by a flow parameter. The most common flow parameter is the flow function expressed as follows:

$$\phi = \frac{\dot{m}\sqrt{T_{o,in}}}{A_c P_{o,in}} \qquad (1)$$

The primary operating parameter that governs the leakage flow is the pressure ratio across the seal. Thus, the measured leakage flow is presented in terms of a relation between the flow function and the pressure ratio.

3. Analysis

3.1 CFD

Since the test seals were two-dimensional, corresponding two-dimensional CFD calculations were adopted in this work. A commercial finite volume code [12] was used. A realizable two-layer k-ε turbulent model was selected. This model combines the realizable k- ε turbulent model with the two-layer approach. The realizable k- ε turbulent model uses equivalent kinetic energy and dissipation rate equations, but has additional flexibility of all y+ wall treatment. The two layer approach is designed to give results similar to the low y+ treatment as y+ approaches zero (viscous sublayer) and to the high y+ treatment for y+>30 (wall function layer). Polyhedral mesh elements were used to create unstructured meshes in the entire domain. The grid density around the clearance was increased to locate sufficiently large number of meshes. The number of meshes was determined to produce sufficiently converged solutions. The number of meshes ranges from 11,000 to 15,000, depending on seal configuration and clearance size. For a given geometry, the exit pressure and mass flow rate was given, and the corresponding inlet total pressure was obtained as a result of calculation. Since the exact inlet and exit conditions of the test were not given, ambient pressure was given as the static pressure at the exit and ambient temperature was given as the total temperature at the inlet. Arbitrary setting of those boundary conditions does not matter significantly because calculation results will be presented in terms of dimensionless parameters such as the flow function defined by Eq. (1) and pressure ratio.

3.2 KTK model

There exist several analytical tools to predict leakage flow of labyrinth seals. Various models can be classified into two categories; global and knife-to-knife (teeth-to-teeth) models. In particular, Tipton et al. [4] summarized characteristics of various available models and suggested their own knife-to-knife model. The model was coded as a computational program [13]. The model dealt with three loss mechanisms inside a seal separately; contraction, venturi and friction, and partial or full expansion. The total pressure loss for a flow passing through a tooth was calculated as follows by summing up the three loss components.

$$\Delta P_o = \Delta P_{o,c} + \Delta P_{o,vf} + \Delta P_{o,e} \tag{5}$$

The loss coefficients are functions of various geometric and flow parameters. They established the model based on a vast amount of available solid seal data. The data are diverse in terms of seal configuration (straight and stepped), clearance size, number of teeth, flow direction for stepped seals (converged and diverged). Performance of each tooth (or cavity) is stacked to produce overall seal performance of a multi-cavity seal. More details of the model can be found in the above mentioned references [4,13].

4. Results and discussion

4.1 Validation

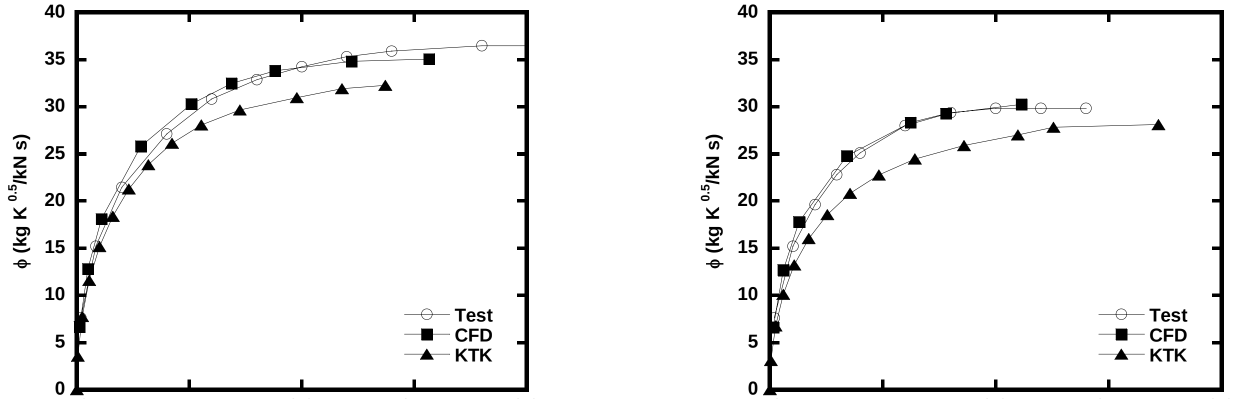
The predicted leakage flows by the CFD and the KTK model were compared with test data. Firstly, the results for the straight seal are shown in Fig. 2. The flow function is presented as a function of pressure ratio across the seal. Both the single tooth case and three teeth case are shown. The leakage flow naturally increases with increasing pressure ratio. In the single tooth case, the CFD predicted a quite similar leakage flow compared to the test. On the other hand, the KTK underestimated leakage. Increasing number of teeth naturally reduces leakage, which was also well predicted by both the CFD and the KTK model. However, the CFD gave much closer agreements with test data.

Secondly, the results for the stepped seal are presented in Fig. 3. The comparison for the single tooth case with the diverging flow arrangement is shown in Fig. 3(a). Here again, the CFD yielded a reasonable agreement with test result. The KTK model's accuracy was better than in the straight seal, but the model still underestimated leakage. The results for three teeth cases (both the diverging and converging flow arrangements) are also shown in the figure. For both flow directions, prediction accuracy of the CFD and the KTK model look similar. Overall, the CFD seems to be more accurate in predicting leakage flow for both the straight and stepped the seals adopted in this study.

4.2 Parametric study

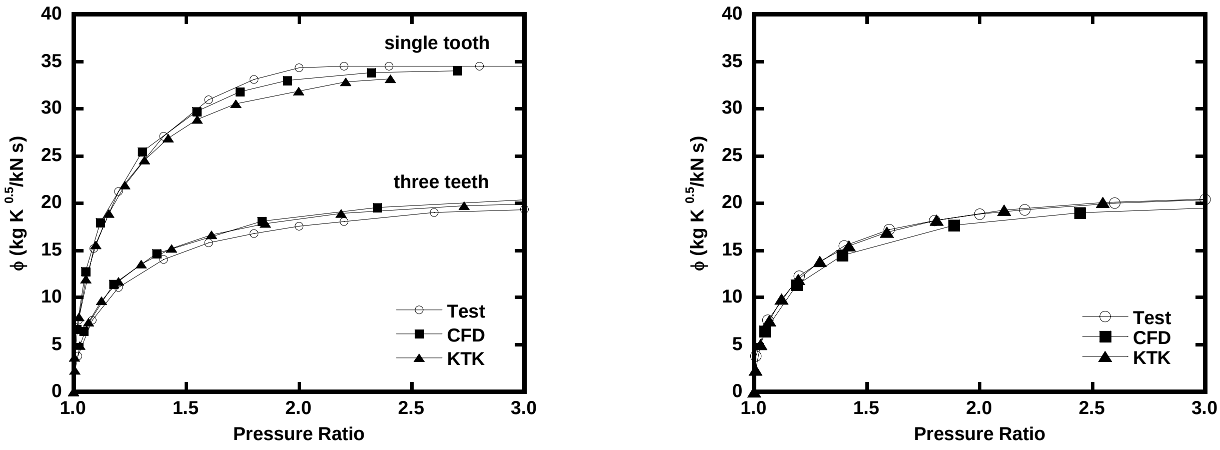
With the validation shown in the previous section, a parametric study on leakage behavior of the two seals was performed. The major parameter was the clearance size. Two clearance sizes, which are half and twofold the reference size in the previous section, were analyzed. First, sealing performance of the straight seal in terms of flow function with varying clearance was analyzed and the results are shown in Fig. 4. The qualitative results between the CFD and the KTK model are the same. In the single tooth case, the flow function does not effectively depend on the clearance size, especially as the clearance becomes larger. When the clearance becomes sufficiently small, the flow function slightly increases at a fixed pressure ratio. According to the CFD, the choking flow functions of different clearance cases converge.

In the three teeth case, the flow function at a given pressure ratio decreased as the clearance becomes smaller. Both the CFD and the KTK model yielded the same trend. In other words, sealing performance in terms of non-dimensional flow enhances as the clearance gets smaller at a fixed pressure ratio across the seal, which means that the absolute leakage of a reduced clearance is smaller than the leakage that is estimated in proportion to the clearance size. This result is quite feasible because a similar pattern was observed both experimentally and numerically [6,10]. The velocity vector plots obtained by the CFD are illustrated in Fig. 5. Plots for two clearance sizes with the same flow function values are shown. In a small clearance case, a sensible flow resistance occurs in both cavities. However, in a larger clearance case, the pressure loss for the flow over the second teeth is relatively small. Around the first teeth, the sudden contraction and the subsequent venturi flow contribute to the pressure loss. A similar pattern



(a) single tooth (b) three teeth

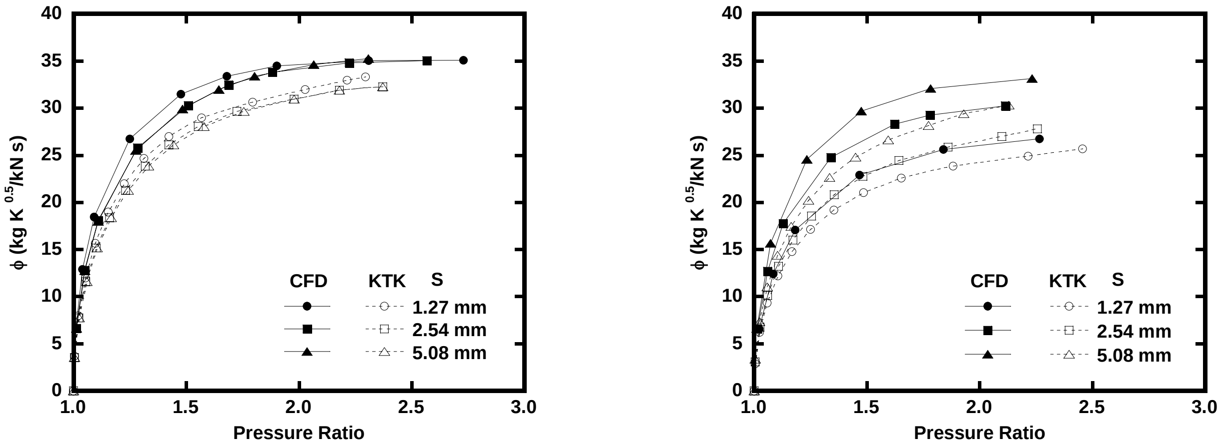
Fig. 2 Comparison between test and prediction for the straight seal (S=2.54mm)



(a) diverging seal

(b) three teeth converging seal

Fig. 3 Comparison between test and prediction for the stepped seals (S=2.54mm)



(a) single tooth

(b) three teeth

Fig. 4 Effect of clearance size on the flow function for the straight seal

occurs around the second tooth in the smaller clearance case. However, in the larger clearance case, much of the through (jet) flow is not affected by the existence of the teeth around the second teeth and thus the dynamic energy of the through flow is not effectively dissipated. As a result, no sensible pressure drop occurs over the second teeth (or in the second cavity). After the last tooth, the full expansion plays the major pressure loss. The total pressure profile through the seal is illustrated in Fig. 6. The averaged total pressure at each section (inlet and exit planes as well as three clearance planes) is shown. As the clearance decreases, the pressure losses over the second and third teeth become larger, resulting in a greater overall pressure loss. Accordingly, for a fixed pressure ratio across the seal, a smaller clearance yielded a lower flow function as shown in Fig. 4.

The predicted effects of clearance size on flow function in case of the stepped seals are shown in Fig. 7. The stepped seal behaves quite differently from the straight seal in terms of the flow function dependence on the clearance size. In other words, the flow function at a given pressure ratio increase as the clearance reduces. The KTK model also exhibits the same trend. In other words, for a given flow function, a larger clearance would provide a greater pressure loss across the seal. The velocity vector plots obtained by the CFD are illustrated in Fig. 8 and 9 for the two different flow directions. Total pressure distribution across the seal

(a) S=1.27 mm

(b) S=5.08 mm

Fig. 5 Velocity vector plots for the largest and smallest clearance cases for the straight seal with the equivalent flow function (ϕ=25 kgK$^{0.5}$/kNs)

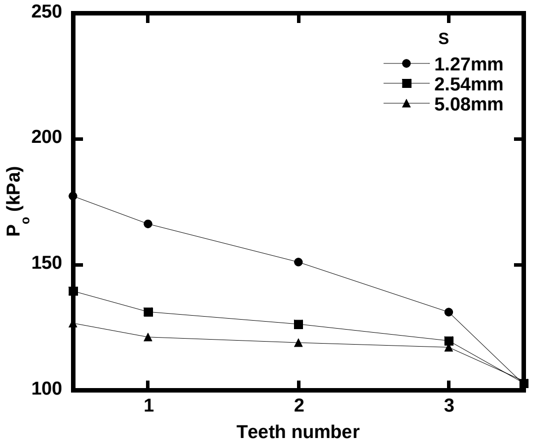
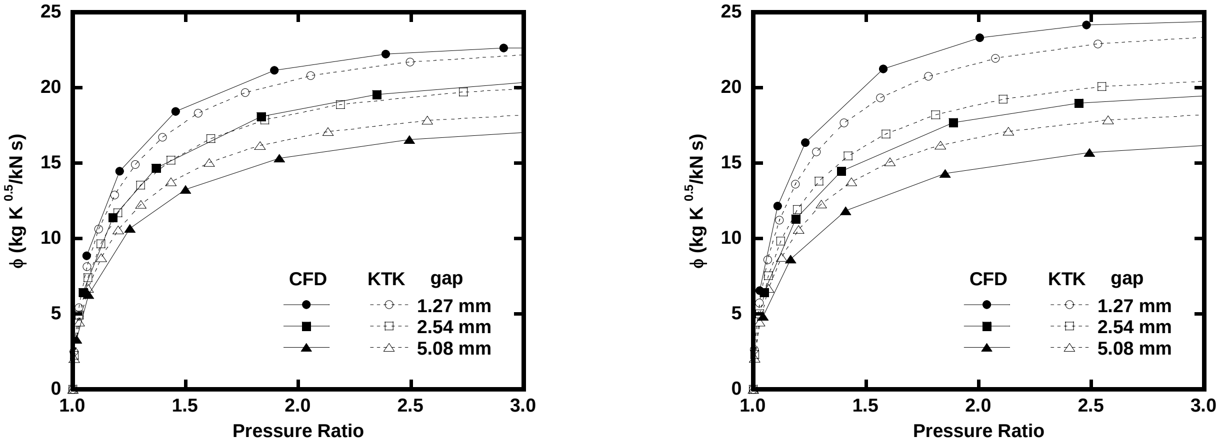


Fig. 6 Total pressure distribution for the straight seal (ϕ=25 kgK$^{0.5}$/kNs)



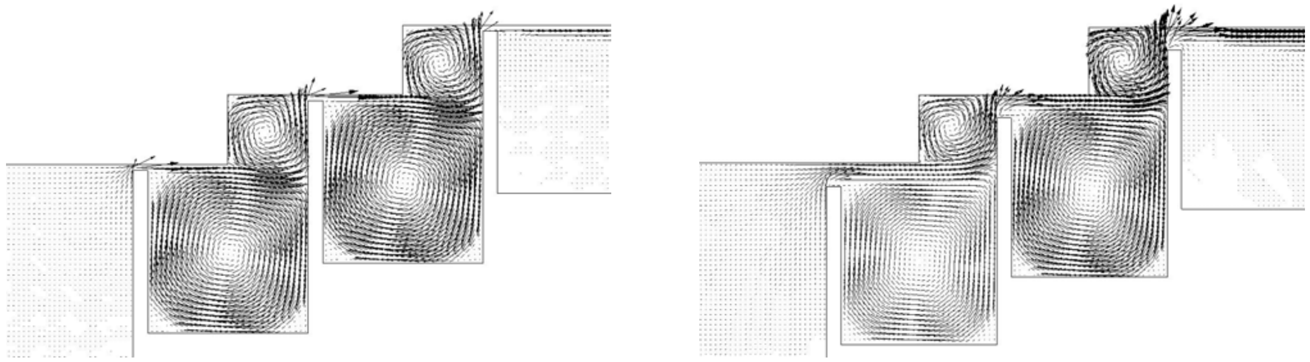
(a) three teeth diverging seal

(b) three teeth converging seal

Fig. 7 Effect of clearance size on the flow function for the stepped seals

is shown in Fig. 10. The flow function is the same in all cases. In the diverging flow arrangement, the jet flow out of a clearance hits the next tooth wall more strongly as the clearance increases, thus suffering a greater pressure resistance around all teeth. In the converging flow arrangement, the flow structures inside the cavities are different depending on the clearance size: a larger clearance provides a more abrupt turning of the flow from a clearance to the next clearance, which causes a greater pressure drop. In both flow directions, a larger clearance yields a greater flow resistance (pressure loss) for an equivalent flow function. In other words, flow function decreases as the clearance widens when the pressure ratio across the seal is the same.

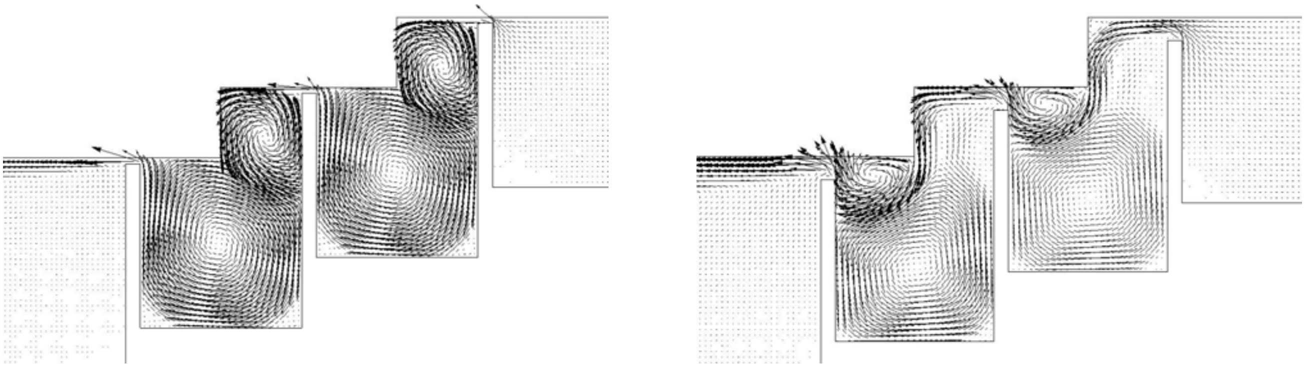
A similar pattern was observed in a recent experimental study on the leakage performance of stepped seals [14]: the flow function at a given pressure ratio increased with decreasing clearance size in three different stepped seal configurations with two to three teeth. In another study for a stepped seal with five teeth [6], a relative weak clearance dependence of the flow function on



(a) S=1.27 mm

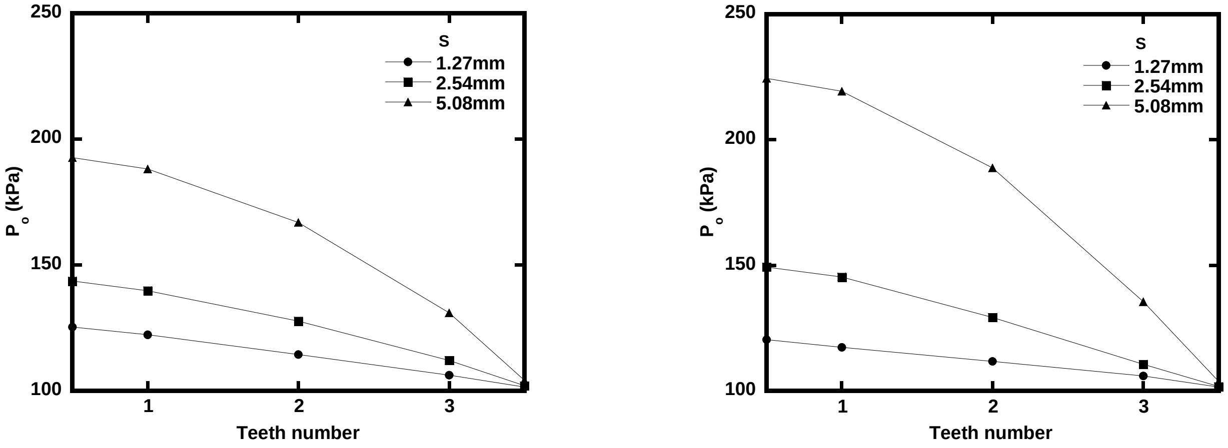
(b) S=5.08 mm

Fig. 8 Velocity vector plots for the smallest and largest clearance cases for the diverging stepped seal with the equivalent flow function (ϕ=15 kgK$^{0.5}$/kNs)



(a) S=1.27 mm (b) S=5.08 mm

Fig. 9 Velocity vector plots for the smallest and largest clearance cases for the converging stepped seal with the equivalent flow function (ϕ=15 kgK$^{0.5}$/kNs)



(a) diverging flow (b) converging flow

Fig. 10 Total pressure distribution for the stepped seals (ϕ=15 kgK$^{0.5}$/kNs)

average compared with the current study and the other reference [14] was reported. In a recent numerical study [10] on the same seal, the CFD yielded a much closer agreement with the test results than the KTK model in terms of the clearance dependence of the flow function. As a careful summary of the relevant works on stepped seals including this study, we can conclude that in the stepped seal, the flow function in general tends to increase with decreasing clearance size for a fixed pressure ratio across the seal but the exact trend seems to be dependent upon design parameters such as the number of teeth. Further studies, either experimental or numerical, would be necessary to get a more general conclusion on the clearance dependence of the stepped seal.

Fig. 11 shows the clearance dependence of the flow function of the present analysis explicitly. The flow function variation with clearance size is illustrated for a pressure ratio. The straight and stepped seals show opposite trends in the clearance dependence. With a normal (or wide) operating clearance, the stepped seal allows much less leakage, which is the main purpose of using the stepped seal instead of the straight seal despite the increased manufacturing cost. However, as the clearance becomes smaller, the advantage of the stepped seal diminishes.

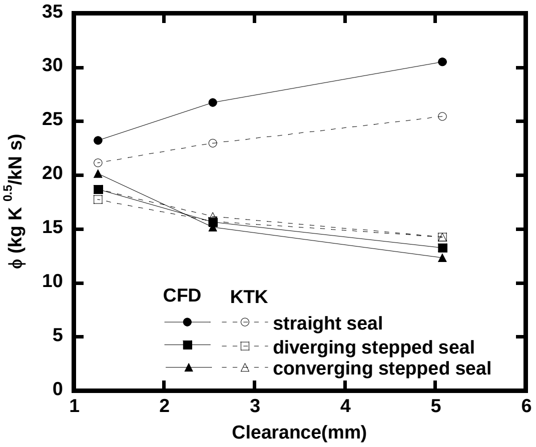


Fig. 11 Clearance dependence of flow function (pressure ratio =1.5)

5. Conclusion

Computational fluid dynamics calculation was applied to labyrinth seals. Its validity was checked and leakage characteristics of straight and stepped seals were comparatively analyzed. The results are summarized as follows.

Comparisons were made between the CFD and a KTK model in terms of their agreements with test data for straight and stepped seals with varying number of teeth. The CFD yielded quite satisfactory agreements with test data for all of the compared cases. The KTK model provided reasonable accuracy for stepped seals but underestimated the leakage for straight seals. Overall, the CFD seems to be more accurate in predicting leakage flow for both the straight and stepped seals analyzed in this study. In the three teeth straight seal, the flow function at a given pressure ratio decreases as the clearance becomes smaller: sealing performance in terms of non-dimensional flow enhances as the clearance gets smaller at a fixed pressure ratio across the seal. With a small clearance, all of the teeth contribute to the pressure loss almost evenly. However, with a large clearance, dynamic energy of the through flow is not effectively dissipated around the second teeth, resulting in only marginal pressure drop over the second teeth (or in the second cavity). As a result, pressure loss becomes greater as the clearance gets smaller for a given flow function. Accordingly, for a fixed pressure ratio across the seal, a smaller clearance yielded a lower flow function. On the contrary, in the stepped seals, the flow function for a given pressure ratio increases as the clearance reduces. A larger clearance yields a greater flow resistance (pressure loss) for an equivalent flow function due to a stronger jet impingement to the step wall (in the diverging flow) or a more abrupt turning of the jet flow (in the converging seal). Accordingly, in a stepped seal, flow function decreases as the clearance widens. With a normal (or wide) clearance, the stepped is far superior to the straight seal in terms of sealing performance. However, as the clearance becomes smaller, the advantage of the stepped seal diminishes.

Nomenclature

A_c	clearance area [m^2]	P_o	Total pressure [kPa]
B	Teeth width [mm]	ΔP_o	Total pressure loss [kPa]
CFD	Computational fluid dynamics	S	Clearance [mm]
H	Step height [mm]	T_o	Total temperature [K]
K	Teeth height [mm]	β	Taper angle [degree]
KTK	Knife-to-knife	ϕ	Flow function [kgK$^{0.5}$/kNs]
L	Distance to contact [mm]	θ	Teeth angle [degree]
$\dot{m}$	Mass flow rate [kg/s]		

References

[1] Vermes, G., 1961, “A Fluid Mechanics Approach to the Labyrinth Seal Leakage Problem,” ASME J. of Engineering for Power, April, pp. 161-169.

[2] Stocker, H. L., Cox, D. M. and Holle, G. F., 1977, “Aerodynamic Performance of Conventional and Advanced Design Labyrinth Seals with Solid-Smooth, Abradable, and Honeycomb Lands,” NASA CR-135307.

[3] Stocker, H. L., 1978, “Determining and Improving Labyrinth Seal Performance in Current and Advanced High Performance Gas Turbines,” AGARD Conference Proceedings 237, Paper 13.

[4] Tipton, D. L., Scott, T. E. and Vogel, R. E., 1986, Labyrinth Seal Analysis – Vol. III: Analytical and Experimental Development of a Design Model for Labyrinth Seals, AFWAL-TR-85-2103, Vol. III.

[5] Zimmermann, H. and Wolff, K. H., 1998, “Air System Correlations, Part 1: Labyrinth Seals,” ASME paper 98-GT-206.

[6] Wittig, S., Schelling U., Jacobsen, K. and Kim, S., 1987, “Numerical Predictions and Measurements of Discharge Coefficients in Labyrinth Seals,” ASME paper 87-GT-188.

[7] Schramm, V., Willenborg, K., Kim, S. and Wittig, S., 2000, “Influence of a Honeycomb Facing on the Flow Through a Stepped Labyrinth Seal,” ASME paper 2000-GT-0291.

[8] Soemarwoto, B. I., Kok, J. C., de Cock, K. M. J., Kloosterman, A. B. and Kool, G. A., 2007, “Performance Evaluation of Gas Turbine Labyrinth Seals Using Computational Fluid Dynamics,” ASME paper GT2007-27905.

[9] Kim, T. S., Kang, Y. and Moon, H. K., 2008, “Aerodynamic Performance of Double-Sided Labyrinth Seals,” Proc. of the 4th Int. Symposium on Fluid Machinery and Fluid Engineering, Beijing, China, pp. 377-381.

[10] Kim, T. S. and Cha, K. S., 2009, “Comparative Analysis of the Influence of Labyrinth Seal Configuration on Leakage Behavior,” J of Mechanical Science and Technology, Vol. 23, pp. 2830-2838.

[11] Waschka, W., Wittig, S. and Kim, S., 1992, “Influence of High Rotational Speeds on the Heat Transfer and Discharge Coefficients in Labyrinth Seals,” ASME J. of Turbomachinery, Vol. 114, pp. 462-468.

[12] CD-adapco, 2007, STAR-CCM+, ver. 2.07.

[13] Chupp, R. E., Holle, G. and Scott, T. E., 1986, Labyrinth Seal Analysis – Vol. IV: User’s Manual for the Labyrinth Seal Design Model, AFWAL-TR-85-2103, Vol. IV.

[14] Kang, Y., Kim, T. S., Kang, S. Y. and Moon, H. K., 2010, Aerodynamic Performance of Stepped Labyrinth Seals for Gas Turbine Applications, ASME paper GT2010-23256.