Effect of the leakage flow in runner on flow characteristics of a Francis turbine model

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Abstract. In the Francis turbine, there are gaps between the runner and the stator structure as the labyrinth seals. The flows inside gaps have the complicated flow phenomena; these complicated flows can affect the hydraulic performance and the downstream of the Francis turbine as the leakage flow. Therefore, it is important to investigate the flow characteristics induced by the runner gaps. However, normally the runner gap that has very complicated flow structure is often disregarded by considering the time and cost of the numerical analysis. But, it is necessary to apply all flow structures correctly to confirm the more accurate and reliable flow phenomena. In this study, the flow characteristics of gaps at the hub and shroud of the Francis turbine model runner were investigated with adding the leakage flow in the runner cone. In addition, the internal flow characteristics were compared by considering with and without the runner gaps application. For observing the influence of the leakage flow on the hydraulic performance and flow characteristics, the three-dimensional steady Reynolds-averaged Navier-Stokes analyses were performed using the shear stress transport turbulence model. The efficiency was decreased by applying the runner gaps; and the complicated flow phenomena were captured in the runner gaps.

1. Introduction
Labyrinth seal is common type of non-contact seal between the runner and the stator structure of a Francis turbine [1, 2]. The leakage flow through the gaps influences the hydraulic performance and the downstream of the Francis turbine [3]. Therefore, it is needed to investigate the flow characteristics induced by the runner gaps as the leakage flow. However, the runner gap that has very complicated flow structure is often disregarded by considering computational cost and time of the numerical analyses. Nevertheless, in order to investigate more accurate and reliable flow phenomena from the numerical simulations, all flow structure domains should be applied correctly.

Regarding the influences of the labyrinth seal or leakage flow, many studies have been conducted. Zhao et al. [1] studied the effects of cavity dimensions and cavity numbers on the leakage loss of the
seal by the numerical analyses. Čelič and Ondráčka [2] investigated the influence of labyrinth loss on the hydraulic efficiency of the Francis turbine using a computational fluid dynamics (CFD); and the validation test for the numerical results was conducted with the experimental data. Feng et al. [3] conducted the investigation of the disk friction loss and leakage effect on performance of the Francis turbine. They also observed the phenomenon of the rotor-stator interaction on both the disk friction and leakage loss. Although several studies related to influences of the labyrinth seal or leakage flow have been performed, the investigation of leakage flow characteristics by both the runner gap and runner cone according to flow rate conditions in the Francis turbine has not yet been elucidated systematically.

In this study, the leakage flow characteristics of runner gaps and runner cone of the Francis turbine model were investigated. In addition, the internal flows were compared by considering with and without the runner gaps application. The three-dimensional steady Reynolds-averaged Navier-Stokes (RANS) analyses were performed using the shear stress transport (SST) turbulence model to observe the influences of the leakage flow on the hydraulic performance and internal flow characteristics.

2. Francis turbine model and numerical method

In this study, the Francis turbine model (D₂=0.35 m) with a specific speed of 270-class was analyzed in steady state calculation using ANSYS CFX-19.1 commercial software [4]. Figure 1 shows the numerical grids of the main components and runner gaps (seals) of the Francis turbine model. The numerical grids were generated with both hexahedral and tetrahedral grid types for the optimum node numbers without runner gap of about 10.62 × 10⁶ through the grid conversion index (GCI) method, and the value of GCI_{fine21} for the selected node number was about 0.00226 for the best efficiency point (BEP). For the numerical grids of runner gap and cone, 5.45× 10⁶ nodes were generated with through 15 node layers at the minimum gaps. Therefore, the total number of the numerical grids was 16.07× 10⁶ for whole computational domain.

As the boundary conditions, the total pressure and static pressure were set at the inlet and outlet, respectively. The working fluid was water at 25 ℃ and the SST model was used as a turbulence model. To connect the surfaces between the stator and rotator domains, the stage-average boundary condition was applied.

3. Results and discussion

Figure 2 shows the validation test for the experimental result (real-scale) and numerical results (model-scale). In order to compare between the real and model-scale efficiencies, the scale-up formulas of the hydraulic efficiency in the IEC 60193 standard were used [5]. Although the results of the experimental
and numerical efficiencies show a slight gap, the trends are similar. These differences in efficiency can be regarded as results of not considering the mechanical loss and the surface roughness in the numerical analysis of the Francis turbine model. Meanwhile the efficiencies of model-scale with runner gaps show slightly lower than turbine without runner gaps.

In order to investigate the influences of runner gaps on the hydraulic performance, the head loss of runner was calculated according to flowrate conditions as shown in Fig. 3. Equation (1) was used to calculate the head loss of runner ($H_{\text{loss\_runner}}$) as follows:

$$H_{\text{loss\_runner}} = \frac{\Delta p_{\text{total}} - T \omega}{Q \rho g}$$

where, the $\Delta p_{\text{total}}$, $T$, $\omega$, $Q$, $\rho$ and $g$ are the total pressure difference, the torque of runner, the angular velocity, the flowrate, the water density and the acceleration due to gravity, respectively. The head losses of the runner were increased as the runner gaps applied or the flowrate decreased from the maximum flowrate. The differences of the head loss between with and without gaps show similar ranges for all observed flow rate conditions. Especially, the flow rate of $1.05Q_{\text{BEP}}$ shows the highest difference of head loss.

Figure 4 shows the flowrate loss distributions induced by the runner gaps with different flowrate conditions. The flowrate loss was calculated as the ratio of the flowrate through the runner gap to the flowrate through the runner. The flowrate loss induced by the runner gaps shows lower value at the BEP, and when the flowrate decreased or increased from the BEP, the flowrate losses were increased relatively. In addition, as the flowrate increased ($Q > 1.05Q_{\text{BEP}}$), the flowrate loss was decreased again. However, the flowrate losses in the whole observed ranges were about 0.2%, indicating a low level of flowrate loss through the runner gaps.

Figures 5 and 6 show the internal flow characteristics in the Francis turbine model as the pressure and streamline distributions according to the flowrate conditions, respectively. Figure 5 shows pressure distributions on the observed plane (Fig. 5(a)) with runner flow passage and the runner gaps and cone. The pressure distributions in the runner cone show the different characteristics slightly according to the flowrate. Meanwhile, the relative higher pressure distributions were shown at near inlet of runner shroud gap for all observed flowrate conditions. It can be seen that the inlet area of runner shroud gap was relatively very narrow, the flow near the inlet of runner shroud was complicated, and the pressure has...
increased relatively. In addition, the pressure passing through the runner gaps and cone results in the pressure loss of the runner. Thus, the cause of the head loss with the application of runner gaps can be confirmed by the pressure loss through these runner gaps and cone as shown in Fig. 3.

Figure 6 shows the streamline distributions inside the runner gaps with complicated flow phenomena on the cross-section plane of the runner gaps as shown in Fig. 5(a) with the dotted lines. For the all observed flowrate conditions, the flow characteristics inside the runner gaps showed similar internal flows. These complicated flows can reduce the hydraulic efficiency and affect directly the flow characteristics in the runner and downstream of runner as the leakage flows.

**Figure 5.** Pressure distributions on (a) observed cross-section plane of the Francis turbine model at flowrates of (b) $0.94Q_{BEP}$, (c) $Q_{BEP}$, (d) $1.05Q_{BEP}$ and (e) $1.1Q_{BEP}$. 
To investigate the effects of the runner gaps and cone to the flow characteristics in the runner, Figs. 7 and 8 show the meridional velocity distributions at the BEP condition along the spanwise direction from the hub (0) to shroud (1) at the leading edge and trailing edge of the runner, respectively. Here, the velocity was normalized with the maximum value. The near hub and shroud at the leading edge show a slight velocity difference with the application of the runner gaps as shown in Fig. 7. The meridional velocities at the trailing edge in Fig. 8 represent a slight velocity difference between the spanwise ranges of about 0.2-0.8 with the application of the runner gaps. Thus, the application of the runner gaps affects the flow inside the runner.

In order to observe the influence of the runner gaps and cone to downstream of runner, the axial and circumferential velocities were investigated as shown in Figs. 9 and 10 through the line in the draft tube cone, where line is located at the height of 0.1D2 from outlet of runner. The abscissa represents the measurement location relative to the diameter from the wall (0) to the wall (1) of the draft tube cone. The axial and circumferential velocities in the draft tube cone show the difference depending on the application of the runner gap and cone. Especially, due to the leakage flow induced by the runner cone, the axial and circumferential velocities were decreased and increased, respectively, at the middle of the flow on observed line. Thus, it was confirmed that the flow through the runner gaps and cone affected directly the hydraulic performance and internal flow characteristics of the Francis turbine model.
4. Conclusion
In this study, the steady state analyses were conducted to investigate the leakage flow characteristics of runner gaps and runner cone of the Francis turbine model. The head and flowrate losses were confirmed with influence of the runner gaps and cone, and the complicated internal flows characteristics inside the runner gaps were confirmed. In addition, the leakage flows induced by the runner gap and runner cone affected the internal flow and downstream of the runner. Therefore, the necessity of adding the gaps was confirmed through the numerical analyses. As the future study, the unsteady numerical analysis will be conducted to investigate the unsteady internal flow and pressure characteristics with runner gaps by considering these influences of the runner gaps and cone in this study. Additionally the internal flow characteristics will be compared and validated by conducting the experiments of the Francis turbine model as the future work.

Acknowledgments
This research was funded by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure, and Transport [grant number 20IFIP-B128593-04].

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