Optimum design of J-Groove for a bulb turbine model to suppress swirl flow in the draft tube

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Abstract. The swirl flow is generated by rotating runner into a draft tube of a hydro turbine, effects on the performance of the turbines. Due to various operating conditions of a hydro turbine, the variation of swirl intensity causes flow instabilities in the draft tube. Therefore, J-Groove is a group of grooves usually mounted on the draft tube wall of a hydro turbine, is considered for suppressing swirl flow in the bulb turbine model. The influence of the J-Groove on the turbine’s performance and pressure pulsation were examined by CFD analysis in the first step. Then, the optimum design of J-Groove will be conducted while considering dimensions as the length ratio, the depth ratio, the angle and the number of grooves in next step. The swirl number was evaluated in the draft tube at various operating conditions to figure inspect the effect of J-Groove to the main flow in downstream of the turbine model. The FFT analysis was employed to analyse the pressure pulsation of the flow in the draft tube of the turbine model.

1. Introduction
Part load operations, as well as start/stop of the turbines are becoming more frequent with the deregulation of electricity markets and the introduction of renewable energy resources [1]. Double regulated reaction turbines of the bulb and Kaplan types are the best adapted for such a scheme because they offer a wide operating range with relatively high efficiency. Nevertheless, they are not designed to operate under unfavorable flow conditions. There is a need to necessity of turbines that can operate beside the best efficiency region. The swirl flow is generated by rotating runner into a draft tube of a hydro turbine, effects on the performance of the turbines. Due to various operating conditions of a turbine, the variation of swirl intensity causes flow instabilities in the draft tube. Many researchers [2-5] have been studied the swirl flow characteristics and methods to suppress the swirl flow in the draft tube. J. Kurokawa et al [4] proposed a group of grooves inserted on the wall of a conical diffuser, called J-Groove, for suppressing swirl flow in the diffuser. He found that the unsteady flow as swirl intensity and pressure fluctuation in the diffuser was significantly reduced by J-Groove.
S. L. Saha et al. [5] suggested a shallow J-Groove to suppress instability in performance curve and gave a criterion for optimum design of J-Groove to stabilize performance curve of a mixed flow pump. In present study, the influence of J-Groove on the turbine’s performance and pressure pulsation will be examined by CFD analysis. Then, the optimum design of J-Groove will be conducted by considering some dimensions as the length ratio, the depth ratio, the angle and the number of grooves in the next step.

2. Turbine model and numerical simulation method

2.1. Turbine model and grids

The full fluid passage, shown in Figure 1a, consists of 6 fluid domains namely as inlet, guide vane, runner, tip clearance gap, draft tube and extension domains. The runner and guide vane have 4 blades and 16 vanes respectively. The initial J-Groove shape has been shown in Figure 1b. The dimensions of a groove are indicated in Table 1. The hexahedral mesh was generated for whole passage domain. The mesh of one pitch of the runner blade and guide vane passages, full inlet and draft tube domains are represented in Figure 2. An O-grid is utilized on the runner blade and guide vane to increase the density of the grid layer number near the walls to achieve reasonable CFD analysis results. Figure 3 illustrates the normalized efficiency and unit power of the full passage domain of the bulb turbine model under various grid numbers. Since the turbine efficiency does not change significantly over 6.5 million nodes, the mesh contained 6.5 million nodes was selected for this study. The mesh information of each domain listed in Table 2.

![Figure 1](image1.png)

**Figure 1.** a) Computational fluid domain; b) The dimensions of J-Groove installation in the draft tube of the bulb hydro turbine model.

| $D_o/D_{RN}$ | Length ratio ($L/D_{RN}$) | Angle ($\alpha$) (deg.) | Number of groove ($n$) |
|--------------|---------------------------|------------------------|----------------------|
| 1.036        | 0.507                     | 12                     | 16                   |

2.2. Numerical method and boundary conditions

The commercial software ANSYS CFX 18.1 [6] is utilized for the numerical simulation, the Shear Stress Transport turbulence model was adopted in the present study. The steady state numerical simulation was conducted to predict the turbine’s performance and calculate swirl number in the draft tube. The boundary conditions for steady state calculation are indicated in Table 3. Runner domain is a
Figure 2. The mesh generation in one flow passage of (a) runner blade, (b) guide vane, (c) full inlet domain and (d) full draft tube domain of the selected grid.

| Domain        | Grid number (million nodes) |
|---------------|-----------------------------|
| Inlet         | 0.84                        |
| Guide vane    | 2.40                        |
| Runner        | 2.28                        |
| Tip-gap       | 0.15                        |
| Draft tube    | 0.44                        |
| Extension     | 0.39                        |

Table 2. Domains grid number.

Figure 3. The mesh independence for all domains.

rotating domain and the others are the stationary domains. The rotating domain is connected to stationary domains via frozen rotor frame interfaces. And the residual target is set at $10^{-6}$. Then, the steady state result was set as initial value for the unsteady calculation. For unsteady calculation, 180 time steps were calculated per one runner revolution. Ten runner revolutions are necessary until the result is considered as periodic in time.

| Boundary condition | Inlet | Total pressure |
|--------------------|-------|----------------|
|                    | Outlet| Static pressure|
|                    | Walls | No-slip        |

Table 3. Boundary conditions for the fluid passage.
3. Results and discussion

3.1. Performance curve and loss analysis

The performance curves of the bulb turbine model in both cases of the draft tube without and with J-Groove by CFD results are indicated in Figure 4. In the present study, the runner blade angle and rotational speed were kept constant for all loads of both cases without and with J-Groove. The numerical analysis is performed by varying guide vane angle to obtain different flow rate. The figure clearly shows the slightly difference efficiency between without and with J-Groove installation. After application of J-Groove on draft tube, the efficiency of turbine model has been dropped by 0.4% approximately without altering performance at BEP.

![Figure 4](image)

**Figure 4.** Comparison of the turbine’s performance without and with J-Groove by CFD analysis

The expressions (1) and (2) are used for calculating the component losses in stationary and rotating domains, respectively in the both without J-Groove and with J-Groove.

\[ h_{\text{loss}} = \frac{\Delta p}{\rho gH} \times 100\% \] (1)

\[ h_{\text{loss-RN}} = \frac{\Delta p - T \omega}{\rho gH} \times 100\% \] (2)

The percentage component losses (except draft tube and extension domains) are listed in Table 4. Figure 5 illustrates the percentage loss in the draft tube and extension domains under various unit discharges. The loss analysis pointed out that the different efficiency between the case without J-Groove and with J-Groove models is almost in the draft tube and extension domains. The losses in draft tube and extension domains increase slightly after implicating the draft tube with J-Groove. At the best efficiency point (BEP), \( Q_{11} = 1.064 \), the loss in the draft tube is lowest in both cases. From Figure 5, the relatively large loss in draft tube and extension domains was found at partial load (\( Q/Q_{\text{BEP}} = 90\% \)), which has lower efficiency than the BEP.
Table 4. Percentage component losses (excepting the draft tube and extension domains).

| Case            | Domain                  | Q/Q_{BEP}=90% | Q/Q_{BEP}=95% | Q/Q_{BEP}=100% | Q/Q_{BEP}=103% | Q/Q_{BEP}=107% |
|-----------------|-------------------------|---------------|---------------|----------------|----------------|----------------|
| Without J-Groove| Inlet                   | 0.08          | 0.09          | 0.10           | 0.11           | 0.11           |
|                 | Guide vane              | 1.06          | 0.73          | 0.42           | 0.33           | 0.22           |
|                 | Runner & tip gap        | 4.98          | 5.66          | 6.44           | 7.11           | 8.40           |
| With J-Groove   | Inlet                   | 0.09          | 0.10          | 0.10           | 0.11           | 0.12           |
|                 | Guide vane              | 1.06          | 0.73          | 0.42           | 0.33           | 0.21           |
|                 | Runner & tip gap        | 5.04          | 5.72          | 6.51           | 7.22           | 8.49           |

Figure 5. Comparison of hydraulic losses in draft tube and extension domains between the draft tube without J-Groove and with J-Groove by CFD analysis.

3.2. Swirl number distribution
The swirl number [7] was used as a reference to evaluate the swirl flow characteristics in the draft tube without and with J-Groove at various operating conditions of the bulb turbine model. The form of the swirl number is indicated in equation (3). The locations for calculating swirl number are shown in Figure 6a. The swirl intensity was calculated at four operating conditions as partial load mode (Q/Q_{BEP} = 90% and 95%), at BEP (Q_{BEP}=100%) and over load (Q/Q_{BEP} = 103%) in both non J-Groove and with J-Groove. Figure 6b illustrates the comparison of the swirl intensity distribution between non J-Groove and with J-Groove in the draft tube at the four operating conditions by CFD analysis. Figure 6b pointed out that, the swirl intensity at the partial load is higher than the other operating conditions such as the BEP condition. The higher swirl intensity at partial load condition also contributes to the large loss in the draft tube. However, the consistent effect of J-Groove on reducing the swirl intensity at the four operating conditions was found in the Figure 6b.
\[ S_{\text{sw}} = \frac{\int V_z r^2 dr}{R \int r^2 rdr} \]  

(3)

Figure 6. (a) The locations for calculating swirl number; (b) Comparison of the swirl number distribution between the draft tube without and with J-Groove by CFD analysis.

3.3. Components velocity distribution
Figures 7 and 8 show the distribution of the axial \( (V_z^+) \) and tangential \( (V_{\theta}^+) \) velocities for two operating conditions in both the draft tube without and with J-Groove installation. Both of the velocities are normalized by the inlet averaged axial velocity \( V_{z0} \) of the runner.

Remarkable difference by the J-Groove is found at the vicinity of the draft tube wall of locations 1 and 2 for both operating conditions. In there, the tangential velocity is decreased relatively by J-Groove installation. As the flow in the groove, which has no swirl, come out from the groove and mixes with the main flow. Thus, the swirl of the main flow in the vicinity of the draft tube wall is suppressed.

3.4. Pressure pulsation analysis
In order to figure out more detail about effect of J-Groove to the flow instability, the unsteady numerical calculation was conducted at the BEP condition. Ten selected points were set on and near centre of the draft tube wall as seen in Figure 9 to measure the pressure pulsation in both cases of the draft tube without and with J-Groove installation. From CFD results, the Fast Fourier Transformation (FFT) analysis is utilized to obtain the pressure pulsation and its frequency in the draft tube. Figures 10 and 11 illustrate the amplitude of pressure fluctuation are significantly suppressed by the J-Groove
Groove was applied in the draft tube of a bulb hydro turbine to suppress the swirl wall gained slightly losses in the draft tube flow. The performance of the bulb turbine model shown that, the J-Groove mounted on the draft tube wall gained slightly losses in the draft tube and extension domains of the turbine model. The high swirl number contributed to the large losses in the draft tube and extension domains at part load and extension domains at part load.

**Figure 7.** The axial and tangential velocity distributions for Q/Q_{BEP}=90% at three locations.

**Figure 8.** The axial and tangential velocity distributions for Q/Q_{BEP}=100% at three locations.

The positive effect of J-Groove on suppressing pressure pulsation can be seen clearly at the peaks pressure amplitude (frequency = 0.11fn and 0.22fn Hz). The highest reduction of pressure amplitude is found at the peaks point.

**Figure 9.** Pressure measurement locations on the draft tube wall (in case J-Groove installation).

4. **Conclusion**

In this study, the J-Groove was applied in the draft tube of a bulb hydro turbine to suppress the swirl flow. The performance of the bulb turbine model shown that, the J-Groove mounted on the draft tube wall gained slightly losses in the draft tube and extension domains of the turbine model. The high swirl number contributed to the large losses in the draft tube and extension domains at part load and...
Figure 10. Comparison of pressure fluctuation on the draft tube wall between the draft tube without and with J-Groove installation by FFT analysis.

Figure 11. Comparison of pressure fluctuation near the draft tube centre between the draft tube without and with J-Groove installation by FFT analysis.

high load conditions. From the CFD analysis results obviously point out that the J-Groove is the affective method to reduce the swirl number in the draft tube of the turbine model. Moreover, the pressure pulsation in the draft tube is significantly suppressed by the J-Groove installation.
5. Future plan
The positive effect of J-Groove on suppressing swirl flow and pressure pulsation was examined by CFD analysis. Then, the optimization design of J-Groove will be conducted to improve the results.

Acknowledgement
This work was supported by the New and Renewable Energy of the Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea Government Ministry of Trade, Industry and Energy (No. 20163010060340).

Nomenclature

- $L$: length of a groove (m)
- $D_0$: Outer diameter of a groove (m)
- $D_{RN}$: Runner diameter (m)
- $\eta$: Hydraulic efficiency of the turbine (%)
- $P_{11}$: Unit power (kW)
- $Q_{11}$: Unit discharge (m$^3$/s)
- $\Delta p$: Different pressure (Pa)
- $\rho$: Density of water (m$^3$/s)
- $g$: Gravity acceleration (m$^2$/s)
- $H$: Effective pressure head (m)
- $Q$: Flow rate (m$^3$/s)
- $T$: Torque in shaft (Nm)
- $\omega$: Angular velocity (rad/s)
- $h_{loss}$: Loss in stationary domain (%)
- $h_{loss-RN}$: Loss in runner domain (%)
- $S_{swr}$: Swirl intensity number
- $V_z$: Axial velocity (m/s)
- $V_\theta$: Circumferential velocity (m/s)
- $V_{z0}$: The inlet average axial velocity in the runner (m/s)
- $f_n$: Frequency of the runner (Hz)

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