Effects of a rectifier on the hydraulic stability of the draft tube

L J Yang¹, J Zhang¹, C M Yan¹, and Z H Deng ²

¹ Guangdong Polytechnic of Water Resources and Electric Engineering, Guangzhou
Guangdong, China
² Created Model Design Corporation of Zhongshan City, Zhongshan, Guangdong,
China

yanglj@gdsdxy.cn

Abstract. The effects of a rectifier on the hydraulic stability of the draft tube is explored with research based on a straight cone-shaped draft tube with constant sized diffusion, where the uninstall rectifier and the installed rectifier in the straight cone section of the draft tube are simulated under different conditions of hydraulic stability. The internal pressure pulsating characteristics of the draft tube, the internal pressure and the output change of the runner, and the internal flow regime change of the draft tube are also analyzed. The results show that the pressure waveform of the draft tube is relatively stable when the rectifier is installed under the typical partial load condition, and the pressure fluctuation amplitude near the tube wall of draft tube is small, the peak value of the mixing peak is large and the frequency component is rich. The installation of a rectifier in the draft tube can guide and rectify the water flow, so that the flow regime of the rectifier inlet tends to be more stable, the differential pressure between the axis and the radial direction decreases, and the recirculation region and secondary flow inside the runner outlet and the straight cone section are reduced. In this way, the production of vortex belt can be inhibited, and the actual water flow and flow uniformity of the inlet cross section of turbine can be improved.

1. Introduction
The pressure vibration caused by the vortex belt of the draft tube is one of the common reasons for the hydraulic vibration of the Francis turbine. The vortex belt usually results in strong rotational pressure pulsations, and can be transmitted to the flow passage components and the simultaneous pressure pulsations of structures, which may cause fluctuations in the flow and pressure of the entire waterway system. In addition, if the pressure fluctuation frequency of the vortex belt on the draft tube is close to or the same as the characteristic frequency of the waterway system, the resulting resonance phenomenon can cause pressure peak to be overlapped and strengthened, resulting in the vibration of the unit, the breakage of the runner blade, the swing of the big shaft, and even the fracture of the penstock. In general, when the water enters both ends of the runner of the hydraulic turbine, the direction of the water flows from the axial to radial, and the flow is subjected to centrifugal forces to produce a secondary flow, resulting in the situation that the hydraulic turbine deviates from the optimal operating condition, and eventually causing the formation of eccentric tail water vortex belt. With the increase of the installed capacity of the hydraulic turbine, the study of the stability of the unit is particularly important [1]. With the rapid development of society, computer technology has also made great progress, CFD is an analysis of systems through computer numerical calculations and image displays, involving related physical phenomena such as fluid flow, and CFD can be seen as a
numerical simulation of the flow under the control of the basic equations of flow\textsuperscript{[2,3]}. Through the numerical simulation, we can obtain the distribution of the basic physical quantities (such as velocity, pressure, etc.) at various positions in the extremely complex flow field, and the changes of these physical quantities over time to determine the distribution characteristics and cavitation characteristics of the vortex and the de-flow zone, etc. We can also calculate other physical quantities according to these things, such as water loss and efficiency. In recent years, domestic and foreign scholars have used the numerical simulation method to carry on extensive research on the hydraulic turbine\textsuperscript{[4,5]}. In this paper, a coaxial rectifier tube with two openings at both ends is added inside the straight cone section of the draft tube, which can increase the axial pressure of the flow through the rectifier, reduce the differential pressure between the axis and the water flow of the peripheral draft tube wall, and reduce or suppress the return flow\textsuperscript{[6,7]}, thereby to suppress the effect of the vortex belt. In order to verify the beneficial effect of the installation of the rectifier, whether or not the rectifier tube is added inside, the straight cone section of draft tube is used as a variable in this paper. Through the analysis of the design condition by CFD technique of simulation, this paper analyzes the influence of the installed rectifier on the hydraulic stability of the draft tube. It is of theoretical significance to improve the stability and economy of the actual unit operation\textsuperscript{[8,9,10].}

2. Comparison of geometrical parameters of the draft tube
The research selects a straight cone-shaped draft tube of the turbine and keeps the size of the diffusion section unchanged. Two kinds of draft tubes are formed depending on whether or not the rectifier is installed. (a) is the prototype draft tube of turbine with the installation of the rectifier. (b) is the modified draft tube of turbine without the installation of the rectifier. Schematic diagrams are shown in figure 1.

![Figure 1. Comparison of the schematic diagram on hydraulic turbine](image)

3. The analysis method of calculation and the calculation of operating conditions
In this paper, according to the calculation of the theoretical simulation, the hydraulic stability of the draft tube is analyzed. The calculation of unsteady flow in the draft tube belongs to the coupling problems of the continuity equation and the momentum equation. The equation is as follows:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]  

(1)

\[
\frac{\partial (\rho u)}{\partial t} + \frac{\partial (\rho uu)}{\partial x} + \frac{\partial (\rho vu)}{\partial y} + \frac{\partial (\rho wu)}{\partial z} = \frac{\partial}{\partial x}\left( \rho u \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y}\left( \rho u \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z}\left( \rho u \frac{\partial u}{\partial z} \right) - \frac{\partial p}{\partial x} + S_u
\]  

(2)

\[
\frac{\partial (\rho v)}{\partial t} + \frac{\partial (\rho vu)}{\partial x} + \frac{\partial (\rho vv)}{\partial y} + \frac{\partial (\rho wv)}{\partial z} = \frac{\partial}{\partial x}\left( \rho v \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y}\left( \rho v \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z}\left( \rho v \frac{\partial v}{\partial z} \right) - \frac{\partial p}{\partial y} + S_v
\]  

(3)

\[
\frac{\partial (\rho w)}{\partial t} + \frac{\partial (\rho uw)}{\partial x} + \frac{\partial (\rho vw)}{\partial y} + \frac{\partial (\rho ww)}{\partial z} = \frac{\partial}{\partial x}\left( \rho w \frac{\partial w}{\partial x} \right) + \frac{\partial}{\partial y}\left( \rho w \frac{\partial w}{\partial y} \right) + \frac{\partial}{\partial z}\left( \rho w \frac{\partial w}{\partial z} \right) - \frac{\partial p}{\partial z} + S_w
\]  

(4)

Where:

\[ \rho \text{— density;} \]
\[ t \text{— time;} \]
\[ u, v, w \text{— the x, y, z direction of the speed;} \]
\[ p \text{— pressure;} \]
\[ \mu \text{— sticky;} \]
\[ S_a, S_b, S_c \text{— generalized source terms.} \]

The SST \( k-e \) turbulence model \(^{[11,12]}\) can be used to obtain the results closer to the actual operating conditions when there is vortex in the turbine. \( k \) and \( e \) are two basic unknowns, and the transport equation corresponding to \( k \) is:

\[ \frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho ku_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho e - Y_m + S_k \quad (5) \]

The transport equation corresponding to \( e \) is:

\[ \frac{\partial (\rho e)}{\partial t} + \frac{\partial (\rho eu_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_e} \right) \frac{\partial e}{\partial x_j} \right] + C_{1e} \frac{e}{k} (G_k + C_{3e} G_b) - C_{2e} \rho \frac{e^2}{k} + S_e \quad (6) \]

Where:
\[ \mu_t \text{— turbulent viscosity;} \]
\[ G_k \text{— turbulent kinetic energy } k; \]
\[ G_b \text{— turbulent kinetic energy } b; \]
\[ C_{1e}, C_{2e}, \text{ and } C_{3e} \text{— empirical constants;} \]
\[ \sigma_k \text{— turbulent kinetic energy } k \text{ corresponding to the Prandtl number;} \]
\[ \sigma_e \text{— dissipation rate } e \text{ corresponding to the Prandtl number;} \]
\[ S_k \text{ and } S_e \text{— source items.} \]

According to the recommended value given by Launder et al and the experimental methods in the subsequent proof procedure, the corresponding values of the model constants are determined as follows: \( C_{1e} = 1.44, C_{2e} = 1.92, C_{3e} = 0.09, \sigma_k = 1.0, \text{ and } \sigma_e = 1.3. \)

The unstructured tetrahedral network is selected for the calculation area. The calculation area includes the runner, the draft tube, the volute, the movable guide vane, the fixed guide vane and the rectifier. The unsteady flow of the selected draft tube under the same typical load condition is calculated and analyzed. This paper uses a volute axial turbine generator, the rated head of which is 8 m and the actual maximum head is 7.12 m, the length of draft tube is 480 mm, the outlet diameter of the draft tube is \( \phi 240 \) mm; the inlet velocity under the typical operating conditions is 4 m/s. The pressure outlet is expressed in standard atmospheric pressure. The blade speed is maintained at 50 rad/s under the operating conditions \(^{[13]}\).

4. Comparison of pressure pulsation characteristics of the two draft tubes

4.1. The wave form of pressure pulsation

Figure 2 shows the pressure pulsation waveform of a recording point on the wall surface of the inlet at the draft tubes without or with the installation of the rectifier. It can be seen from figure 2, when the draft tube does not install the rectifier, both ends of the runner of the turbine exists changes in the direction of the water flow from axial to radial, forming eccentric tail water vortex belts under the action of centrifugal force. The pressure pulsation of the recording point is mainly affected by the tail water vortex belts, and shows a steady-state pressure pulsation waveform. Wherein, the pressure at the point of the draft tube near the wall surface is much greater than the pressure near the axis. When the rectifier is installed, the pressure of the draft tube at the recording point of the fracture surface of the inlet is observably lower than that without the rectifier, and the whole pressure fluctuation waveform presents another regularity. Because of the installation of the rectifier, the axial pressure of the water flow through the rectifier increases, and the differential pressure between the water flow near the axis
and the wall of the draft tube is reduced under the guidance and rectification of the rectifier, resulting in a significant reduction or suppression of the reflux so that the pressure of the recording point is significantly reduced by the influence of the tail water vortex belts.

Figure 2. Two kinds of the pressure pulsation waveform on 1m from the inlet inside the straight cone section of the draft tubes

4.2. Pressure pulsation frequency and amplitude

Figure 3 shows the pressure pulsation spectrum of a recording point on the wall surface of the inlet at the draft tubes without or with the installation of the rectifier. It can be seen from figure 3 that the main pressure pulsation frequency of the draft tube is 2.49 Hz and the main frequency is not obvious when there is no rectifier, and the frequency components also include 25 Hz, 33 Hz, 50 Hz and 75 Hz. When the rectifier is installed, the main pressure pulsation frequency of the draft tube is broad and rich. The components of the pressure pulsation frequency include 2.49 Hz, 17 Hz, 22 Hz, 32 Hz, 50 Hz, 75 Hz. The main pressure pulsation frequency component is 2.49 Hz and the main frequency is more obvious. Table 1 lists the main pressure pulsation frequency and the corresponding amplitude at the recording points of the two draft tubes. It can be seen from figure 3 that the pressure pulsation amplitude of the draft tube is significantly reduced and the percentage of the amplitude of the mixing peak increases significantly when the rectifier is installed. This is because of the reduction of the reflux after the installation of the rectifier and the relative inhibition of the vortex belts. And the flow of water is more stable, the energy of the spectrum is more concentrated.

Figure 3. Two kinds of the pressure pulsation spectrum at the recording point of the outlet of the draft tubes
Table 1. The main pressure pulsation frequency and the corresponding amplitude of the internal recording points in two kinds of draft tubes

|                  | When the rectifier is not installed | When the rectifier is installed |
|------------------|-------------------------------------|---------------------------------|
| Frequency (Hz)   | 2.497                               | 2.494                           |
| Amplitude (Pa)   | 14834                               | 3164                            |
| The percentage of the amplitude (%) | 0.607                              | 1.683                           |

5. The influence of the installed rectifier and the uninstalled rectifier on the pressure of the runner

Based on the draft tubes with or without the rectifier, 6 points are taken in the pipeline of the runner inlet respectively, and the characteristics of the pressure fluctuation of the fluid flow is recorded. It can be seen from figure 4 that the pressure pulsation at the outlet of the runner is relatively steady and the percentage of amplitude is low at each recording point, which indicates that the flow of water is relatively stable, the vortex is less and the vortex belt is suppressed. Comparing pressure fluctuation diagrams of the inlets of the runners without the rectifier and with the rectifier, it can be seen that there is a frequency of 100 Hz in the pulsation diagram of the runner without the rectifier, and the amplitude is large at this frequency. It is indicated that there is a vortex belt in the runner under this operating condition, which intensifies the disturbance of the flow field. When the rectifier is installed, the amplitude of the recording point in the pressure pulsation diagram at the inlet of the runner is very low, which proves that the installation of the rectifier further inhibits the vortex belt the water flow is more smooth, and the stability of the flow field within the runner is increased.

(a) The pressure pulsation spectrum of the inlet of the runner without the rectifier
(b) The pressure pulsation spectrum of the inlet of the runner with the rectifier

Figure 4. The pressure pulsation spectrum of the inlet of the runner in 2 kinds of draft tubes

6. The influence of the installed rectifier and the uninstalled rectifier on the internal flow of the draft tubes

6.1. Comparison of the internal flow of the draft tubes with the rectifier or without the rectifier

Figure 5 and figure 6 show the velocity vector at different cross sections of the uninstalled rectifier and the installed rectifier. The velocity distribution at the cross sections of the draft tubes and the rectifier in figure 5 shows that the vortex section is circular, and the center velocity of the vortex belt is less than the wall velocity, forming a recirculation region. The wall velocity is high, and the changes of vortex belts in the inlet cross section of the draft tube and the cross section of the installation position of the rectifier are small and relatively stable. The velocity distribution at the cross section of the draft tube and the rectifier in figure 6 shows that the vortices formed at the inlet cross section of the draft tube have slight changes compared to those in figure 5, and the formation of the recirculation zone is
positively correlated with the vortex formation and vortex shape in the draft tube [14]. The center velocity of the vortex belt is lower than the wall velocity, and the velocity of the vortex is weakened at the cross section of the installation position of the rectifier, and the shape of the vortex becomes blurred. It is indicated that the surrounding pressure distribution is relatively similar, which restrains the impact of the reflux, and it is further verified that the rectifier has played an important role in improving the stability of the draft tube.

Figure 5. The velocity vector at the cross section without the rectifier

Figure 6. The velocity vector at the cross section with the rectifier

6.2. Comparison and analysis of vortex belts without or with the rectifier in the draft tubes

Figure 7 shows the distribution of the vortex belts of two kinds of draft tubes in the same typical operating conditions. The direction of rotation of the vortex belt is counterclockwise and contrary to the direction of rotation of the runner, which indicates that the water flow in the runner has velocity circulation that is opposite to the direction of rotation of the runner[15]. From the distribution of the vortex belts of the draft tube without the rectifier, there is an obvious large vortex belt, and in the same operating conditions when the rectifier is installed, the vortex belt has become more dispersed, the intensity of the vortex is weakened and the shape becomes blurred. The diagram is in line with the velocity vector of figure 5 and figure 6, which proves that the installation of the rectifier can suppress the generation of the vortex belt and improve the flow uniformity of the actual water flow in the inlet section of the turbine.
6.3. Axial velocity distribution of the inlet of the draft tube

The pressure pulsation in the runner and the draft tube is closely related to the formation of the vortex belt [16]. In the straight cone-shaped draft tube, the eccentric vortex belt has enough space to develop downstream, and then forms the vortex belt, which is detrimental to the stability of the flow field of the draft tube. The axial velocity distribution of the draft tube without the installation of the rectifier in figure 8 shows that two interacting vortices are distributed on both sides of the axial direction and form a strong secondary flow, which corresponds to the high amplitude percentage in the pressure pulsation distribution diagram; the axial velocity distribution of the draft tube with the installation of the rectifier under the same typical operating condition shows that the vortex has slowly spread out, the shape of the vortex becomes blurred, and the velocity distribution is more uniform, which indicates that the flow of water is relatively stable.

7. Conclusions

The present invention discloses a draft tube for a hydraulic turbine in which a rectifier having openings at the front and rear ends is arranged in the channel of the draft tube. The rectifier is coaxial with the tapered pipe section, the water flow of the hydraulic turbine flows out through the outlet of the runner and enters the tapered pipe section of the draft tube. After the water flow enters the tapered pipe section, the water pressure of the axis in the tapered pipe section is less than the pressure of the periphery. It is further analyzed the characteristics of the pressure pulsation and the internal flow in the two kinds of draft tubes and the runners. The results are as follows:

When the water flow in a certain position of the tapered pipe meets the rectifier with front and rear openings, it will make the pressure of the axis increase, and the surrounding pressure will be reduced inversely, therefore, the differential pressure between the axis and the periphery will be reduced, so
that the generation and influence of the eccentric vortex belt can be suppressed.

The installation of the rectifier can effectively suppress or reduce the reflow phenomenon without any influence on the output power of the hydraulic turbine, and can make the water flow more stable and then extend the duration of continuous operation of the hydraulic turbine runner.

The influence of the rectifier on the internal flow of the draft tube is analyzed from three angles of the velocity vector at the cross section of the rectifier, the vortex view of the draft tube and the axial velocity distribution of the inlet of the draft tube. The results show that the vortex belts in the draft tube with the installation of the rectifier is more dispersed under the same operating condition, the intensity of the vortex is weakened and the shape becomes blurred, which indicates that the installation of the rectifier can suppress the generation of the vortex belt and improve the flow uniformity and the actual water flow of the inlet cross section of the hydraulic turbine, playing an important role in the stability of the draft tube.

Acknowledgments
Thanks are due to Guangdong water conservancy science and technology innovation project (2014-02) and Guangdong province brand professional construction of higher professional education project -- water conservancy and hydropower construction engineering (2016gzpp014) for assistance.

References
[1] QIUhe Numerical Simulation of Francis Turbine Draft Tube Vortex and Pressure Pulsation[J]. Journal of Water Resources & Water Engineering, 2017(6):168-172.
[2] Motycak L, Skotak A, Obrovsky J Analysis of the Kaplan turbine draft tube effect[C]// 2010:012038.
[3] Mohamed Adel and Nabil H Mostafa Numerical investigation of performance of kaplan turbine with draft tube[C]. Eighteenth International Water Technology Conference . Sharm ElSheikh:, 2015(3): 12-14.
[4] ZHOU Lingjiu, Wang Zhengwei, Huang Yuanfang. The Performance Predicting of influence of Draft Tube Height on its Hydraulic Stability [J]. Large Electric Machine and Hydraulic Turbine, 2004(4):47-51.
[5] WANG Zhengwei, ZhouLingjiu, Huang Yuanfang. Simulation of unsteady flow induced by in vortexes the draft tube of a Francis turbine [J]. Journal of Tsinghua University (Science and Technology), 2002, 42(12):1647-1650.
[6] Galván S, Reggio M, Guibault F. Numerical optimization of the inlet velocity profile ingested by the conical draft tube of a hydraulic turbine[J]. Journal of Fluids Engineering, 2015, 55(93):527-541.
[7] Yang Lijing, An Yuan, Wang Youqing, etc. Unsteady flow and interaction control of counter-rotating double-rotor turbine [J] Journal of Drainage and Irrigation Machinery Engineering, 2011, 29(4):307-311.
[8] Yang Lijing 3-D steady flow analysis on double-rotor bulb turbine [J]. Water Resources and Hydropower Engineering, 2012, 43(7):123-126.
[9] Takashi K New Bulb Turbine with Counter-rotating Tandem-runner[J]. Chinese Journal of Mechanical Engineering, 2012, 25(5):919-925.
[10] Han Fengqin, Huang Leping, Yang Lijing, etc. Geometrical Analysis of Adjustable Guide Vanes for Blub Turbine [J]. Journal of Engineering Thermophysics, 2010, V31(2):263-266.
[11] Dong Liandong, Yuan Huixin, Fu Shuangcheng, etc. Applicability of turbulence models in numerical simulation of decanter centrifuge[J]. Chemical Industry and Engineering Progress, 2013, 32(s1):36-41.
[12] Bardina J E, Huang P G, Coakley T J Turbulence Modeling Validation, Testing, and Development[J]. 1997.
[13] Yang Lijing. Utility model patents: A draft tube for a turbine: China, ZL 2014 2 0291918.1[P].
[14] Wu Gang, Dai Yongfeng, Zhang Kewei, etc. Relationship between the inlet of the flow field
and water pressure pulsation of Francis turbine draft tube [J]. Water Resources and Power, 2000(1):58-61.

[15] Mei Zuyan. Pumped Storage Power Generation Technology[M]. CHINA MACHINE PRESS, 2000.

[16] Poole J N, Frey W J. Retrofit of a recovery boiler ID fan with a dual channel high reliability LCI drive[C]// Pulp and Paper Industry Technical Conference, 1988. Conference Record of 1988. IEEE, 1988:23-37.