Optimization of surge tank structures in hydropower station based on VOF method

Z Y Yang\textsuperscript{1}, Y G Cheng\textsuperscript{1}, K Liu\textsuperscript{1}, Q Wang\textsuperscript{2} and F Yang\textsuperscript{3}

\textsuperscript{1} State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan 430072, China
\textsuperscript{2} Ministerial Key Lab of Hydraulic Machinery Transients, Ministry of Education, Wuhan University, Wuhan 430072, China
\textsuperscript{3} Construction Management Company for Chushandian Reservoir Project of Henan Province, Zhengzhou 450000, China

E-mail: ygcheng@whu.edu.cn

Abstract. During transient processes of hydropower stations, large surging waves under load rejection condition and air-trapped vertical vortices under start-up condition in surge tanks are the critical factors that influence the safety of hydropower stations. In this study, model tests and volume of fluid (VOF) model based three-dimensional (3D) simulations were conducted to check the rationality of surge tank structures in transient processes, and after intensive analysis, an optimized scheme was proposed. The results show that the original scheme leads to the violent water level fluctuations in steady operation and load rejection conditions, and some air-trapped vertical vortices occur during start-up process. The air-trapped vertical vortices can provide bubbles into the penstock, which is not permitted. With the impedance orifice and bottom plate shapes changed, the optimized scheme gives limited water level fluctuations during both load rejection and start-up conditions, and eliminates the step water falling and air-trapped vortex swirling phenomena effectively, meeting the requirements of design, construction and operation.

1. Introduction

For decades, hydropower has been developing rapidly to meet the large demand for electricity. But there were many safety and stability problems for hydropower stations \cite{1,2}. The safety of hydraulic systems and turbine units during transient processes are the main concerns in design and operation phases. As a kind of pressure suppression structure, surge tank or chamber should be carefully set. A surge tank, connected to the headrace or tailrace tunnel, undertakes the function of reflecting water hammer waves from the penstocks or tailrace conduits, so as to restrict the water hammer pressure in the hydraulic systems and turbines. The long-corridor-shaped surge tank (LCSST), which connected to multiple units, is a newly developed surge tank type for large underground hydropower stations. Due to the large aspect ratio of cross-section in LCSST, open channel flow characteristics and complex flow patterns are presented during transient conditions. Rapid rising and falling of water levels, obvious longitudinal oscillation, and air-trapped vertex flows are the common phenomena. A reasonable design should control or eliminate these problems.

To analyze the surge tank wave fluctuations, the method of characteristics (MOC) was widely used \cite{3}. However, the detailed flow characteristics cannot be calculated by MOC because it is a one-dimensional (1D) method. Therefore, three-dimensional (3D) computational fluid dynamics (CFD) should be employed in analyzing the flow patterns and optimizing the surge tank structures. Houde et al. \cite{4} conducted 3-D CFD simulations of water flow during hydraulic transients in the tailrace surge
tank of a hydropower station. The results of free surface fluctuations are in good agreement with those in a model test. Xia [5] simulated the 3D flow characteristics under the load rejection within a corridor-shaped air-cushion surge tank, and reported the free surface waves, flow patterns, and the pressure change histories. Cai [6] elucidated the formation mechanism of the air-trapped vertical vortices in the tailrace LCSST during load rejection, and proposed adding baffles near the impedance orifices to eliminate them. Wu [7] also investigated the air-trapped vertical vortices in the LCSST and found that the area of impedance orifices, the shape of surge tank, and the length of tailrace tunnel had obvious influence on the vertical vortices. Deng [8] conducted an extensive analysis of the flow characteristics in a practical LCSST, and a pier-based structure located around the impedance orifices was adopted to eliminate the harmful air-entraining vertical vortices. The above researches show that the information of complex flow patterns in LCSST are more clear, and more methods have been proposed to solve these unstable flow phenomena.

In this study, the load rejection and start-up processes in a practical headrace LCSST were investigated by using model tests and numerical simulations. This paper reports the analyzing and optimizing steps, findings, and proposed scheme.

2. Numerical methods

2.1. The LCSST and its simulation model

The simulation object was the model test system of a practical hydropower station, which consists of an upstream reservoir, a diversion tunnel, a bifurcation, a surge tank, and two penstocks, as shown in Figure 1. The upstream reservoir was used to keep the water level constant, especially in transient processes. The surge tank, which has a rectangular horizontal cross section of 2.68 meters long and 0.4 meters wide, is a long-corridor-shaped one with large aspect ratio 6.7. The bifurcation, which is connected to the two penstocks, is just under the surge tank. The bottom plate of the surge tank has a step, on the right there are two circular impedance holes and gate holes, which form the flow passage between the surge tank and penstocks. In model test system, the hydraulic turbines at the end of the penstocks are replaced by the valves, which can be opened and closed quickly to regulate the discharge, so as to simulate the load variations.

![Figure 1. Schematic of the model test system and the 3D model of the surge tank](image)

2.2. Numerical schemes

The 3D CFD has been well applied to simulations of many industrial problems. However, to successfully simulate the complex water level fluctuations an air-trapped vertical vortices in a surge tank, choosing appropriate numerical models is particularly important.

Turbulence model: To reflect the strong turbulence characteristics in the surge tank under transient processes, the volume of fluid (VOF) model [9] for two-phase flow and the realizable $k - \varepsilon$ model [10,11] for turbulence were selected.
Mesh generation: The software ICEM was used to generate mesh. In order to capture accurate free-surface, hexahedral grids are used for whole geometry, and sufficient grids were given near the gate and impedance holes. In general, the total elements of the original scheme were about 3.7 million, while the total elements of the optimized scheme 3.85 million.

Numerical solution: The PISO algorithm for velocity and pressure equations and body force scheme for pressure interpolation were chosen. After many comparisons, the timestep was set to 0.00075s, and the residual precisions for the parameters were 10E-4.

Boundary conditions: The Open Channel model provided by Ansys Fluent was used to set constant pressure boundary condition at the upstream reservoir, and mass flow rate was set at the outlets of penstocks. Both the top of the upstream reservoir and the surge tank are given constant zero pressure. When the transient process happened, User-Defined-Function (UDF) was used to set the changes of mass flow rate at the outlets to simulate the closing and opening processes of valves. Under the load rejection condition, the mass flow rates at the outlets decreased linearly from 18.866 kg / s to 0 within 1.49 s, while under start-up condition, they increased linearly from 0 to 18.866 kg / s within 2.29 s. The remaining boundaries were treated as the non-slip walls.

3. Operating conditions and comparisons between numerical and model test results
Two worse operating conditions were selected for the simulation and analysis, including the simultaneous load rejection of two units (W1) and the start-up process of unit 2 during normal operation of unit 1 (W2), as shown in Table 1, where the elevation datum is set to the central line of the diversion tunnel.

| Constant water level in the upstream reservoir (m) | Initial mass flow rates at the outlets (kg / s) | Final mass flow rates at the outlets (kg / s) |
|---------------------------------------------------|-----------------------------------------------|---------------------------------------------|
|                                                   | Unit 1 | Unit 2 | Unit 1 | Unit 2 |
| W1                                                | 0.27   | 18.866 | 18.866 | 0       | 0         |
| W2                                                | 0.27   | 18.866 | 0       | 18.866  | 18.866    |

To verify the accuracy of simulation for steady working conditions, comparisons of the simulated water levels in the surge tank with the model test results are shown in Table 2. It shows that the errors are all within reasonable ranges. Also, Iso-surfaces with phase fraction 0.5 were set to characterize the air-liquid interfaces. The model test shows that the flow patterns in surge tank are relatively calm except for the area above the impedance holes when units are in steady operation, and the numerical results also reflect the same phenomena (Figure 2).

| Numerical results | Model test results | Error  |
|-------------------|--------------------|--------|
| W1                | 0.229              | 0.233  | 1.72%   |
| W2                | 0.258              | 0.262  | 1.53%   |
4. Flow characteristics of the original surge tank scheme

4.1. Simultaneous load rejections of two units

Figure 3 shows the histories of discharge in the diversion tunnel and water level in the surge tank within the first 60 s. Overall, the water level at each measuring point rises greatly at the initial stage in the load rejection process, but attenuates rapidly. For the impedance surge tank, the hydraulic oscillation period (T) between surge tank and upstream reservoir satisfies the following formula (Equation 1) [11]. Therefore, the hydraulic oscillation period T=25.9 s calculated by Equation 1 is in good agreement with the time between the two peaks (27.8 s) shown in Figure 3 (a).

\[ T = \frac{2\pi}{\sqrt{\frac{L^2}{gF}} / \sqrt{f}} \]  

where, \( L \) denotes the length of diversion tunnel (11 m); \( F \) denotes section area of surge tank (1.072 m\(^2\)); \( g \) denotes gravitational acceleration (9.81 m / s\(^2\)); \( f \) denotes section area of diversion tunnel (0.07069 m\(^2\)).

In this scheme, the elevation of bottom plate is higher, leading to the less water above the bottom plate. Therefore, at the initial stage of the load rejection process, the rapid valve closing at the outlets pushes flow to rush into the surge tank with high surge waves, which then decays rapidly and becomes stable gradually under the action of gravity and resistance. In addition, the longitudinal oscillation in the surge leads to significant peak values. It is gratifying to note that the highest water level is within the design value.

In the transient process, the valve was closed rapidly in 1.49 s, and the discharge decreased linearly from 18.866 kg / s to 0. The water in the diversion tunnel affected by inertia action, through the gate and impedance holes, rushes into the surge tank, showing too high and uneven peak waves (Figure 4, \( t = 2 \) s). Due to the LCSST in this paper, especially the large aspect ratio, therefore, it is impossible for air-
liquid surface to rise evenly and the flow characteristics are similar to those in open channel. As can be seen (Figure 4, $t = 4$ s), the water above the impedance holes suddenly rises and transmits along the axis of the corridor to the other side, after hitting the wall at the end, obvious wave breakages generate. During this period, the flow velocity in the middle of the surge tank is too large while that at both ends is small, therefore, the impact caused by this uneven distribution is great, which is not conducive to the safety of the side walls. As the surge tank water level continues to rise, the water level difference between surge tank and upstream reservoir decreases, leading to further decline of discharge. Therefore, the rise of water level in surge tank is not as intense as before, but is replaced by stable longitudinal oscillations and dissipated gradually under the action of gravity (Figure 4, $t = 14$ s).

Generally speaking, in the transient process, the water level fluctuations in the surge tank are too uneven. Also, the longitudinal oscillation waves are serious and wave breakages may destroy the side plate.

![Typical flow patterns during the load rejection process](Figure 4)

4.2. Start-up process of unit 2 during normal operation of unit 1

During the start-up condition, the discharge in the diversion tunnel increases and the water level in the surge tank decreases. Under the action of gravity and inertia, water level fluctuations also show periodic characteristics and their periods satisfy the Equation 1 only after 30 s. The main reason is that the step water falling flow occurs around the impedance holes (Figure 6).

![Histories of parameters during the start-up process (CFD)](Figure 5)
Figure 6. Comparison of flow patterns in the model test and numerical simulation

Figure 7 shows the evolutions of flow patterns during the start-up process. At the initial stage of the start-up process, the valve at the outlet opens rapidly in 2.29 s. The discharge in the diversion tunnel cannot meet the demand of load change immediately due to the inertia, forcing a sharp drop of water level in the surge tank. Because of the large aspect ratio of this LCSST, the water level only drops sharply around the impedance hole and gate which are connected to Unit 2. As a result, a new water level difference between the upstream reservoir and surge tank forms rapidly and speeds up the change of discharge in the diversion tunnel. The water falls from the floor, and collides with each other, and breaks into droplets, then gets involved in the air into the penstock, which endangers the normal operation of the unit (Figure 8). Then, due to the large water level difference between the upstream reservoir and surge tank, the discharge continues to increase and exceeds the operation needs of the turbine, pushing the water into the surge tank and causing water level fluctuations. After the discharge is relatively stable, accompanied with the water level, there are still longitudinal fluctuations in the surge tank but the amplitude is small and decays rapidly because of the shallow depth of water.

In the decline process of water level (Figure 5 (b)), it can be found that the water above the bottom plate has little supplementary effect on the flow demand, especially at the left end of the surge tank, because the floor has no gradient. It shows that bottom plate with no gradient in this case cannot be effectively utilized during start-up process, which should be modified to guarantee that flow at the left end can replenish the discharge demand in time.

Figure 7. Typical flow patterns during the start-up process
5. Flow characteristics of the optimized surge tank structures

5.1. The proposed optimized surge tank structure

Because of the serious rolling in the steady condition, the wave breakages in the load rejection process, and the step water falling and air-trapped vortices in the start-up process, the original scheme is not in line with the actual projects and needs to be modified.

In order to alleviate the serious rolling in steady condition, two circular impedance holes are merged to one, which is moved to the root of the bifurcation (Figure 9).

In order to eliminate the wave breakages and avoid unfavorable involving air into penstocks, the bottom plate step is cancelled by a slope. As shown in Figure 9, the bottom plate elevation near the impedance holes is reduced, with no change at the other side.

5.2. Simultaneous load rejections of two units

The water level fluctuations in LCSSTs during transient processes are mainly affected by two factors: one is the fluctuation between surge tank and upstream reservoir, and the other is in surge tank due to its large length-width ratio. Existing researches [11,12] show that the longitudinal oscillation amplitude is closely related to the volume of water in surge tank. In the optimized scheme, the adjustment the bottom plate increases the volume of the water in surge tank, leading to the more obvious longitudinal oscillation. (Figure 10 (b)).

For the flow patterns (Figure 11), the degree of water rolling above the impedance holes in stable condition has been alleviated, and the inhomogeneity of water level during the load rejection process is obviously improved compared with that of the original scheme. And it can be clearly seen that the flow
velocity in surge tank is very small, and there is no intense uneven flow above the impedance holes and wave breakages, which can guarantee the safety of side plates of surge tank.

(a) History of discharge in diversion tunnel
(b) Water level fluctuations in surge tank

Figure 10. Histories of parameters during simultaneous load rejections of two units

(a) Model test results
(b) Numerical results

Figure 11. Stable flow patterns above the impedance hole in the steady condition for the optimized scheme

Figure 12. Typical flow patterns during load rejection process for the optimized scheme

5.3. Start-up process of unit 2 during normal operation of unit 1
In the start-up process, the fluctuations of water level and discharge in the optimized scheme is relatively simple (Figure 13). After experiencing large fluctuation before 30 s, the water level stabilizes in a short time, and the lowest water level is much higher than that of original scheme, which also has obvious effect on eliminating the air-trapped vertical vortices.
Figure 13. Histories of parameters during start-up process for the optimized scheme

(a) Water level fluctuations at monitoring point 1 (b) Water level fluctuations at monitoring point 2

Figure 14 shows the typical flow patterns during the start-up process. At the initial stage, no abnormal hydraulic phenomenon in the surge tank, and the water level drops smoothly. However, during this time, the inclined floor appears out of the falling water surface due to excessive discharge, therefore the fluctuation period between the upstream reservoir and surge tank also does not satisfy the Equation 1. In addition, unlike the original scheme, the optimized scheme has no air involved into the penstocks, and the water level near the gate slots and impedance hole decrease steadily to ensure the safe operation of the units.

Figure 14. Typical flow patterns during start-up process

6. Conclusions
In this paper, 3D CFD simulations of surge tank waves and flow patterns during the load rejection and start-up transient processes of a model hydropower system are presented. The water level fluctuation characteristics in the long-corridor-shaped surge tank are similar to those in open channels. In the case of shallow water, the open channel waves propagate from one end to the other, and obvious wave breakages generate after hitting the wall at the end. In addition, air-trapped vortices may occur at the gate and impedance holes, and even may be involved into the penstocks. But for the deep indoor water, the main performance is that the oscillations at the two ends of the tank have a phase difference, reflecting the water sloshing.

In the original scheme, the bottom plate of surge tank is a not inclined type with step, therefore, not only the vortices at the gate and impedance holes, and higher wave breakages are prone to occur, but also the water fall near the step is difficult to control. However, the optimized scheme eliminates the
step and modifies the bottom plate into the slope one, contributing to the disappearance of the water fall and other harmful phenomena due to the deeper water depth.

To sum up, the design criterion is to deepen the minimal water depth as far as possible, and the bottom plate should have a certain slope. Also, distributing the gate and impedance holes and the reducing influences of gate walls on main flow should be payed attention to.

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8. References
[1] Popescu M, Arsenie D and Vlase P 2003 Applied hydraulic transients for hydropower plants and pumping stations CRC Press.
[2] Cheng J S 2005 Transients of hydraulic machinery Beijing: Higher Education Press 7-10.
[3] Kim S H 2010 Design of surge tank for water supply systems using the impulse response method with the GA algorithm J. Mech. Sci. Technol. 24 629-636.
[4] HOUDE S, PAGEÉRIC M and MAINVILL E 2007 Numerical investigation of the dynamic behavior of surge chamber under normal operating conditions 2nd IAHR International Meeting of the Work Group on Cavitation and Dynamic Problems in Hydraulic Machinery and Systems. Timisoara, Romania 10 24-6.
[5] Xia L S, Cheng Y G and Zhou D Q 2013 3-D simulation of transient flow patterns in a corridor-shaped air-cushion surge chamber based on computational fluid dynamics J. Hydrodyn. 25 249-257.
[6] Cai F, Cheng Y G, Xia L S and Jiang Y Q 2017 Mechanism of air-trapped vertical vortices in long-corridor-shaped surge tank of hydropower station and their elimination J. Hydrodyn. 29 845-853.
[7] Wu J, Yang J D 2008 Three-dimensional Flow Field Analysis of Erect Swirl in Strip-shaped and Restricted-orifice Surge Chamber Water resources and power 26 105-107.
[8] Deng S Y, Zhang J and Cheng Y G 2009 Flow Characteristics of long corridor-shaped surge tank and elimination of the air-entraining vertical vortices: CFD simulation and analysis Shuili Fadian Xuebao/Journal Hydroelectr. Eng. 28.
[9] Tang X L, Wang F J and Li Y J 2011 Numerical investigations of vortex flows and vortex suppression schemes in a large pumping-station sump Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science 225 1459-1480.
[10] Keshavarzi G, Yeoh G H and Barber T 2013 Comparison of the VOF and CLSVOF Methods in Interface Capturing of a Rising Bubble The Journal of Computational Multiphase Flows 5 43-55.
[11] Hu M, Cai L F, and Zhou J X 2002 Experimental study on hydraulic dynamic characteristics of tailrace system of Xiluodu hydropower station Water resources and hydropower engineering 3 11-13.
[12] Liu J X 2015 Study on surge wave of impedance surge chamber of hydropower station during load rejection Science and Technology 10.