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Study of surge phenomena in a hydropower plant: A numerical approach

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Abstract

Sudden closure and opening of valves might cause unwanted water hammering effects in hydropower plants. In many cases, surge shafts are used as pressure neutralizers to dampen out the generated pressure pulsations. This study focuses on analyzing the surge phenomena and effects of using simple surge and restricted orifice surge on the flow behavior during the closing and opening of turbine inlet valves. A case of a Nepalese hydropower plant was taken and calculations were done over a simplified water transportation system of the plant. Analytical result was compared with the result obtained from an open-source CFD toolbox, OpenFOAM. A 3D fluid domain was made in SolidWorks and the mesh was created using snappyHexMesh utility of OpenFOAM. This study uses a multiphase solver called interFoam with the implementation of κ-ω SST turbulence model. The analytical result for maximum increase in water level in the surge shaft was calculated as 18.68 meters assuming a case of U-tube oscillation. The calculations neglected the presence of penstock pipes and assumed instantaneous closure thus giving a maximum value for upsurge height. Similar physical condition was recreated in OpenFOAM but with the presence of penstock, and a change in surge height with respect to time was analyzed. The obtained CFD result showed the average water level height in surge shaft to be 11.23 meters, which is less than the analytical result as expected. Then, the time of closure and time of opening were increased to 6 seconds and 30 seconds respectively and the effect of surge with and without orifice were visualized with respect to mass oscillations, pressure inside penstock and velocity of water in headrace tunnel. The numerical techniques used in this study can be applicable to other hydropower plants, which could provide a basis for the verification of the analytical designs.

Keywords: Surge; Mass oscillations; OpenFOAM; interFoam

1. Introduction

The surge tank is a crucial component of a hydropower which is designed to protect the conduit system from high interior pressures. It is required to reduce the effect of water hammer due to the pressure change in closed pipes, particularly produced by the rapid opening and closing of valves. The sudden acceleration or deceleration of water mass creates a pressure wave, which affects the structural integrity of the penstock pipes. The surge tank is made such that it brings the free water surface near to the turbine inlet, which reduces the effect of the produced pressure waves. It also works as a reservoir to supply or store extra water during load acceptance or rejection until the conduit velocity has converged to the new steady state value. According to the Indian Standard for hydraulic design of surge tanks [1], there are three different types of surge tanks, which are Simple surge tank, Restricted Orifice Surge tank and Differential Surge tank. In this paper, the difference in performance of simple surge tank and restricted orifice surge tank is visualized.

The complexity and importance of surge phenomena in a hydropower requires an extensive study and research for its safe operation. Consequently, there have been a lot of researches and study regarding the hydraulic transients. One of the oldest work on surge tanks was done by Shima et al [2] to analyze the role of restricted orifice in a surge tank for the case of rapid closure of gate. They carried out experiments on water hammer phenomena, and compared between theoretical and experimental water hammer waves. Their experimental results showed that the effect of the restricted-orifice surge tank changes rapidly as the orifice area is reduced below a certain percentage of the conduit area which is dependent upon the ratio of initial flow velocity to the velocity of the wave. In 2013, a theoretical study has been carried out by Ramadan et al. [3] based on some design considerations for a surge tank. They solved a system of non-linear Ordinary differential equations with the help of a FORTRAN 77 program to observe the effects of surge tank cross-sectional area and friction losses coefficient on the water mass oscillations and total discharge. With the results, they concluded that increasing cross- sectional area of the surge shaft and friction losses coefficient causes the decrease in first upsurge water level and discharge rates. Also, they observed that the height of the pressure waves and fluctuations are reduced with the increase in the above parameters.

Similarly, another study was done to analyze the orifice surge tank using RK-4 method with MATLAB [4] , in which the similar results were obtained with respect to the changes in surge shaft cross-sectional area and friction coefficients of pipe walls. Additionally, it was noticed that the dampening effect of orifice friction coefficient was more remarkable than friction coefficient of pipe walls. It was seen that the wave damping in case of orifice surge tanks is remarkably small. Another work was done by Moghaddam [5] trying to derive a general solution for the oscillations in a simple surge tank in terms of non-dimensional parameters. In that study, the equations for maximum and minimum surge height with their corresponding time of occurrence were obtained and an equation for the surge oscillation was found.

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One another study was done to determine the analytical expressions of the worst superimposition time of surge waves in different combined operating conditions using the basic equations of surge analysis and nonlinear vibrational asymptotic method [6]. They verified the analytical solutions with the numerical simulation results and concluded that the analytical approach for determining extreme water levels in surge tank are correct due to good coherence with the numerical results. An optimization based study [7] was performed to develop a general model for the optimal design of hydropower tunnels and surge tanks employing the Genetic Algorithm technique. Considering the benefit cost ratio as the objective function in the optimization analysis, the optimal diameter for the headrace tunnel, penstocks and surge tanks were obtained, that resulted in considerable savings in construction cost.

Similarly, another study by Kendir et al [8] attempted to derive an optimized surge tank form to reduce the cost of a hydropower plant. They used two different methods, namely characteristic and finite difference methods to determine the optimum tank configuration. With their study, it was found that a straight V-type surge tank inclined by 2 degrees was the optimum configuration. The results were verified using the results from an experimental model and were found to be in agreement. A different study was done by Amara et al [9] implying a finite element technique to compute the mass oscillations in surge tank. Various weighting functions, point collocation, subdomain collocation and Galerkin's method were tested and compared. The results showed that the suggested numerical approach leads to the correct simulation of motion of the water surface. Some site specific studies were also performed with respect to surge tank. One of them is the study by Nabi et al [10] where they analyzed the hydraulic design of surge tanks for surge wave height and time to dissipate under the conditions of complete closure and complete opening for two probable sites in Pakistan. With the results, they recommended suitable surge tank system for the two hydropower stations.

From the literature study, it was found that substantial amount of work has been done in the analytical calculations and numerical study of surge behavior in hydropower. A few studies have also been done with the CFD analysis, particularly with commercial CFD codes like ANSYS CFX ([11], [12]). This indicates the importance of the study of surge phenomena for a hydropower station. Nepal, being a country having an enormous potential for Hydropower, has a lot of scope for the study of such surge tanks in different potential sites. Hence this paper develops a methodology to investigate the design and performance of surge tanks using an Open source CFD toolbox, OpenFOAM. A geometry pertaining to a Nepalese hydropower plant was taken and fluid analysis was performed. The results of numerical simulation were validated with the analytical results for instantaneous opening and closure of valve gates. Then, the effect of using simple surge shaft and orifice restricted surge shaft on the pipes was visualized with increased opening and closure times.

2. Materials and method

2.1. Geometry

The data for total head, flow rate, and geometry of head-race tunnel and penstock for a potential Nepalese hydropower was considered. Based on the dimensions, a 3D geometry for the whole water transportation system including headrace tunnel and penstock pipe was prepared in SOLIDWORKS. For the dimensioning of surge tank, the Thoma criterion was used with the parameters as shown in Fig. 1. It is used in initial dimensioning of all surge tanks [13].

According to the Thoma criterion, for stability,

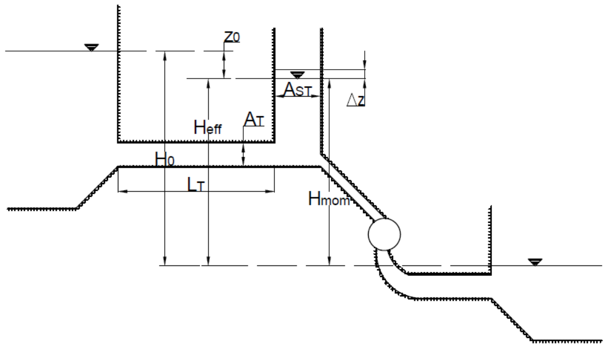

Figure 1: Schematic of Hydropower plant with parameters as defined by Thoma [13].

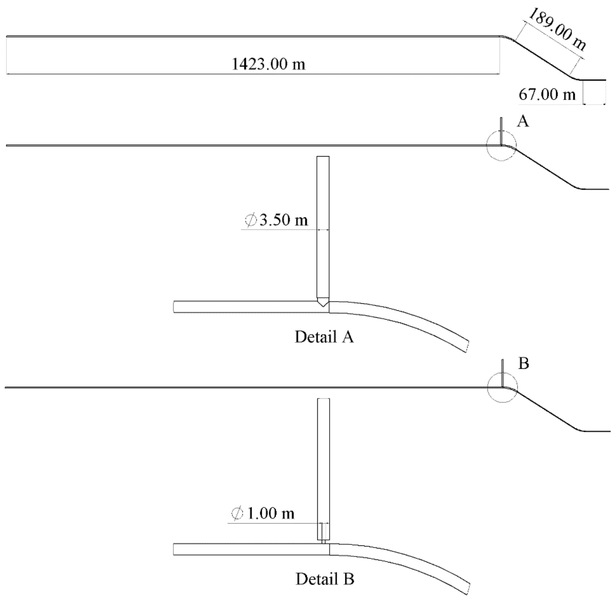

Figure 2: Computational geometries: without surge (upper); with simple surge (middle); restricted orifice surge (lower).

$$A_{\text{ST}} \geq \frac{A_T L_T}{2g\alpha H_{\text{eff}}} \tag{1}$$

Where A_{ST} = Area of surge tank
A_T = Area of tunnel
L_T = Length of tunnel
g = Acceleration due to gravity
α = Loss coefficient
H_{eff} = Effective head of water

Neglecting the losses, α = 1, the effective head of water equals to total head of water, i.e. $H_{\text{eff}} = H_o$

Then, keeping a factor of safety of 2 with the calculated area from eq. (a), the diameter was approximated as 3.5 meters and the surge tank was added to the geometry. Also, to observe the effects of orifice, an orifice plate with diameter 1 meter was added in another geometry.

So, altogether, three geometries were prepared for surge analysis, one without surge, and other two with simple surge tank and restricted orifice surge tank as shown in Fig. 2.

2.2. Analytical calculations of first upsurge after closing

The upsurge and down-surge heights can be estimated using the equations for the U-tube consisting of reservoir and shaft. The mass oscillation equations (rigid water column theory) for a flow Q_T through the turbine are [14]:

$$Q_S = Q - Q_T \tag{2}$$

$$\frac{\mathrm{dz}}{\mathrm{dt}} = \frac{Q_S}{A_{\mathrm{ST}}} \tag{3}$$

$$\frac{L_T}{gA_T}\frac{\mathrm{dQ}}{\mathrm{dt}} = -\Delta z - \frac{K}{2g\,A_T^2}Q\,|Q| - J_{\mathrm{CS}} - \frac{Q_S^2}{2g\,A^2} \tag{4}$$

Where Q_S = Flow rate in surge tank
Q = Flow rate through reservoir
Q_T = Flow rate to turbine
K = Tunnel Loss coefficient
J_{CS} = Junction Loss coefficient

Similarly, the continuity equation for connection between shaft and tunnel is given by:

$$A_{\mathrm{ST}}\frac{\mathrm{dz}}{\mathrm{dt}} = Q_S \tag{5}$$

The last term in equation (d) represents the velocity head due to flow of water in surge shaft. For maximum and minimum levels in the surge shaft, the velocity of water in the surge shaft is zero. So, neglecting the velocity head and losses, equation (d) can be simplified into:

$$\frac{L}{gA_T}\frac{\mathrm{dQ}}{\mathrm{dt}} = -\Delta z \tag{6}$$

For the turbine closure, $Q_S = Q$ since $Q_T = 0$

Assuming instantaneous closure for simplicity, $dQ = -Q,\ dt = \Delta t$ and $dz = \Delta z$

Then, from equations *(e)* and *(f)*, we obtain the maximum surge height,

$$\Delta z = \pm \Delta Q\sqrt{\frac{L/A_T}{gA_{\mathrm{ST}}}} \tag{7}$$

The positive sign gives the maximum upsurge during instantaneous closing and the negative sign gives maximum down-surge during instantaneous opening. This value neglects the penstock length i.e. considers the valve to be right after the surge shaft.

For the geometry used in this study, the maximum upsurge/down-surge for instantaneous closing/opening is calculated as 18.68 meters. However, when a certain delay is given for the valve closure and opening time, the upsurge/down-surge height decreases. Also, the height decreases due to the distance of valve from the surge, which is penstock length.

2.3. Meshing

OpenFOAM meshing utility snappyHexMesh was used to prepare the mesh for the 3D geometry. The snappyHexMesh utility is used to generate a 3D mesh automatically from triangulated surface geometries in Stereo-lithography (STL) format [15]. The blockMesh utility of OpenFOAM was used to create the background mesh for snappyHexMesh. Then, the stl files of the geometry surfaces saved from SolidWorks were used by snappyHexMesh to approximately conform the mesh to the required surface. Two meshes were prepared, one with 215K cells and the other with 400K cells. Upon analysis of the first down-surge height after opening, both the mesh produced similar results. So, for all the cases, the mesh with 215K cells have been used to save the computational time and cost.

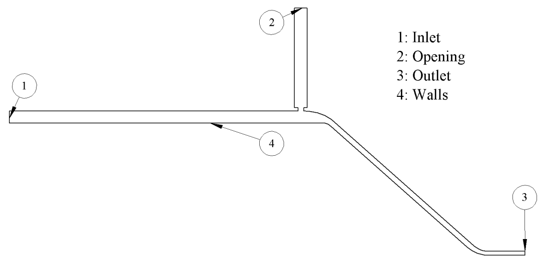

Figure 3: Boundary conditions in surge geometry (not in scale).

2.4. Physical parameters

All the simulations carried out were done by considering multiphase condition with two phases, air and water as done by CFD based studies of surge [11] and [12]. In case of OpenFOAM, there isn't any generic solver for all the cases. Instead, the users have to choose a suitable solver which matches with the physics of the case. One such solver is interFoam which solves fluid problems including two incompressible, isothermal and immiscible fluids using a VOF (Volume of Fluid) based multiphase approach [16]. It matched with the two-phase physics to be solved in Surge tank simulation. So, interFoam solver was used in this study with κ–ω SST turbulence model. The same turbulence model was also used in studies [11] and [12]. The density and kinematic viscosity of air and water were defined for a temperature of 20°C as 1000 kg/m^3, 1e-06 m^2/s and 1 kg/m^3, 1.48e-05 m^2/s respectively. Similarly, a surface tension coefficient was defined as 0.072 N/m, which is the surface tension between air and water at 20°C. Also, all the simulations were done under the influence of gravity. Owing to the used co-ordinate reference of the geometry, gravity was defined as -9.81 m/s^2 in positive Y direction.

2.5. Boundary conditions

The boundaries in the computational domain were taken as inlet, opening, outlet and walls as shown in Fig. 3. The upstream end of the headrace tunnel was treated as an inlet patch, since it acts as the inlet of water from the reservoir to the considered domain. The inlet patch was given a totalPressure boundary condition with a value of 222883.2 Pa representing the head of the reservoir from the tunnel inlet, which was taken as 22.72 meters. The value of water volume fraction at inlet patch was defined to be a fixed value of 1 since only water flows in and out of the patch.

The upper end of the surge tank was named opening since it's an opening to the atmosphere. The opening patch is given a zero totalPressure boundary condition. The water volume fraction was defined with an inletoutlet boundary condition with value 0, which means that outside the patch, there is air. Also, the patch is given a pressureInletOutletVelocity boundary condition, which applies zero gradient condition for outflow and a specified velocity for inflow which is zero as defined in Table 1.

Similarly, the inlet to the turbine or the end of the penstock pipe was named outlet as it is outlet for water from the computational domain considered. The outlet patch was given a variable flowrate boundary condition, where the flow rate of water changes with time corresponding to the closing and opening of valves. The flowRateInletVelocity boundary condition was given with volumetric flow rate defined as a table (Table 1). With the table, the flow rate was defined as 0 m^3/s from 0 to 100 seconds and the out-flow rate was increased linearly to 8.4 m^3/s from 100 to 130 seconds, keeping 30 seconds as valve opening time. And, steady out-flow rate of 8.4 m^3/s was continued up to 6000 seconds, which was reduced to 0 m^3/s linearly in 6 seconds of closure time. Finally, the 0 m^3/s flow rate was kept up to 12000 seconds in order to stabilize the water level in the surge shaft. In order to compare with the analytical result, one simulation was performed with a simple surge tank with instantaneous opening/closure effect by putting the time of opening/closing as 0.1 seconds. Similarly, the outlet patch was given inletOutlet boundary condition for water volume fraction and zero gradient condition for pressure.

Finally, all the walls of headrace tunnel, penstock and surge shaft are named as walls. The walls are treated as rigid and are given a no slip boundary condition, but without friction to simplify the case. The patch is given a zero gradient boundary condition for water volume fraction and fixedFluxPressure boundary condition for pressure which sets the pressure gradient to the provided value, zero such that the flux on the boundary is that specified by the velocity boundary condition.

2.6. Calculation method

All the simulations performed were transient with total simulation time of 12000 seconds. The transient nature of the simulation is due to the varying outlet flow rate as defined in Table 1, corresponding to the opening and closing of valve at turbine inlet. The time-step of the transient simulation was set as adjustable to maintain a Courant number of 10. Also, a simulation was performed with Courant number 1, and the value of maximum first down-surge was compared. It was observed that the values obtained with both the cases were not significantly different for the prepared mesh. Hence, for saving computational time and cost, a Courant number of 10 was used in all simulations performed. The simulations were carried out using a HPC, parallelly on 12 nodes, decomposed using hierarchical decomposition method. Each simulation required approximately 24 hours of time for completion.

3. Results and discussion

For the post processing, function objects were defined in controlDict dictionary inside system folder of the case directory. Function objects of different types like volFieldValue, probes and surfaceFieldValue were defined to write the values of total liquid volume in the domain, pressure and velocity values at specified points inside the domain and flow rates at inlet and outlet patches. The time-step folders of only some time-steps were observed in Paraview to visualize the streamlines, velocity vector and contours of different field variables.

The first simulation was performed with simple surge with instantaneous opening and closure. The results of the simulation gave maximum down surge height of 11.40 meters during opening and maximum upsurge height of 11.05 meters during closing. These values are less than the analytically calculated upsurge/down-surge height value, as required. Then, time of opening and closing were increased and results were observed and compared.

3.1. Surge analysis

Graphs were plotted between different field variables and derived variables in order to visualize the time development of the flow characteristics inside the closed pipes with and without surge.

The time evolution of water flow rate through the inlet and outlet patches of the domain throughout the simulation time of 12000 seconds is shown in Fig. 4. The case in Fig. 4 was for a surge geometry with orifice, but it can be taken as the general representation of the flow rate pattern observed in the presence of surge shaft. The lagging of the flow continuum at the inlet from the outlet of the domain can be seen in Fig. 4. When there is sudden closing and sudden opening at the outlet, the flow rate at the inlet cannot accommodate itself fast enough, which creates the fluctuations. To

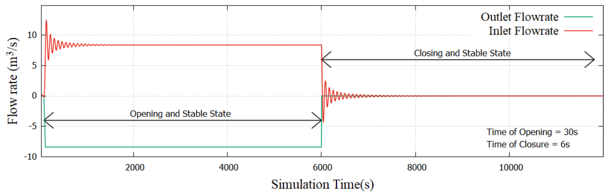

Figure 4: Graph explaining opening and closing regions.

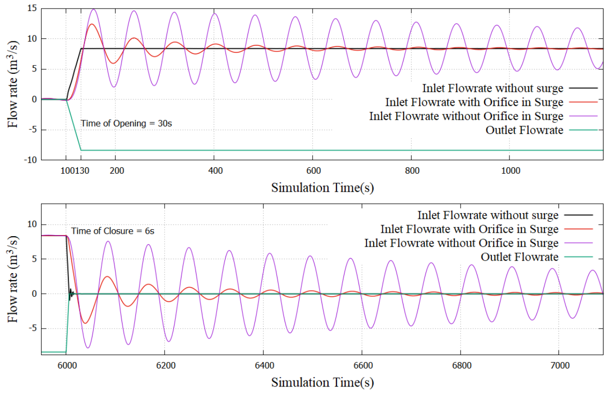

Figure 5: Inlet flow rates during opening (upper) and closing (lower).

have a closer look into the effects, the values of flow rates during opening and closing were plotted separately.

The inlet flow rates at different conditions of surge with the defined outlet flow rate during the opening and closing condition of turbine inlet valve are shown in Fig. 5. It was observed that the inlet flow rate is almost similar to the outlet flow rate when there is no surge, which is justified since there cannot be any void inside the domain. However, when surge was provided at the end of the headrace, the oscillations started appearing in the values of inlet flow rates as discussed earlier. It was also observed that the oscillations are dampened out faster in the case of surge tanks with orifice.

In Fig. 6, the mass oscillation in a surge shaft with and without orifice have been shown. A clear distinction between both the cases can be seen, as the orifice kept at the bottom of the surge shaft restricts the flow of water in and out, which reduces the mass oscillation from the simple surge shaft case. The maximum upsurge after closing of the gate is reduced from 10.7991m to 7.9429m with the use of orifice.

In Fig. 7, the mass oscillation effect in opening and closing cases are shown separately. It was observed that the maximum upsurge after closing of the valve is higher than the maximum down-surge after opening of the valve. It is because of the reason that the time of closure of gates is smaller than the time of opening of the gates. Also, like flow rates, the mass oscillation in surge tank was also damped more quickly in surge tanks with orifice.

Similarly, the pressure value at a point in Headrace tunnel under the surge shaft was observed, which is shown in Fig. 8. It was observed that, in case of pipe flow without surge, the pressure change

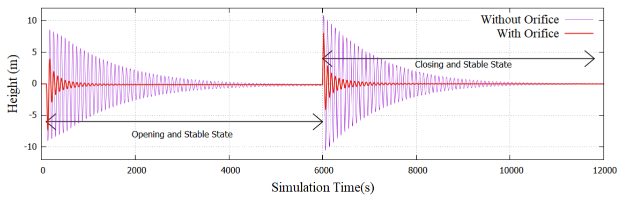

Figure 6: Up-surge heights in surge shaft with and without orifice.

Table 1: Boundary Conditions used in OpenFOAM simulation.

Boundary	alpha.water		p_rgh	
inlet	fixedValue	1	totalPressure	222883.2
opening	inletOutlet	0	totalPressure	0
outlet	inletOutlet	0	zeroGradient	-
walls	zeroGradient	-	fixedFluxPressure	0
Boundary	**U**			
inlet	zeroGradient	-		
opening	pressureInletOutletVelocity	(0 0 0)		
outlet	flowRateInletVelocity	volumetricFlowRate table (		
			(0 0)	
			(100 0)	
			(130 -8.4)	
			(6000 -8.4)	
			(6006 0)	
			(12000 0)	
		);		
walls	fixedValue	(0 0 0)		

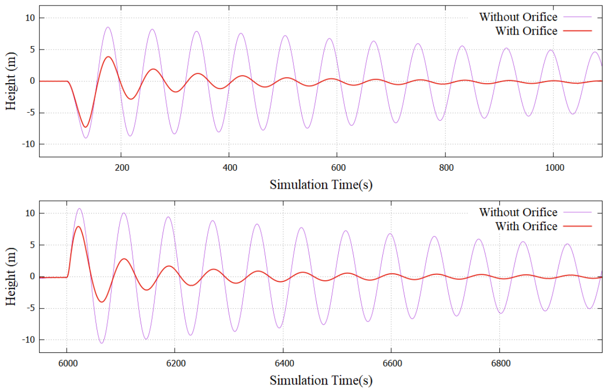

Figure 7: Upsurge heights in the surge shaft during opening (upper) and closing (lower).

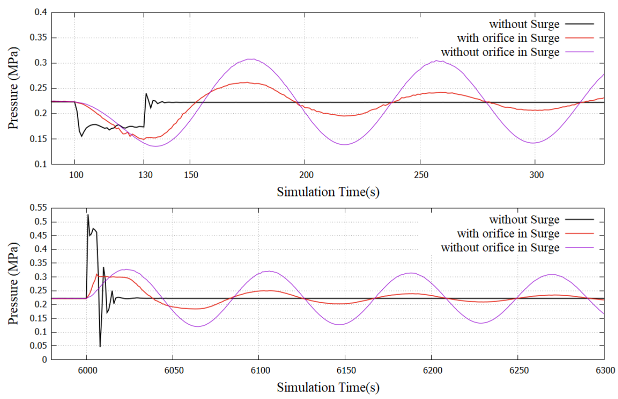

Figure 8: Pressure at a point in Headrace tunnel below the surge shaft during opening (upper) and closing (lower).

at the point during opening and closing is discrete rather than continuous and higher than cases with surge. It was noticed that the pressure change is oscillatory but smoother when there is a surge in the domain. This is how surge shafts protect the penstock pipes from pressure pulse, by dampening the pressure waves. While comparing the cases with and without orifice in the surge shaft, the orifice had a similar effect on pressure like the mass oscillation and flow rate, which is the dampening with time.

The discrete nature of field variable in case of absence of surge tank can also be observed in case of velocity in the headrace tunnel, as shown in Fig. 9. The discrete development of velocity signifies the sudden acceleration and deceleration, which is the reason of water hammering in pipe flows. As the cases with flow rate, mass oscillation and pressure, the orifice in the surge shaft dampens the oscillation faster than the simple surge shaft with no restricted orifice.

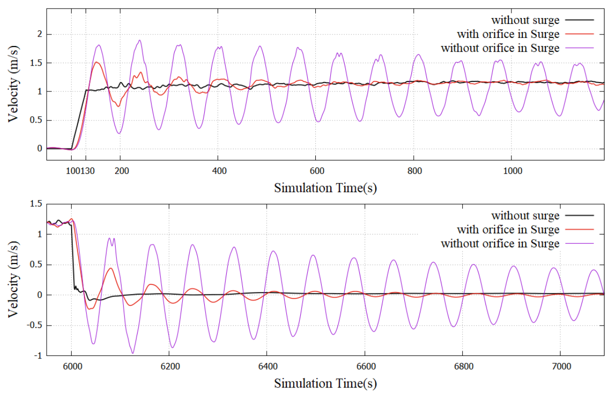

Figure 9: Water velocity 200 m upstream of surge shaft during opening (upper) and closing (lower).

3.2. Flow visualization

The velocity vector plots and contours of water volume fraction at the surge shaft were visualized using Paraview. The difference in flow to the surge shaft with and without orifice can be observed from Fig. 10. It can be seen from Fig. 10 (a) that the water in headrace tunnel haven't started moving although the gate is partially open at the end of the penstock, so the water flows down from the surge shaft. Similarly, it can be seen from Fig. 10 (b) that the water

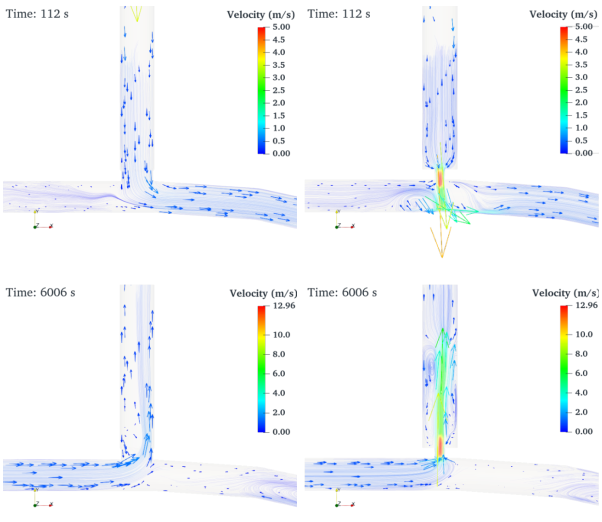

Figure 10: Velocity vector plot in simple and restricted orifice surge tank during opening (upper) and closing (lower).

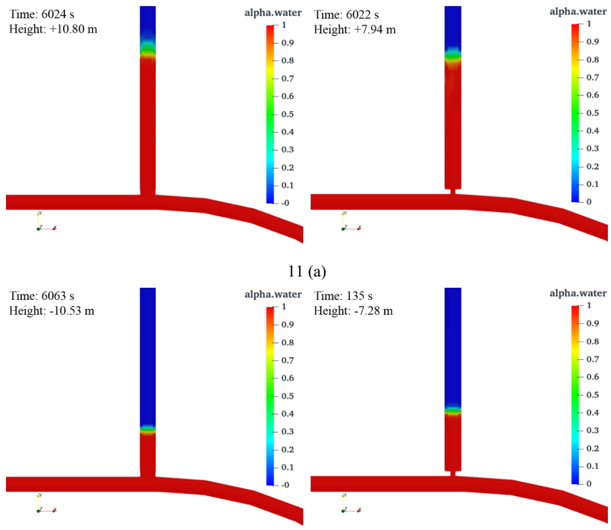

Figure 11: Water volume fraction contour showing maximum upsurge (upper) and down-surge (lower) in simple and restricted orifice surge tank.

from headrace tunnel still possess velocity although the gate at the outlet is already closed, so the water flow towards the surge shaft through the junction. It can be clearly observed the restriction to the flow that is created due to the presence of the orifice. This is how the orifice dampens the oscillations faster than the case with no orifice.

The maximum upsurge and the maximum down surge in the shaft with orifice was found to be less than the shaft without orifice as shown by Fig. 11. It is because of the restriction caused due to orifice. The maximum upsurge height of 10.80 meters was obtained in the simple surge shaft after closing at 6024 seconds and for the restricted orifice surge shaft, the maximum upsurge height of 7.94 meters was also obtained after closing of valves at 6022 seconds. Similarly, the maximum down surge of 10.53 meters was obtained for the simple surge shaft at 6063 seconds after the maximum upsurge had occurred during closing. But for the restricted orifice surge tank, the maximum down surge of 7.28 meters was obtained at 135 seconds after the valves were opened. In case of restricted orifice surge tank, the second down surge after closing is not the maximum down surge because the orifice dampens the mass oscillations very quickly. So, the first down surge after opening at 135 seconds is the maximum down surge in the case with restricted orifice.

4. Conclusion

In this paper, a numerical study of surge phenomena in hydropower plants has been performed using OpenFOAM which is an open source CFD code. The effect of using surge tank with and without orifice is studied with a simplified 3D geometry identical to a Nepalese Hydropower plant. The diameter of surge tank was calculated using Thoma stability criterion and an analytical solution was obtained as 18.68 meters for the maximum possible upsurge/down-surge for a case of instantaneous closure/opening. With the numerical analysis in OpenFOAM, the upsurge/down-surge values during instantaneous closure/opening were obtained as 11.05 meters and 11.40 meters, respectively. The numerically obtained values were less than the analytical value due to the considerations of penstock length, which was neglected in analytical calculations. Then, numerical simulations were performed in OpenFOAM by increasing the time of opening to 30 seconds and time of closure to 6 seconds. The increased time of closure and opening showed reduced values of mass oscillations, upsurge height and pressure fluctuations. Also, the cases without surge, with simple surge and with restricted orifice surge were compared. And, it was observed that if surge isn't used, then during sudden acceleration or deceleration of water caused due to closure and opening of turbine inlet valve, water hammering effect appears with a sudden increase in pressure inside the penstock pipe. When surge pipes were provided, such pressure waves were dissipated with damped mass oscillation. The use of orifice in the surge shaft increased the damping of those oscillations.

This study lays a foundation for the future research on the numerical analysis of surge phenomena in a hydropower using OpenFOAM. The methodology applied in this study can be implemented in commercial projects to validate the design with the open source free CFD code. Future works can be continued in order to validate the numerical results with experimental results. Also, the effect of area of orifice on the dampening effect can be studied with the use of OpenFOAM.

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