Proceedings of 11th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2022 Month: March Volume: 11

Numerical Analysis of Manifold: A Case Study of Phukot Karnali Hydroelectric Project

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Abstract

Numerical analysis is widely used in designing, optimizing, and predicting the influence of different parameters where geometry, load, and materials are complex. The need for this analysis is significant in the design of penstock branches because they have been designed by classical approaches. The classical design philosophy reduces chance of having the least head loss and better structural strength. In this study, computational simulations have been performed to study hydraulics and structural strength in manifold of Phukot Karnali Hydroelectric Project (480 MW). The head loss, velocity distribution, pressure distribution, deformation and stress in manifold are observed. For hydraulic analysis, effects of branch angle, cone length and sickle plate are studied. Results show that head loss is decreased with the reduction of branching angle and cone length. The best branching angle is computed to be 30° and best cone length is 9 m. Optimized manifold profile is created with best branch angle, best cone length and sickle plate. Head loss in the optimized profile at outlet-1, outlet-2 and outlet-3 is computed to be 0.13 m, 0.46 m and 0.31 m, respectively. The optimized case is compared to base case. The manifold profile designed by NEA Engineering Company is considered as base case. It is found that head loss is decreased in optimized case by 37 %, 15 % and 24 % at outlet-1, outlet-2 and outlet-3, respectively. For structural analysis, maximum stress near branches of optimized manifold profile is checked. For this, manifold is divided in two parts: first bifurcation and second bifurcation. Initial pipe thickness is provided as 60 mm at first bifurcation and 50 mm at second bifurcation. The provided pipe thickness is insufficient to meet allowable stress criteria. Thickness of pipe is increased for better structural strength. Equivalent (von-Mises) Stress at first bifurcation with 130 mm thick pipe and second bifurcation with 70 mm thick pipe is 166 MPa and 161 MPa, respectively for which allowable stress is 167 MPa.

Keywords

Bifurcation, Deformation, FVM, FEM, Head loss, Manifold, Sickle Plate, Stress

1. Introduction

Manifold is the region in closed conduit flow that combines or divides conduits. Profile of penstock manifold affects net head for power generation [1]. Different model tests were carried out in manifolds and wyes to determine head losses. First detailed experimental study of head loss coefficients using cylindrical sharp-edged, cylindrical-rounded and conical transitions with different branch angles and diameters was carried out at the Institute of Hydraulic Research of Munich Technical University from 1928 to 1931 [2]. Head loss decreased significantly with the decrement in branch angle and conical transition at 13° was regarded as best cone angle. Laboratory tests were done in manifold with 45°, 60°, and 90° branches by inserting and removing an internal tie rod [3]. It was found that coefficient of head loss depended on ratio of flow in branch pipe to main pipe, size of tie-rod and subtending angle. Numerical analysis was also used in the study of manifold layout and geometry of branches. Malik and Paudel (2009) [4] performed 3D flow modeling in the trifurcation of 3.2 MW Madi Khola Hydro power Project. They choose best manifold profile for which energy loss is 0.42% after performing analysis on 20 models.

Arrangement of branches within manifold also affects hydraulic behavior. Kandel and Luitel (2019) [1] compared three types of branching manifolds in Solu Khola DudhKoshi Hydro power Project. They selected trifurcation as best manifold profile based on least head loss and least mass flow variation. Thapa et al. (2016) [5] changed the shape of bifurcation by changing flair angle and replaced top edge by curved section in Kulekhani III Hydro power project. They concluded that head loss can be reduced as the branch geometry in the manifold improved. It was found that coefficient of head loss decreased from 0.44 to 0.21.

Turbulent flow can be studied either with experimental analysis or numerical analysis. Numerical analysis have become very popular in understanding fluid flow and stresses induced in the wall containing fluid flow. Dhakal et al. [6] used this method to compare the maximum power generation of cylindrical and conical basins in gravity water vortex power plant, Wong et al. [7] used different numerical models to predict the flow pattern, velocity distribution, and turbulence intensity distribution when a cylindrical pipe suddenly expands for diesel to flow, Bajracharya et al. [8] did numerical modeling to study the abrasive behavior of sand flow with the nozzlle-niddle surface of Pelton turbine. Various softwares can be used to solve turbulence using different modeling methods: Detached Eddy Simulation (DES), Large Eddy Simulation (LES), Reynolds-Averaged-Navier–Stokes (RANS), hybrid LES/RANS [9]. However, the computing power developed upto now is not enough to directly solve turbulence under high Reynolds number. Therefore, simulation should be run at a low Reynolds number, or Navier Stokes (NS) equation that governs flow should be averaged. RANS simulation is found to have best quantitative results in the circular pipe of fully developed turbulent flow with the least cost of CPU [10]. Thus, flow near branches in the penstock can be studied with RANS based turbulence model. Hydraulic behavior in the manifold can be monitored with numerical analysis by creating different models.

Along with being hydraulic efficient profile, strength in the manifold is necessary to withstand water pressure. The failure of penstock is disastrous to project cost and human life. Branches are again more sensitive because it is welded and fabricated on site [11]. Stress analysis near branches is very difficult by hand calculation. It is recommended to use advanced computational method to check stresses under various consequences [12].

Most studies of penstock branches are based on wye analysis, with the least studies of manifolds. The manifold analysis of a 480 MW hydro power station case is done in this study. The manifold serves the purpose of dividing 174 m^3/s flow to three pipes equally. During the division of flow, it is expected to have best hydraulic performance with least head loss. In addition, branches should have enough structural strength. Stress in the body need to be within allowable range under all conditions. This study optimizes the layout of manifold by performing fluid analysis and also checks the structural strength near branches of optimized profile. Head loss is evaluated with the variation of branch angle, cone length, and addition of sickle plate in manifold. The pressure and velocity distribution in the manifold is also visualized. In addition to this, structural analysis is also performed to check that stresses are allowable or not. All of this works that were done during the study period justifies the need for numerical analysis in the design of branches.

2. Methodology

The study was divided into two parts: fluid analysis and structural analysis. Both analyses were carried out by doing numerical simulation on Ansys platform. Ansys fluent performs best in determining the maximum velocity and re circulation flow rate using the tetrahedral mesh of the bifurcated model [13]. Fluent performs numerical analysis based on finite volume method (FVM) code for turbulent water flow. In FVM, fluid domain is discretized into a finite set of control volumes called cells. Governing equations are applied to each cell [14]. For incompressible flow, governing equations for fluid flow are defined by equation 1 and equation 2.

Conservation of Mass Equation:

$$\frac{\partial p}{\partial t} + \nabla \cdot (\rho \overrightarrow{V}) = 0 \tag{1}$$

Conservation of Momentum Equation:

$$\rho \frac{\partial \overrightarrow{V}}{\partial t} + \rho (\overrightarrow{V} \cdot \nabla) \overrightarrow{V} = -\nabla p + \rho \ \overrightarrow{g} + \nabla \cdot \tau_{ij} \tag{2}$$

The differential form of equation 1 and eqaution 2 is transformed into an integral form. The integral form is converted into a system of algebraic equations, and finally they are linearized [15].

A 3D-CAD spaceclaim was used to create a virtual model of manifold. The original data includes a branch angle of 45°, an inlet diameter of 6.5 m, a main pipe diameter of 5.3 m after first branch and an outlet diameter of 3.75 m. Four sections were made near bifurcations to compute pressure and velocity as shown in figure 1.

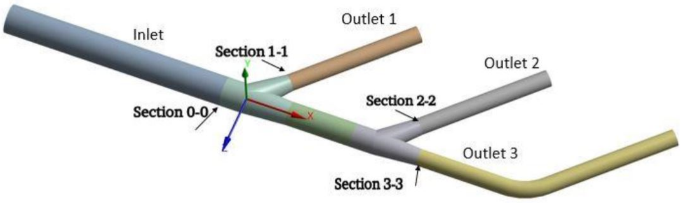

Figure 1: Schematic diagram of physical model with different sections. Section 0-0 for inlet, Section 1-1 for outlet-1, Section 2-2 for outlet-2, Section 3-3 for outlet-3

Different geometries of manifold layout were produced by changing branch angle from 30° to 60°. Then, simulation was run after providing boundary conditions and model setup. Study of cone length and sickle plate was also done. The cone length on branches was varied from 9 m to 12 m. After that, effects of sickle plate in the branch was observed. Then, optimized profile was created by combining best branching angle and best cone length with sickle plate. Head loss calculation and flow pattern visualization was done in the optimized profile. Finally, optimized profile was compared to the base profile. Base profile was provided by NEA Engineering Company. In that base profile, sickle plate was added. Steps that were followed in fluid analysis is shown in figure 2.

To solve governing equations, a steady state pressure based solver with double precision was used. k-ω SST was used as a turbulence model because it incorporates advantages of both k-ε and k-ω models. k-ω behaves well near the boundary and k-ε in the free stream of pipe [16]. For boundary Conditions: pressure head at inlet was 169 m, mass flow rate at outlet was 58000 kg/s and no-slip wall was adopted. After specifying necessary boundary conditions, solution process involves specifying water as fluid in all cells of the domain.

Simulation was run under 1×10^{-4} residuals with hybrid initialization. When solution converged, pressure and velocity were computed by function calculator available on fluent platform at the sections defined in figure 1. After that, head loss in between two sections was calculated by the equation 3 [17].

$$h_l = p_1 - p_2 + \frac{v_1^2 - v_2^2}{2g} \tag{3}$$

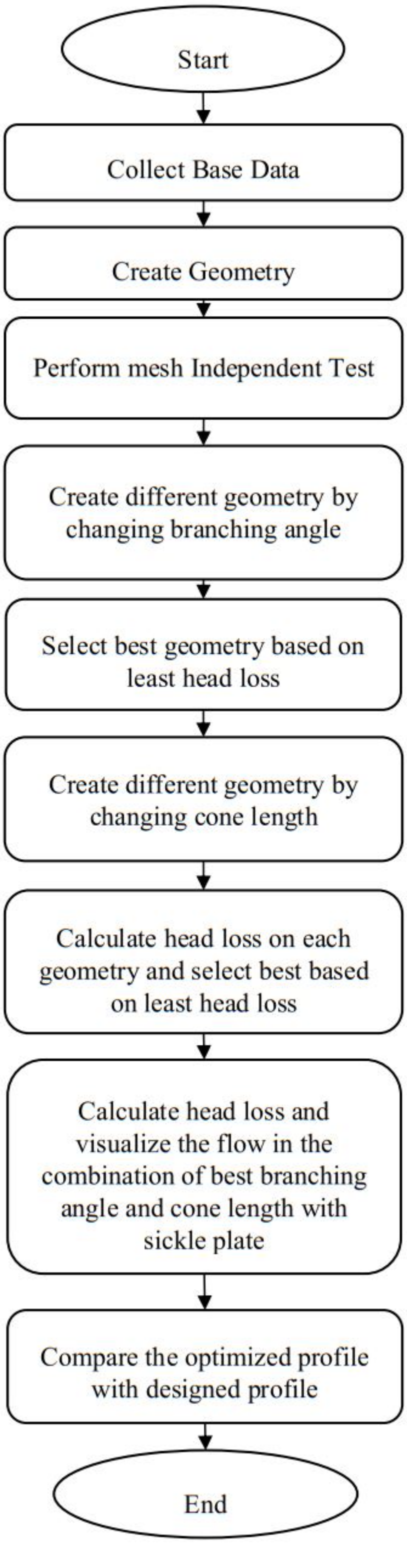

Figure 2: Flow chart showing steps involved in fluid analysis

Manifold is composed of complex geometric shapes around branches. It is difficult to calculate stresses by hand calculation in this geometries. Numerical analysis based on Finite Element Method (FEM) is used to calculate stress and deformation. In FEM, geometry of structure is divided into meshes, and a separate stiffness matrix is defined for each element. The combination of individual stiffness matrices forms a global stiffness matrix. Equation is defined using a global stiffness matrix, boundary conditions and external loads. Then, equation is solved [18]. Commercial solvers use methods that involve iterative approximation of displacements. Once the displacement is found, other parameters are calculated throughout meshes. Ansys static structure based on FEM was used for structural analysis in branches of the manifold. The domain was truncated into two parts: first bifurcation and second bifurcation. Singhal and Kumar (2015) [19] determined thickness of pipe (T) as a function of mean internal pressure at the bifurcation center (P), internal diameter (D), allowable stress (σ) in pipe material and joint efficiency (J) as shown in equation 4.

$$t = \frac{PD}{2\sigma J} \tag{4}$$

Pipe thickness was calculated separately for first and second bifurcation from the relation defined in equation 4. Mean internal pressure at bifurcation center was equal to the value of surge pressure. The normal pressure is increased by 1.4 times to calculate surge pressure as 2.32 MPa. Allowable stress and joint efficiency were 167 MPa and 0.9, respectively. Bifurcations were created by adopting this pipe thickness. After creating each bifurcation geometry, a tetrahedral mesh was generated. Mesh size obtained from the mesh independent test was provided as body size in mesh for all geometries. For boundary conditions, fixed support was assumed at inlet and outlets, and surge pressure of magnitude 2.32 MPa was provided in all inner walls. Simulation was run to determine total deformation and Equivalent (von-Mises) Stress. Initially, providing thickness of pipe determined by the equation 4, Equivalent (von-Mises) Stress was computed. It was observed that maximum stress was higher than allowable stress. Then, pipe thickness was increased until stress becomes allowable. The steps that were followed in structural analysis is shown in figure 3.

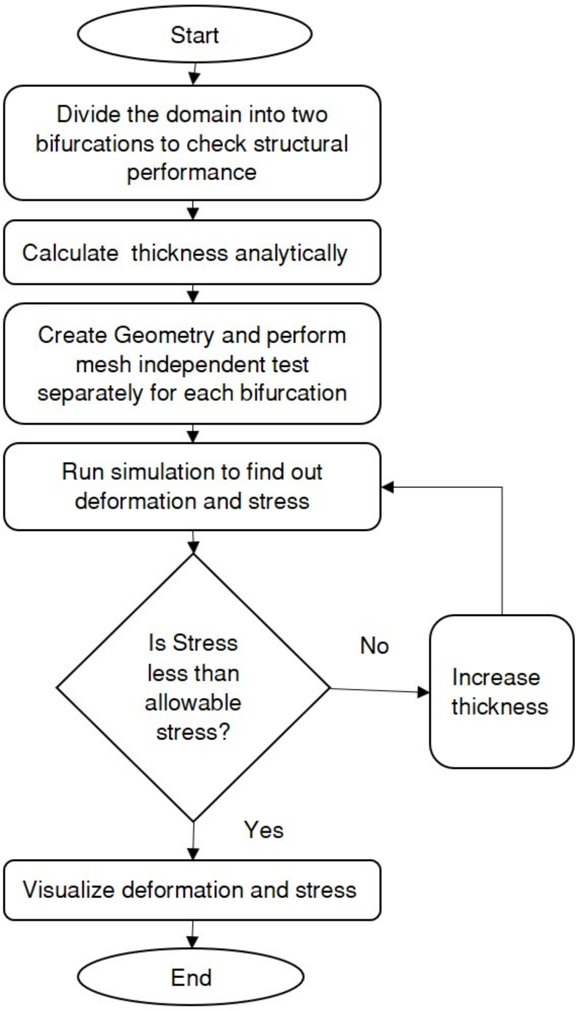

Figure 3: Flow chart showing steps involved in structural analysis

3. Results

3.1 Mesh Independent Test

Mesh independence test is done to ensure that result of simulation is independent of mesh size. For hydraulic analysis, pressure and velocity is observed at section 2-2 of 45° branch angle because it is mid outlet among three. Head loss is calculated by decreasing mesh size from 0.7 m to 0.2 m. The mesh size of 0.3 m is selected because percentage change in head loss between 0.3 m and 0.2 m is less than 1%. Similarly, for structural analysis, deformation at first bifurcation and second bifurcation with 60 mm and 50 mm thick pipe, respectively is observed. The cell size is decreased from 0.5 m to 0.15 m. At first bifurcaion, as mesh size is decreased from 0.25 m to 0.2 m, the variation is less than 1% and at second bifurcation, percentage change is less than 1%, when mesh size is changed from 0.2 m to 0.15 m. The mesh independence graph for structural analysis is shown in figure 4 and figure 5. As per analysis, mesh size for first and second bifurcation is maintained at 0.25 m and 0.2 m.

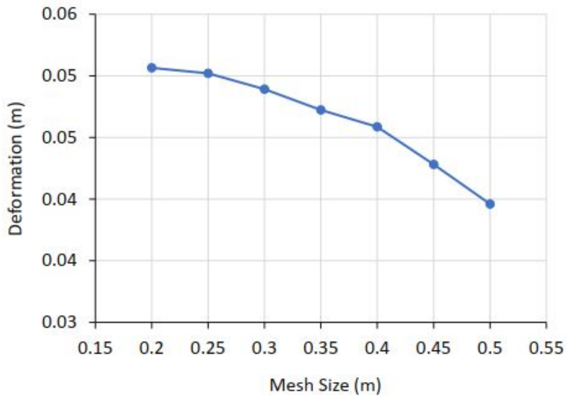

Figure 4: Deformation with different mesh size at first bifurcation

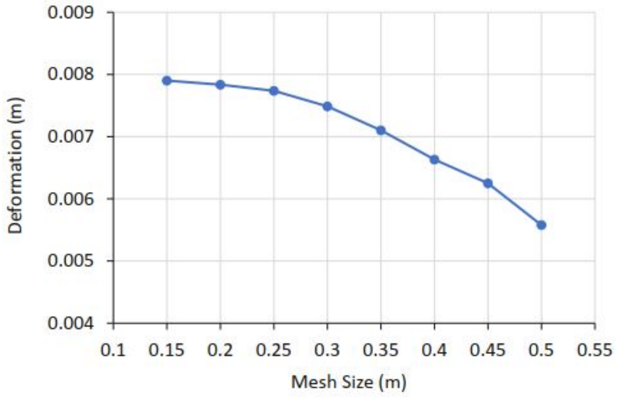

Figure 5: Deformation with different mesh size at second bifurcation

3.2 Head loss Calculation

Pressure and velocity are computed at four sections of the geometry with the help of function calculator available on fluent platform where sections are defined in figure 1. Head loss is calculated at those sections with the relation described in equation 3. Calculated head loss at three sections with different branch angle is presented in table 1. It is found that head loss decreases with the decrease in branching angle and 30° branch angle has least head loss among them.

Table 1: Head loss at sections with the change of branching angle

Branch Angle	Head Loss (m)		
	Section 1-1	Section 2-2	Section 3-3
60°	0.64	0.57	0.09
55°	0.57	0.50	0.09
50°	0.50	0.43	0.09
45°	0.43	0.37	0.09
40°	0.36	0.31	0.09
35°	0.27	0.26	0.09
30°	0.13	0.17	0.09

Cone length is changed from 9 m to 12 m as shown in table 2. The least head loss is computed to be for 9 m.

Table 2: Head loss at sections with the change of cone length

Cone length	Head Loss (m)		
	Section 1-1	Section 2-2	Section 3-3
9 m	0.10	0.14	0.08
10 m	0.13	0.17	0.09
11 m	0.16	0.20	0.09
12 m	0.21	0.22	0.09

During the division of flow, a large volume of water hits intersecting plane that can erode penstock material. The sickle plate is provided as an internal reinforcement at the bifurcation plane to protect branches. The variation in head loss due to addition and removal of sickle plate is presented in table 3. The significant increment in head loss is observed at section 2-2 and section 3-3 with the addition of sickle plate while minimal effect of sickle plate is observed at section 1-1.

Table 3: Head loss at sections with the addition and removal of sickle plate

Sections	Head Loss (m)	
	Addition of sickle plate	Removal of sickle plate
Section 0-0	-	-
Section 1-1	0.15	0.13
Section 2-2	0.45	0.17
Section 3-3	0.34	0.09

3.3 Comparision between optimized case and base case

Manifold profile designed by NEA Enginneirng Company is taken as base case which is compared with the optimized case. Optimized case is the combination of best branch angle, best cone length and sickle plate. The calculated head loss for optimized case and base case is presented in table 4. It is observed that head loss for optimized case at section 1-1, section 2-2 and section 3-3 is 37 %, 15 % and 24 % less as compared to the base case.

Table 4: Head loss at sections in the optimized case and base case

Sections	Head Loss (m)	
	Optimized Case	Design Case
Section 0-0	-	-
Section 1-1	0.13	0.21
Section 2-2	0.46	0.54
Section 3-3	0.31	0.41

3.4 Flow Patterns

As shown in figure 6, disturbances can be seen near the junction of optimized manifold profile. The first bifurcation has an asymmetric cone angle due to unequal diameter with same length in branches, and the second has a symmetric cone angle. This effects can be seen as uneven velocity distribution at first bifurcation, while velocity distribution at second bifurcation is uniform. The pressure on opposite sides of the sickle plate at first bifurcation varies greatly as shown in figure 7, which may cause abnormal deformation of sickle plate. This problem may require serious repair and maintenance in future. In case of second bifurcation, there is no such pressure difference.

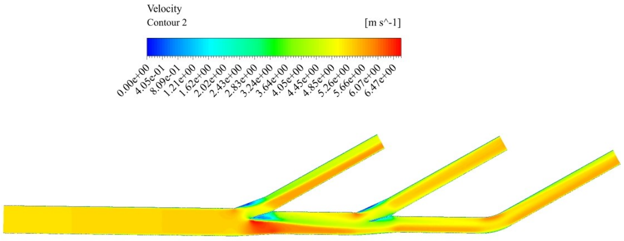

Figure 6: Velocity distribution in the midplane of optimized manifold

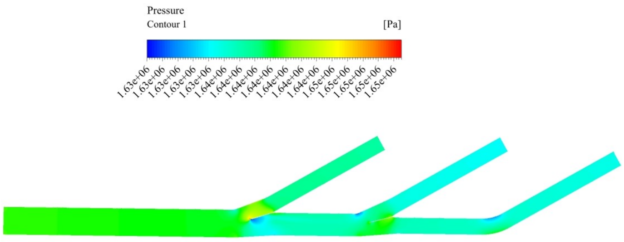

Figure 7: Pressure distributuion in the midplane of optimized manifold

3.5 Stress Calculation

3.5.1 First Bifurcation

Initially, when pipe thickness is maintained at 60 mm, Equivalent (von-Mises) Stress is higher than allowable stress. Then, pipe thickness is increased to 130 mm at 10 mm interval until it meets the allowable yield strength. As shown in figure 8, the maximum stress is 166 MPa, of which allowable stress is 167 MPa.

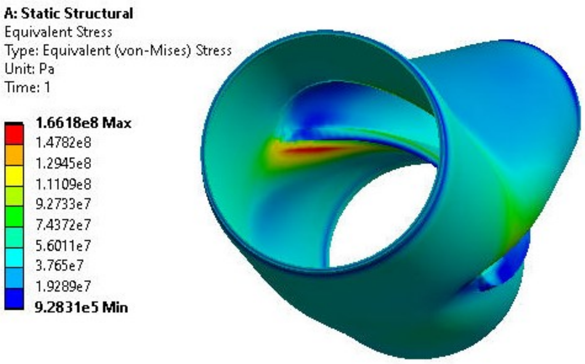

Figure 8: Equivalent (von-Mises) Stress in the first bifurcation for 130 mm thick pipe

3.5.2 Second Bifurcation

Initially, when pipe thickness is maintained at 50 mm, Equivalent (von-Mises) Stress is higher than allowable stress. Then, pipe thickness is increased to 70 mm at 10 mm interval until it meets the allowable yield strength. As shown in figure 9, the maximum stress is 161 MPa, of which allowable stress is 167 MPa.

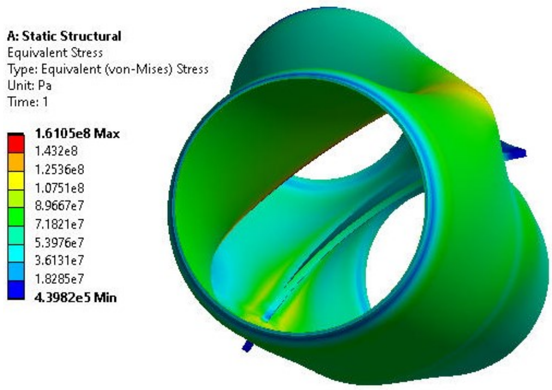

Figure 9: Equivalent (von-Mises) Stress in the second bifurcation for 70 mm thick pipe

4. Conclusion

In this study, numerical analysis in manifold of Phukot Karnali Hydroelectric Project was carried out. Intially, branching angle in the manifold was designed to be 45°. Numerical analysis is done on Ansys platform by changing branching angle in both forward and background direction at the interval of 10°. Head loss is computed to be minimum for 30°. In addition, cone length is also changed, and it is observed that shorter the length, the smaller is head loss. However, when conical length is too small, it makes difficult to fabricate on site. The analysis is also done by adding and removing a sickle plate. With the addition of sickle plate, head loss increases by 1.2 times at outlet-1, 2.6 times at outlet-2 and 3.8 times at outlet-3. The optimized profile is created by combining best branch angle, best cone length and sickle plate. The head loss at outlet-1, outlet-2 and outlet-3 for the optimized profile is computed as 0.13 m, 0.46 m and 0.31 m, respectively. When head loss at three scetions in optimized case and base case is compared. It is foud that head loss for optimized case at outlet-1, outlet-2 and outlet-3 is 37 %, 15 % and 24 % less as compared to the base case. Flow pattern analysis leads to the conclusion that symmetry should be kept in mind as much as possible in the design process. In order to ensure the branch strength, structural analysis is also carried out. It is found that pipe strength needs to be increased. The pipe thickness is increased to 130 mm at first bifurcation and 70 mm at second bifurcation. This thickness can be adjusted by adding ring girdles and external stiffners, which requires further analysis. It is recommended to optimize the manifold profile in terms of head loss, structural strength and practicability, which needs more comprehensive study. The findings of this study suggest the necessity and importance of numerical analysis during design of penstock branches.

Acknowledgments

Authors would like to acknowledge NEA Engineering Company for providing base data of Phukot Karnali Hydroelectric Project. The authors would also like to thank Department of Mechanical and Aerospace Engineering of Pulchowk campus for computer access.

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