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Computational Analysis of Bifurcation of Raghuganga Hydropower Project

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Abstract

Computational analysis is the modern design optimization tool used widely for determining the effect of different loading parameters where operating conditions and geometry are complex for manual solutions to execute. This study has great significance in the design and optimization of penstock branches as the ancient technology used for the design has least chance of having minimum head loss and good structural strength at the same time. Bifurcation of Raghuganga Hydropower Project of 40 MW installed capacity is chosen for this study in which, head loss, velocity and pressure distribution and stress distribution around the branching regions have been observed by varying the angle of cone of bifurcation. Upon varying the cone angles gradually starting from 3 degrees up to 15 degrees, the values of head loss have been reduced from 0.972 m to 0.086 m till 13-degree angle of cone and upon further increasing the angle to 15 degrees, the head loss increased sharply to 2.201 m. Also, for the structural analysis on the optimized cone angle profile, pipe thickness was varied from 25 mm till the values of stress was in the acceptable range. Upon simulations, it was found that optimum pipe thickness is 40 mm and sickle reinforcement of 75 mm with the value of maximum stress (Von-Mises) at the branching to be 167 MPa and minimum factor of safety of 1.49 for the material chosen i.e. E 250 corresponding to I S 2062.

Keywords: *Computational Fluid Analysis (CFD), Finite Element Analysis (FEA), Bifurcation, Head Loss, Taper Angle of cone*

2 Introduction

Hydropower stations have two or more generating units depending upon the availability of water and head. Penstock pipes are divided into two or more branches depending upon the flow requirements for each unit. Penstock pipe is the water transport system used to transfer water from higher head point to turbine. Penstock is pressurized conduit usually made up of steel plates of varying thickness for high head applications and HDPE pipes in low head applications.

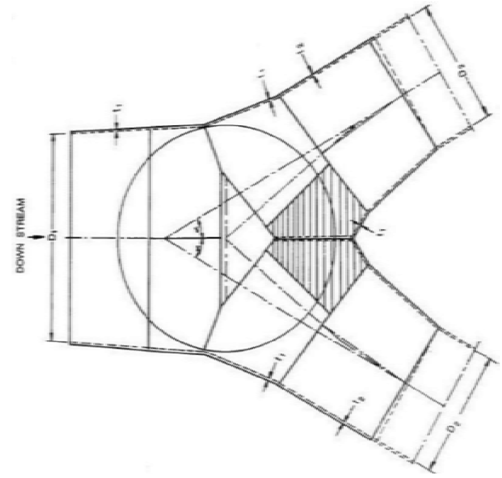

Figure 1: Typical Structure of Bifurcation [1]

It is not economical to use separate penstock pipes for each unit and in most of the cases penstock convey the water near the power house and is then branched into different units. A penstock bifurcation is a point in a hydroelectric power system where a single water intake splits into two or more separate channels to feed water to multiple turbines. This allows for the distribution of water flow and pressure to multiple turbines, increasing the overall efficiency and power output of the hydroelectric system. This division may be symmetric or unsymmetric depending upon the requirements of the powerplant. In symmetric bifurcation, the flow is divided equally and in unsymmetric bifurcation, division of flow is unequal. Since bifurcation is installed near the power house and is located at the point of maximum pressure, it is a critical section and thus has to be designed with special care and considerations. The major factors to be considered are angle of bifurcation, losses in bifurcation and its structural stability as it affects the power plant in long run-in terms of vibration, power generations and repair maintenances.

The design and analysis of a penstock bifurcation system for a hydroelectric power plant presents a complex engineering challenge. The goal is to design and analyze a penstock bifurcation system that can effectively distribute water flow and pressure to multiple turbines, while also ensuring structural integrity and minimizing energy loss. Bifurcation must also be designed to minimize vibrations and cavitations that might arise due to the change in pipe dimensions of the flow. If the wye branches are not designed carefully, the losses contribute to the reduction in power generation of the power plant and thus affect the revenue of the company.

Selection of bifurcation profiles can be done either by experimental analysis from reduced model tests in labs or numerical modeling of the fluid flow. Since the results from past experimental study don’t give empirical relations for all the hydropower stations as they are site specific, the analysis for minimum losses and best profile for the bifurcation should be done for penstock of each power plants and analytical approach

3 Literature Review

Numerical simulation using computational fluid dynamics (CFD) has been widely used now days in the analysis and optimization of penstock bifurcation systems for hydroelectric power plants. A number of studies have employed CFD to investigate the flow and pressure distribution in penstock bifurcation, in order to optimize the system's performance.

The study by Sirajuddin Ahmed tested five symmetrical wye branches of conventional and spherical types for hydraulic losses under symmetrical and unsymmetrical flow conditions. The results showed a wide variation in loss factor depending on the type of wye and flow condition, and the minimum loss coefficient did not always occur under conditions of symmetrical flow. [2]Similarly, the study by Hua Wang conducted laboratory tests to determine head losses in conventional wyes and manifolds, with and without an internal tie-rod at the theoretical center of the wye. The wyes and manifolds had subtending angles of 45, 60, and 90 degrees and were symmetrical about the main pipe's longitudinal axis. The tests were conducted using a range of Reynolds numbers and the results were analyzed using the energy equation of Bernoulli for one-dimensional conditions. It was found that the coefficient of form loss is a function of the proportion of flow through the branches, the size of the tie-rod used and the subtending angle of the wye. [3]

The investigation revealed several problems that should be addressed during the design, modernization, and operation of hydropower plants to ensure safe operation. These problems include:

- The rate of flow cut-off and resulting maximum pressure rise in the flow system;
- Increased stress concentration in geometrically irregular elements of the flow system, such as penstock bifurcations
- poor quality of welded or riveted joints.

The study found that an excessive pressure rises due to water hammer after a rapid flow cut-off resulted in the bursting of a penstock. The failure was also attributed to the low strength of the penstock, caused by poor weld quality and lack of reinforcement at points of high stress concentration. The incident serves as a warning that even small hydropower plants are at risk of breakdowns caused by water hammer, and it is important to check the quality of materials used and analyze various operating conditions using current computational methods and strain measurements to prevent such situations. [4]

A study was conducted to compare various relations for the optimum design of penstock in hydro power projects. It was found that these relations provide different values for the optimum penstock diameter, leading to different costs. Some of these relations only consider friction loss, but other losses also occur in practice and need to be considered. A new method was developed to optimize the design of penstock based on minimizing annual project cost while considering total head loss (friction and other losses) using the Darcy Weisbach formula. The new method was applied to 21 hydro power projects of capacities ranging from 25 kW to 60 MW and was found to result in a net saving in annual cost of penstock. The savings ranged from 0.613% to 9.714% of the earlier penstock cost, which justifies the applicability of the new method for optimum design of penstock in hydro power projects. [5]

Study for optimization of the design of the penstock manifold and bifurcation in hydropower plants using modern techniques such as Computational Fluid Dynamics and Finite Element Method was done by Dipesh Thapa et. all. The study aimed to enhance the theoretical knowledge base for the application of these techniques in the context of Nepal. The Kulekhani-III Hydropower Project's manifold arrangement was chosen for the optimization, and the proposed design was modeled, analyzed, and refined until an acceptable geometry was achieved. The bifurcation was then given thickness and reinforcements, and a solid model was prepared and analyzed using Finite Element Analysis. The results were checked against design codes, and an acceptable design was recommended for fabrication and installation. [6]

The study by Ravi Koirala et all discusses the importance of optimizing the design of hydro power plants to ensure their reliability and efficiency. It notes that past design practices were based on experience and theoretical foundations, but modern technologies such as computational fluid dynamics (CFD) and finite element analysis (FEA) can now be used to improve the design process. The paper suggests that using these modern tools in conjunction with conventional methods can lead to more accurate and reliable designs for penstock bifurcation, which is a key component of hydro power plants. [7]

The research focuses on the design and analysis of bifurcation in Upper Kallar Small Hydro electric project (2 Mw) using modern techniques such as Computational Fluid Dynamics (CFD) and Finite Element Method (FEM) to improve the reliability and safety of the design. The use of ASTM A285 Grade C steel is found to be strong enough to withstand the stresses caused by the complex shape of the bifurcation. The result of the FEM analysis shows that a bifurcation with 20 mm in wall thickness and a sickle plate with 32 mm thickness meets the design requirements. Additionally, it is noted that it would be extra safe to have the bifurcation inside a reinforced concrete structure. [8]

This study focuses on the quantification of head losses in a system that uses bifurcation, trifurcation, and other configurations to transport water from surge tanks to power houses in order to feed several turbines at the same time. The study uses Computational Fluid Dynamics (CFD) to determine the coefficient of head losses and validate with previous results. Different mesh settings are analyzed and the k-ω turbulence model is used with refinement to elements near the wall to check y+. The SAS model is also used for analysis of instability in the trifurcation. [9]

The study focuses on quantifying head losses as a function of volumetric flow rate using Computational Fluid Dynamics (CFD) and comparing results with previously published data. Three basic designs for branching were prepared, and pressure, velocity, head loss, and mass flow variations were studied. The study recommends further intense study in one of the designs, and the results are mostly site-specific. It is recommended to design the branching section very carefully after generalizing or detailed analyzing basic parameters and to consider the potential for flow irregularity within branching. [10]

This study used numerical analysis to study the hydraulics and structural strength in the manifold of the Phukot Karnali Hydroelectric Project (480 MW). Computational simulations were performed to observe the head loss, velocity distribution, pressure distribution, deformation, and stress in the manifold. The effects of branch angle, cone length, and sickle plate were studied for the hydraulic analysis. The results showed that the head loss was decreased with the reduction of branching angle and cone length, and the best branching angle was computed to be 30° and the best cone length was 9m. The optimized manifold profile was created with the best branch angle, best cone length and sickle plate. The head loss in the optimized profile at outlet-1, outlet-2, and outlet-3 was computed to be 0.13m, 0.46m, and 0.31m, respectively. The optimized case was compared to the base case, which was designed by NEA Engineering Company. It was found that head loss was decreased in the optimized case by 37%, 15%, and 24% at outlet-1, outlet-2, and outlet-3, respectively. For the structural analysis, the manifold was divided into two parts: first bifurcation and second bifurcation. The initial pipe thickness was provided as 60 mm at the first bifurcation and 50 mm at the second bifurcation. The provided pipe thickness was insufficient to meet the allowable stress criteria, so the thickness of the pipe was increased for better structural strength. Equivalent (von-Mises) Stress at the first bifurcation with 130 mm thick pipe and second bifurcation with 70 mm thick pipe was 166 MPa and 161 MPa, respectively, for which the allowable stress is 167 MPa. [11]

4 Methodology

The methodology adopted for this study is illustrated in the figure below. The modeling shall be done in Solid works and then it is imported to ANSYS CFX to perform hydraulic and structural analysis to obtain the desired profile and plate thickness.

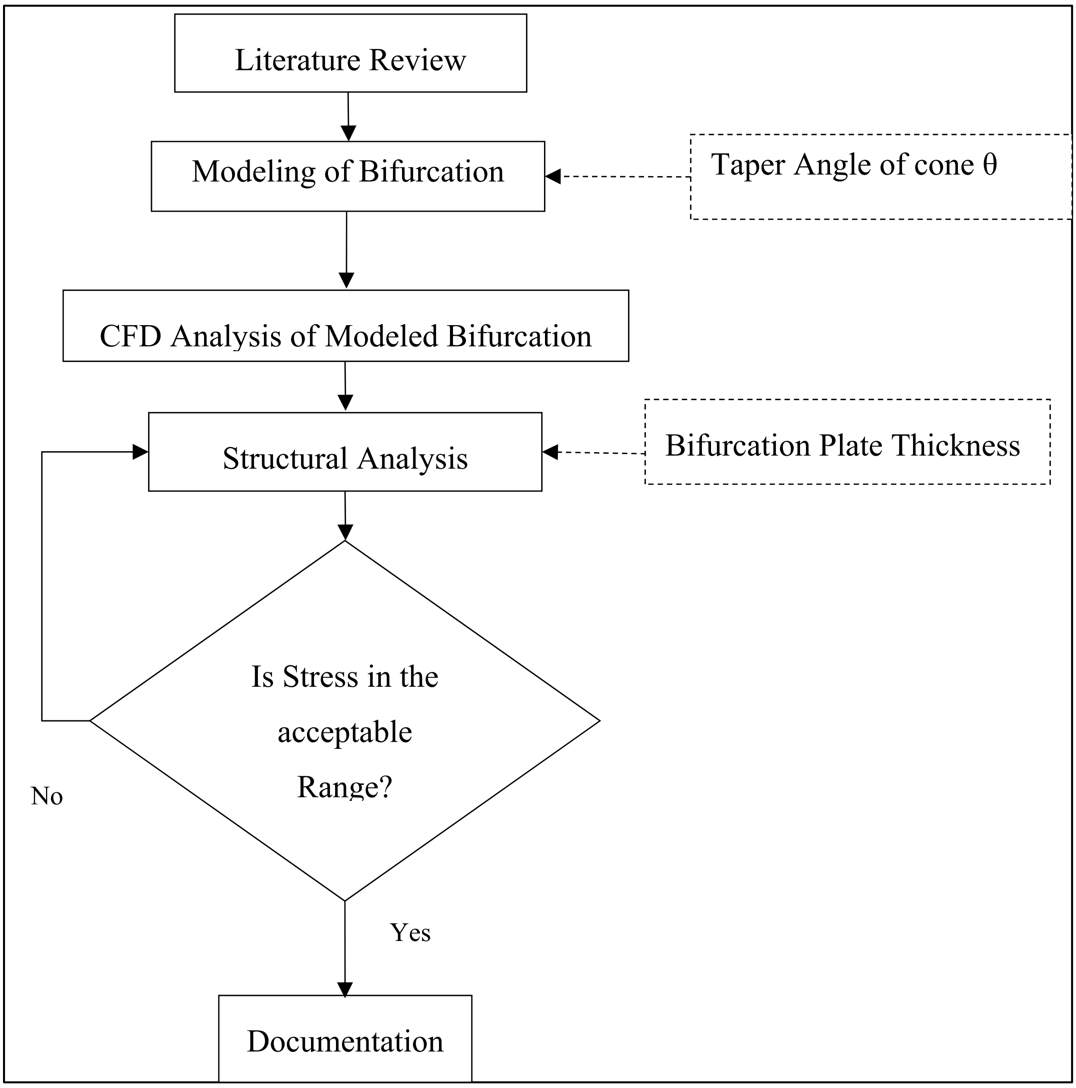

Figure 2: Research Methodology

4.1 Geometry Modeling

A penstock bifurcation is a point where a single penstock splits into two or more separate branches. In order to model this geometry, it is important to take into account factors such as the flow rate and pressure at the bifurcation point, as well as the angle and shape of the branches. Solid works is the software used to create a 3D model of the bifurcation in this study.

The plan for the first case to be modeled by changing the taper angle of bifurcation is shown in the figure below.

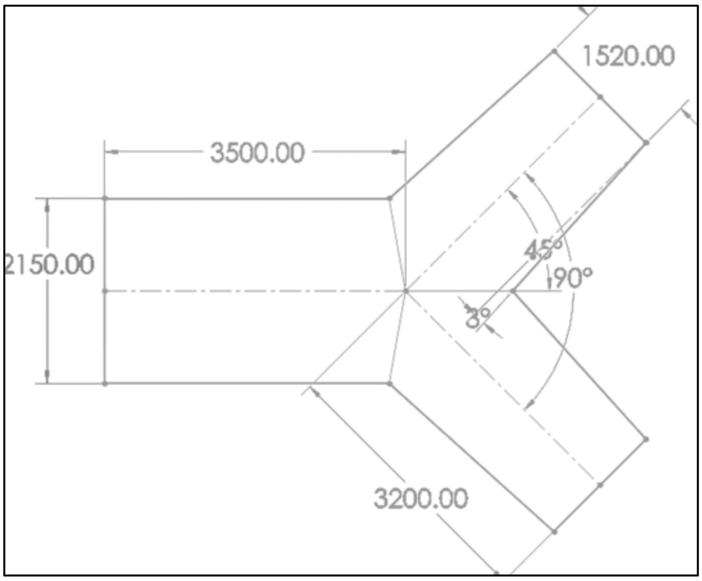

Figure 3: Plan for modeling of Case-1(All Dimensions are in mm)

The major dimensions used here are given by Civil designers i.e., the Pipe diameters for inlet and outlet of Bifurcation, the angle of bifurcation and the length segments of the branched pipes. For modeling of pipe branching, the taper angle of cone of the branch pipe is gradually increased from 3 degree up to 15 degrees by increasing by 2 degrees simultaneously and then its model is exported to ANSYS CFX in. STEP and then CFD analysis is carried out to get the profile with minimum hydraulic loss at the branching of the pipe. The process explained above is carried out for 6 more times to get the 3D models of each case obtained by changing the taper angle of branched pipe from 3 degree to 15 degree.

4.2 Computational Fluid Modeling

The 3D modeled bifurcations mentioned above are then imported to ANSYS CFX for CFD analysis. Mesh is generated in CFX Mesh and the set-up conditions and boundary conditions used for the analysis based on the available data are presented in the table below.

Table 1: Boundary Conditions setup for CFD Analysis

Domain	**Boundaries**	
Default Domain	**Boundary - Inlet**	
	Type	INLET
	Location	Inlet
	Settings	
	Flow Direction	Normal to Boundary Condition
	Flow Regime	Subsonic
	Mass And Momentum	Total Pressure
	Relative Pressure	3.1870e+00 [MPa]
	Turbulence	High Intensity and Eddy Viscosity Ratio
	Boundary - Unit1	
	Type	OUTLET
	Location	Unit1
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Mass Flow Rate
	Mass Flow Rate	8.3400e+03 [kg s^-1]

	Boundary - Unit2	
	Type	OUTLET
	Location	Unit2
	Settings	
	Flow Regime	Subsonic
	Mass And Momentum	Mass Flow Rate
	Mass Flow Rate	8.3400e+03 [kg s^-1]
	Boundary - Walls	
	Type	WALL
	Location	Walls
	Settings	
	Mass And Momentum	No Slip Wall
	Wall Roughness	Smooth Wall

4.2.1 Mesh Independence Test

in order to carry out further simulations, mesh independence test is carried out by varying mesh number and noting the value of turbulent kinetic energy and its values are plotted to obtain the graph as shown in figure below.

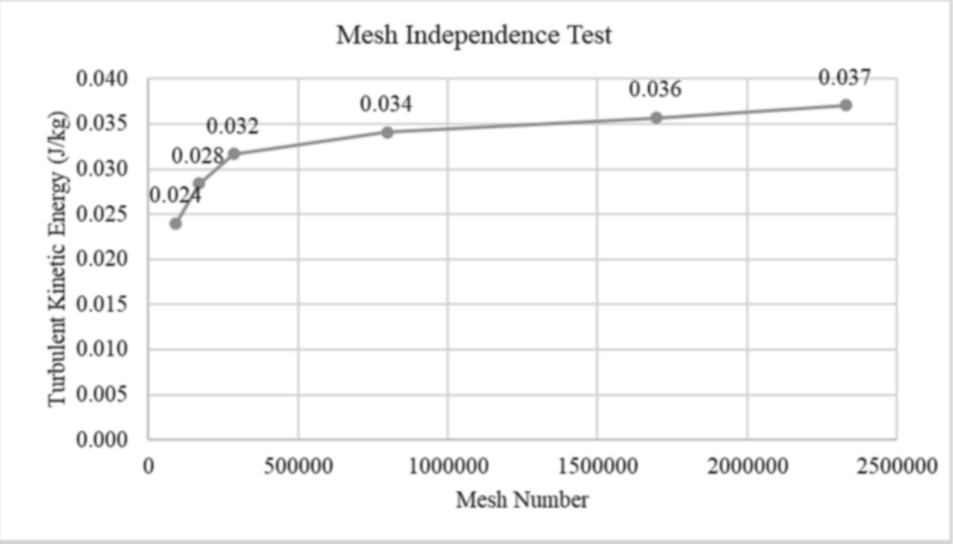

Figure 4: Mesh Independence Test

The results obtained from the above graph and table show that there is not more than 3.84% variation in output values when the mesh number is varied from 1695639 to 2327152. Thus, the mesh number of 1695639 is taken for subsequent simulations.

5 Results and Discussions

5.1 Hydraulic Analysis

The Bifurcations as described in methodology were modeled and the boundary conditions were set and its CFD analysis was carried out in ANSYS CFX and the results were noted.

5.1.1 Pressure and Velocity Distribution

The Distribution of Total Pressure and Velocity at the mid plane of each simulated case was evaluated. The figures below are the results for the plot of velocity at mid plane for all seven simulated cases.

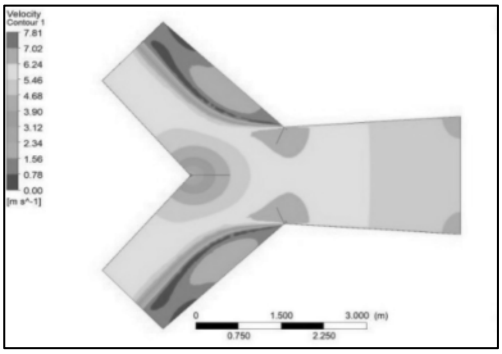

Figure 5:Velocity Plot at mid plane for case-1

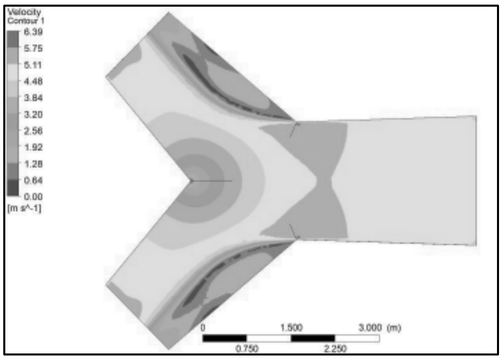

Figure 6:Velocity Plot at mid plane for case-2

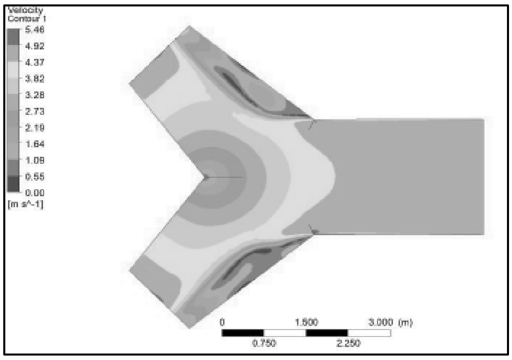

Figure 7:Velocity Plot at mid plane for case-3

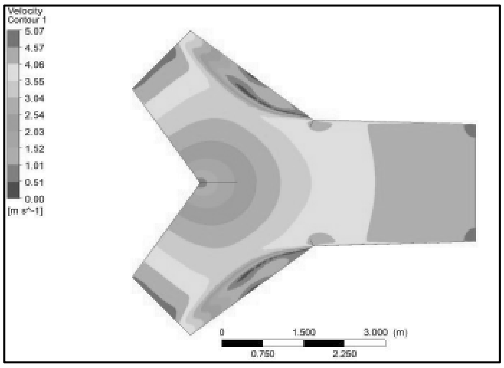

Figure 8:Velocity Plot at mid plane for case-4

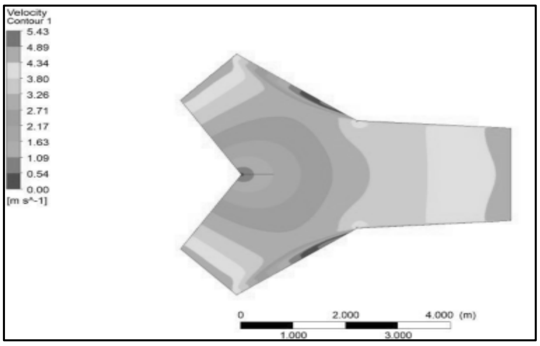

Figure 9:Velocity Plot at mid plane for case-5

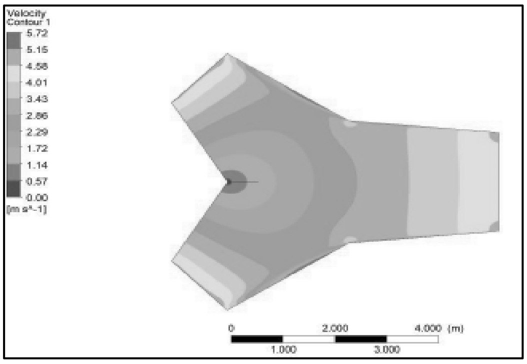

Figure 10:Velocity Plot at mid plane for case-6

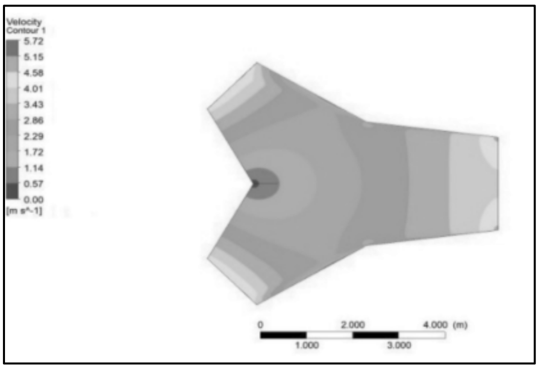

Figure 11:Velocity Plot at mid plane for case-7

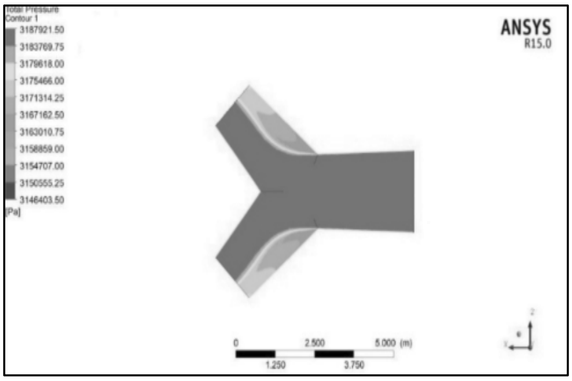

Figure 12 Pressure Plot at mid plane for case-1

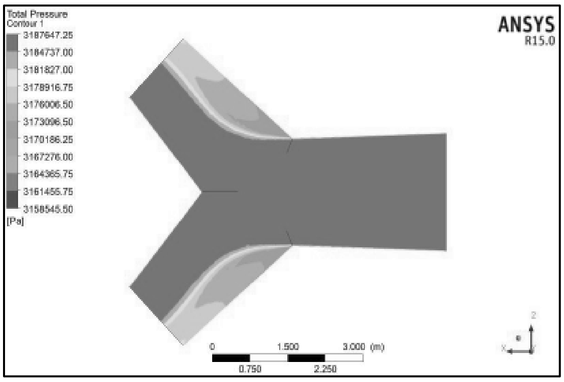

Figure 13:Pressure Plot at mid plane for case-2

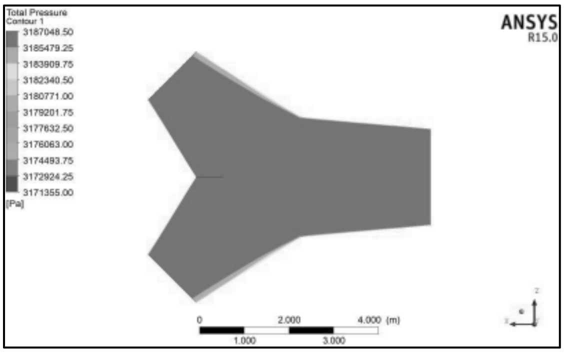

Figure 14:Pressure Plot at mid plane for case-3

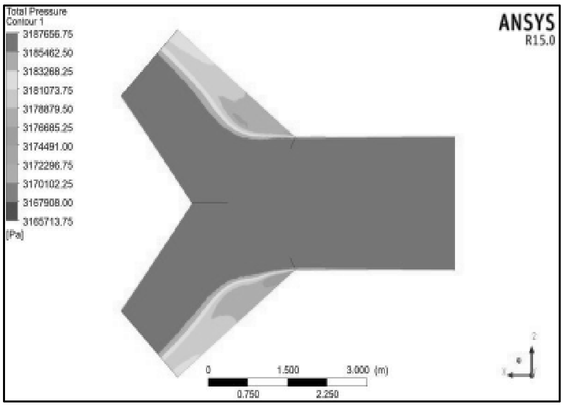

Figure 15:Pressure Plot at mid plane for case-4

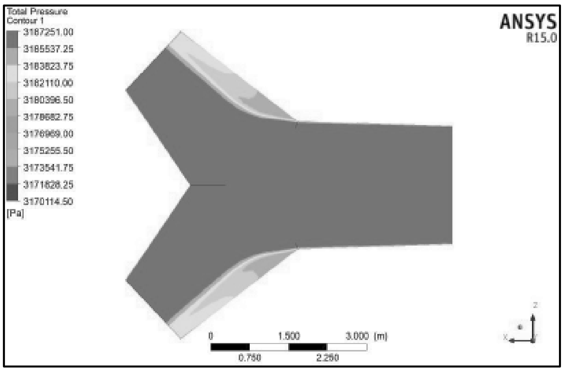

Figure 16:Pressure Plot at mid plane for case-5

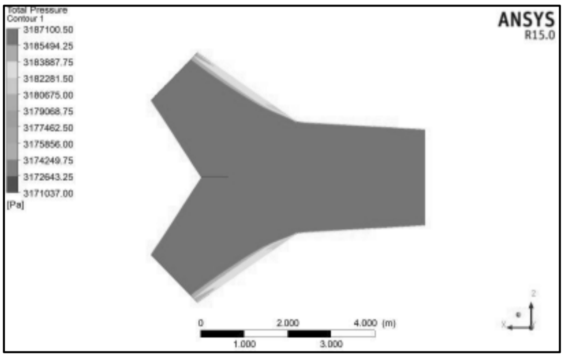

Figure 178: Pressure Plot at mid plane for case-7

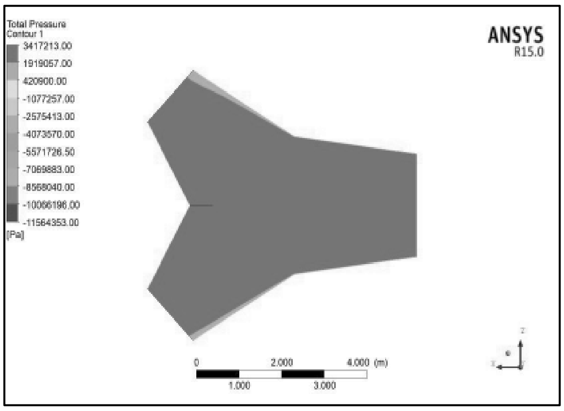

Figure 187: Pressure Plot at mid plane for case-6

5.1.2 Calculation of Head Loss

Head Loss Was Calculated by using equation-1 by using the values from the results of simulations. [12]

$$H_{l_i} = \left(\frac{P_{in}}{\rho g} + \frac{V_{in}}{2g}\right) - \left(\frac{P_{Out_i}}{\rho g} + \frac{V_{Out_i}}{2g}\right) \quad \text{Equation 1}$$

Head loss for each branch in all simulated cases is calculated and tabulated as below.

Table 2: Head Loss Calculation and Data from Simulations

Cases	**Taper Angle (Degree)**	**Inlet Pressure (Pa)**	**Inlet Velocity (m/s)**	**Outlet Pressure-1 (Pa)**	**Outlet Velocity-1 (m/s)**	**Outlet Pressure-2 (Pa)**	**Outlet Velocity-2 (m/s)**	**Total Head Loss (m)**
1	3	3186990	4.532	3182140	4.681	3182150	4.684	0.972
2	5	3186990	4.573	3184810	4.594	3184860	4.608	0.436
3	7	3186990	4.615	3185840	4.568	3185840	4.573	0.239
4	9	3186970	4.654	3186290	4.580	3186280	4.581	0.147
5	11	3186940	4.694	3186510	4.598	3186510	4.600	0.097
6	13	3186920	4.726	3186550	4.612	3186560	4.612	0.086
7	15	3098660	4.226	3088000	4.114	3087840	4.107	2.201

A graph is plotted for the total head loss calculated and the taper angle of the cone. The graph below shows the result.

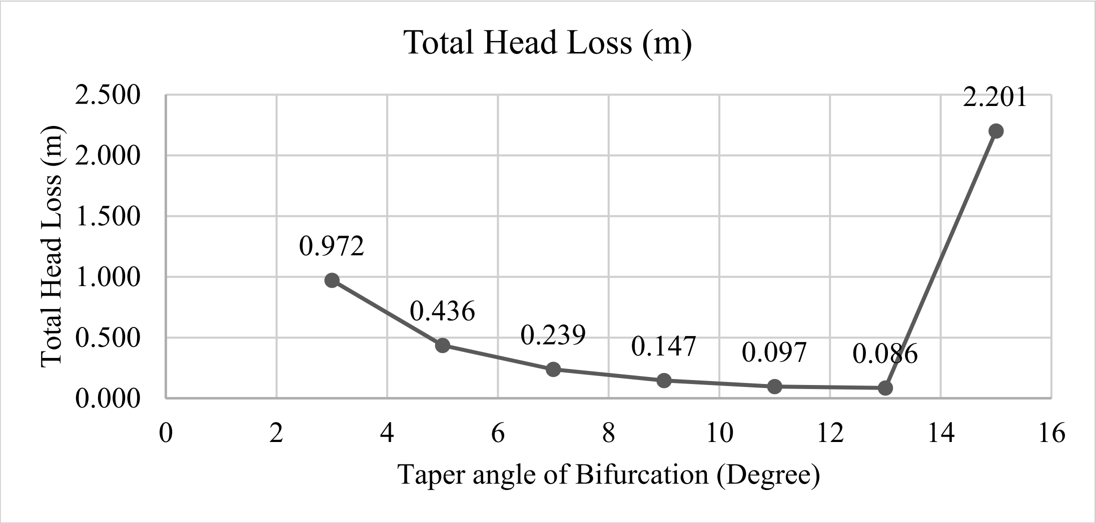

Figure 19: Head Loss Vs Taper Angle of Bifurcation

The result shows that, head loss is minimum for taper angle of 13 degrees for branching of pipes with total head loss of 0.086 m in branched section. The pressure and velocity distribution also show the same results as there is less velocity drop and pressure distribution in the junction.

5.2 Structural Analysis

The thickness of pipe at penstock bifurcation was varied from 25 mm gradually by 2 mm with the necessary sickle and other reinforcements and its structural analysis was done to obtain the values of equivalent stress under the acceptable range. The material of bifurcation is structural steel E 250 having yield stress of 250 MPa corresponding to the Indian Standard Code of practice IS 2062: 2011. Upon simulation with the necessary boundary conditions in ANSYS STATIC STRUCTURAL, the acceptable stress at branching is obtained for pipe thickness of 40 mm. The results are shown in the figure below.

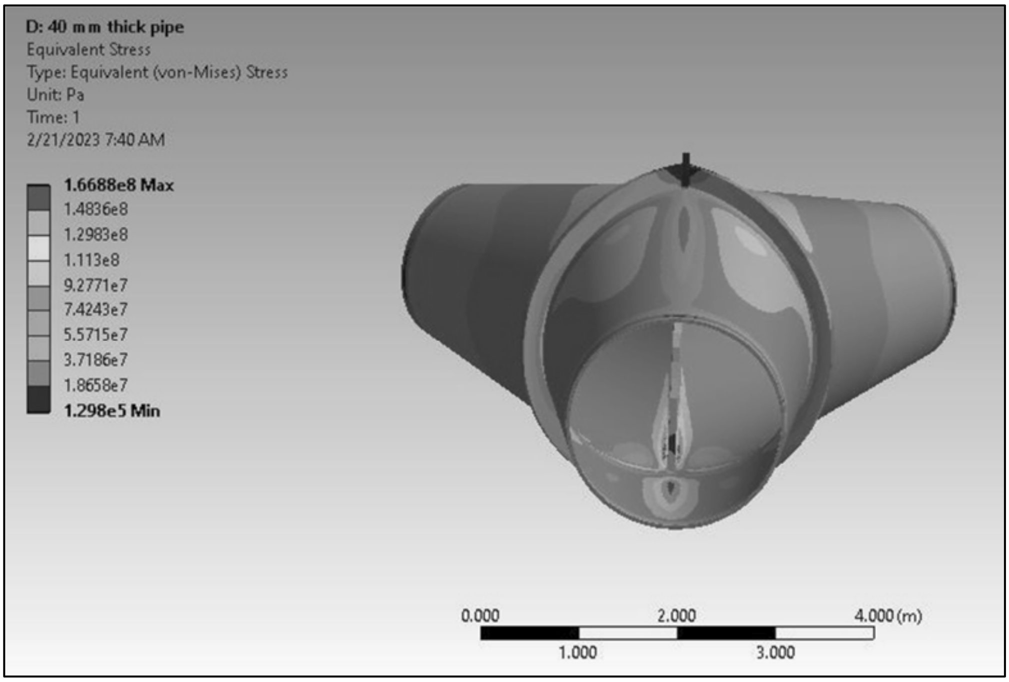

Figure 20: Equivalent Stress for Bifurcation

The results obtained from structural analysis show that, the maximum stress for the selected material is 167 MPa and the factor of safety is a minimum of 1.498 which is under acceptable range for the pipe thickness of 40 mm. Also, the thickness of reinforcements is 75 mm.

6 Conclusion

In this study, the taper angle of cone of bifurcation was increased starting from 3 degree to obtain the profile with minimum loss and then its structural analysis was carried out to know the necessary pipe thickness and reinforcements Penstock bifurcation on given angle and cone length was modeled by varying the taper angle of cone by starting from 3 degree to 15 degrees increasing the angles by 2 degrees. CFD analysis was carried out for all the modeled cases in ANSYS CFX and the corresponding values for head loss was calculated and corresponding pressure and velocity distribution in the mid plane was observed. The analysis of results showed that upon varying the taper angle of cone of bifurcation, the head loss decreases gradually, reaches minimum and then increase sharply. In this case, the value of head loss has decreased from 3 degree till 13-degree taper angle of cone, is minimum for 13 degrees (0.086 m) and has increased to 2.201 m for 15 degrees angle.

For Structural analysis, the profile with minimum loss, branched pipe was modeled by varying the pipe thickness from 25 mm and its structural analysis was carried out to obtain the details of pipe thickness and necessary reinforcements so that the stress is within the acceptable limits. The material is chosen to be E 250 corresponding to IS 2062:2011. The results from structural analysis showed that, the pipe with the material of E 250 with thickness of 40 mm and reinforcements of 75 mm thickness is suitable so that the maximum stress in the pipe with 167 MPa and minimum factor of safety to be 1.49.

7 Acknowledgements

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