Research on the Design of Crescent Ribbed Steel Bifurcation Pipe of High Head Hydropower Station- Take Jinzhan River -I Hydropower Station as an Example

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Abstract. The design of the steel bifurcation pipe of hydropower station should be based on the actual situation of the project, and the reasonable arrangement, structure form and structure calculation method should be selected to meet the requirements of bearing capacity, stability and stiffness of the steel bifurcation pipe. In this paper, the selection, arrangement and design of the crescent-ribbed steel bifurcation pipe of Jinzhan River -I hydropower station are analyzed and calculated, so that its structure is reasonable, economical and meets the requirements of safe and stable operation. The steel bifurcation pipe has been built and put into operation, which proves that the design is safe, feasible and reasonable.

Keywords. Jinzhan River first stage hydropower station, crescent-ribbed steel bifurcation pipe, shape design, structural calculation.

1. Introduction
The key to the bifurcation pipe design of hydropower station is the shape design and the stress analysis of pipe body. The correct shape design can make the bifurcation pipe force reasonable, stress distribution even, hydraulic flow smooth, so as to make the bifurcation pipe safe and reliable, and achieve the purpose of saving steel, safe and stable operation [1]. The surface steel bifurcation pipe of Jinzhan river-I hydropower station has the characteristics of high head, small flow and narrow plant location. The bifurcation pipe type is selected as the internal reinforced crescent-ribbed-shaped bifurcation pipe, and the shape design and structure calculation of the bifurcation pipe are carried out to verify the rationality of the shape design.

2. Project Overview
The Jinzhan Rive-I hydropower station, the first cascade of Jinzhan River, is an unregulated diversion plant on the left branch of the Yangbi River in the middle reaches of Dali Prefecture, Yunnan Province. The installed capacity of the power station is 12000 kW (3X4000 kW). The water diversion system is arranged on the left bank of Jinzhan River. The pressure steel pipe is an open pipe. The main pipe length is 1326.767 m, and the outside diameter is from 1.2 m to 1.0 m. The main pressure steel pipe is divided into three branch pipes by two bifurcated pipes upstream of the main workshop, which enter the workshop forward through the ball valve.

In this project, the bifurcation pipes are arranged in a narrow position in the main factory area, so the bifurcation pipes are arranged in a linear manner. The main axis and the longitudinal axis of the main factory building are at an Angle of 5°, while the branch pipes are perpendicular to the
longitudinal axis of the factory building. The bifurcation pipe section is 12.556 m long and consists of two bifurcation pipes and a section of connecting pipes. The length of no.1 bifurcation pipe is 4.273 m, with an average diameter of 0.978~0.8 m; the length of no.2 bifurcation pipe is 4.143 m, with an average diameter of 0.8 ~0.505 m. There are three branch pipes with an inner diameter of 0.5 m, all of which connect the branch pipe and branch pipe through elbow pipe. Since the calculation principle and method of 1# bifurcation pipe and 2# bifurcation pipe are the same, this paper mainly discusses the design calculation and analysis method of crescent-ribbed steel bifurcation pipe with 1# bifurcation pipe. The plane layout of the bifurcation area of this project is shown in figure 1.

3. Bifurcation Pipe Type Selection
The design of bifurcation pipe requires reasonable structure, no excessive stress concentration and deformation, small head loss, less eddy current and vibration, and easy to manufacture, transport and installation. Based on the above requirements, this project chooses two types of three-beam bifurcation pipe and inner reinforced crescent-ribbed bifurcation pipe for economic and technical comparison. The inner reinforced crescent-ribbed bifurcation pipe has the following advantages [2]:

(1) The acting point of the main bifurcation and bifurcation conical shells on the strengthened floor force is located in the tube, and the crescent floor is inserted to make the cross-section centrepiece coincide with the acting point of the resultant force, so that the crescent floor is mainly subjected to axial tensile stress. The section can be designed according to the same strength, the floor size is correspondingly smaller, and the force of the bifurcation pipe is reasonable [3].

(2) The main cone of the crescent-ribbed bifurcation pipe is inverted cone-shaped, which reduces the turning Angle of the pipe wall, makes the geometric shape transition smoothly, and reduces the stress concentration at the bending Angle of the waist line.

(3) Because the main cone of the crescent-ribbed bifurcation pipe is inverted, the flow condition is improved, the hydraulic flow state of the bifurcation pipe is smooth, and the water head loss is reduced more than that of the general bifurcation pipe.

(4) The furcated pipe reinforced beam adopts crescent shaped intercalated floor plate, and the outer reinforced U beam and waist beam are cancelled, which greatly reduces the external dimension of the furcated pipe, facilitates transportation and installation, and reduces the amount of outsourced concrete work.

The internal reinforced crescent-ribbed bifurcation pipe has the advantages of low production cost, small head loss, small size of the bifurcation pipe, good stress condition and easy to arrange [4], so the internal reinforced crescent ribbed bifurcation pipe is finally selected.

4. Bifurcated Pipe Design
In order to meet the requirements of uniform force, small head loss and smooth flow, the key to the design of bifurcated pipe body is to correctly select the bifurcated sphere radius, bifurcated Angle and the bend Angle of pipe waist line. If the radius of the common cutting sphere is too large, the thickness of the pipe wall will be increased and the external dimension of the bifurcation pipe will be increased. On the contrary, if the radius of the common tangent is too small, the total stress and local stress of the
The bifurcation pipe will increase, and the thickness of the pipe wall will also increase. If the value of waist line folding angle is too small, the number of pipe segments is bound to increase, thus increasing the bifurcation pipe size. On the contrary, if the waist line angle is too large, the number of pipe joints will decrease, at the same time, the head loss and the local stress of the pipe wall will increase.

The internal stiffened crescent-ribbed bifurcation consists of the basic pipe joint, the floor and the transition pipe joint. The basic pipe section is the main pipe and branch pipe connected with the floor plate. The transition pipe section connects the front and rear steel tubes to the basic pipe section one by one, generally taper pipe or elbow pipe. The diameter and direction of water flow between the pipe and the bifurcation pipe are adjusted by the transition pipe joint. For the convenience of comparison, the corresponding relationship between the number of each tube segment in figures 2 and that in table 1 is as follows: tube segment 1, 6 and 8 are the first vertebral body, tube segment 2 and 5 are the second vertebral body, and tube segment 3, 4 and 7 are the third vertebral body.

In accordance with "Design Specification for Pressure Steel Pipes for Hydropower Stations" NB/T35056-2015 [1], the division of each pipe segment shall meet the following requirements in the design of bifurcated pipe body: (1) The minimum bus length after each pipe section is expanded shall not be less than 300mm, so the pitch value of each cone in each section along the waist line must be controlled at the same time to make it reasonable and convenient for manufacturing. (2) Since the Angle of the adjacent tube joint shell will affect the water head loss of the bifurcation tube and the stress concentration of the tube wall, the Angle should be small but not large. (3) The intersecting line of adjacent pipe joints should be designed according to binary conic curve (controlled by common cutting ball). (4) In order to meet the requirements of smooth water flow, the shell edges of the main pipe and one side of the main bifurcated pipe should be arranged into a straight line in addition to expanding pipe diameter with inverted cone and adjusting the transition pipe joint. (5) The difference value of the wall thickness shall not exceed 4mm if the wall thickness of adjacent pipe joints changes.

There is a mutual restriction relationship between the radius of the common tangent sphere RT, the radius of the small head section of the tri-cone Ri, the bifurcation Angle ω23, the half-cone αi, and the waist line folding Angleθij, and the pitch s and d of the tri-cone along the waist line [5]. According to the specification requirements, the parameters selected in the bifurcation pipe shape design of this project follow the following principles: (1) The spherical radius of the bifurcation pipe body is 1.1~1.2 times of the small-head radius of the main cone. (2) The bifurcation Angle of the bifurcation pipe is suitable for 55°~90°, and the bifurcation pipe is suitable for a small value [6]. (3) The half-cone top Angle of the main cone of the bifurcation pipe body and the main bifurcation cone is suitable for 10°~15°, the half-cone top Angle of the bifurcation cone can be about 20°, and the difference of the
half-cone top Angle of each section is between 4°~7°. (4) The bending Angle at the waist line of bifurcation pipe body and the bending Angle at the transition of each cone is suitable for 10°[7].

The shape design and calculation of 1# bifurcation tube are carried out based on the above design principles. The final selected bifurcation tube shape and parameters are shown in figure 2 and table 1.

| Table 1. Bifurcation pipe design parameters. |
|----------------------------------------------|
| Name                          | Geometric parameters | Symbol | The main | The main | The |
| Connect cylindrical tube radius(mm) |                       | Ri(0)  | 489      | 400      | 400  |
| Section 1 Radius of common tangent between cone and cylindrical tube(mm) |                       | RT(0)  | 489      | 400      | 400  |
| Half cone apex Angle(degree) |                       | ai(1)  | 0°       | 0°       | 0°   |
| Capitulum radius(mm)         |                       | Ri(1)  | 489      | 400      | 400  |
| Radius of common cut sphere(mm) |                      | RT(1)  | 400      | 400      | 400  |
| Distance from cone head to center of common cut ball(mm) |  | Ai(1)   | 599.5    | 798.6    |      |
| pitch(mm)                    |                       | Si1    | 491      | 461      |      |
| pitch(mm)                    |                       | di1    | 440      | 440      |      |
| Half cone apex Angle(degree) |                       | ai(2)  | 6°       | 3°       | 0°   |
| Capitulum radius(mm)         |                       | Ri(2)  | 486.3    | 399.5    | 400  |
| Radius of common cut sphere(mm) |                   | RT(2)  | 546.7    | 440.5    | 400  |
| Distance from cone head to center of common cut ball(mm) | | Ai(2)   | 599.5    | 798.6    |      |
| pitch(mm)                    |                       | Si2    | 549      | 773      | 454.6|
| pitch(mm)                    |                       | di2    | 440      | 706      | 440  |
| Half cone apex Angle(degree) |                       | ai(3)  | 12°      | 9°       | 10°  |
| Capitulum radius(mm)         |                       | Ri(3)  | 534.4    | 435.3    | 393.9|
| Radius of common cut sphere(mm) |                   | RT(3)  | 667.3    | 667.3    | 667.3|
| Distance from cone head to center of common cut ball(mm) | | Ai(3)   | 695.4    | 1517.3   | 1608.8|
| pitch(mm)                    |                       | Si3    | 567      | 1432     | 602.6|
| pitch(mm)                    |                       | di3    | 440      | 500      | 1403 |
| Bifurcation Angle of bifurcation |                  | ω23    | 55°      |          |      |

5. Structure Design of Bifurcation Pipe

5.1. Calculation of Pipe Wall Thickness of Bifurcation Pipe

According to the relevant literatures and experiments, the failure of crescent-ribbed bifurcated tube usually occurs at the waist line break Angle in the obtuse Angle area, so the wall thickness of film stress zone and local stress zone should be calculated at the same time when calculating the wall thickness of the bifurcated tube, and the large value of both should be used [8]. In the calculation of wall thickness, the internal water pressure is the maximum internal water pressure under both normal and short operating conditions (hydrostatic test conditions). According to the hydraulic calculation results of pressure pipeline, the maximum internal water pressure in normal operating conditions is $P_{\text{operating}} = 4.368\text{MPa}$, and the maximum internal water pressure in hydrostatic test conditions is $P_{\text{test}} = 5.46\text{MPa}$. In addition, in order to make full use of the material strength, different thickness can be used for each cone in each section of the bifurcation pipe according to the calculated results.

According to the maximum inner radius, half-cone apex Angle of each pipe segment calculated according to the body type and the above relevant parameters, the pipe wall thickness of each section of the bifurcated pipe is calculated as shown in table 2.
Table 2. The thickness of each pipe segment of bifurcation pipe.

| Name         | Union no. | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) |
|--------------|-----------|-----|-----|-----|-----|-----|-----|-----|-----|
| 1# Bifurcation| Thicknes (mm) | 24  | 24  | 24  | 24  | 20  | 20  | 24  | 20  |

5.2. Interior Reinforced Crescent Floor Design

Two conditions were considered in the design of the internal reinforcing crescent floor: (1) IN the testing condition. The bifurcation pipe end was welded with a plug and the pipe end was subjected to axial force. (2) In the operating condition, there is no axial force acting on the main pipe and branch pipe ends. Because the basic pipe joint is connected with the transition pipe joint, the deformation of the pipe end is constrained by the pipe system, and the internal water pressure is the basic load. The structural mechanics method was adopted in the calculation, and the detached body was analyzed separately with the floor plate, and the uniform distribution of internal water pressure was assumed. In this project, the influence of local bending moment and torque is ignored when calculating the width of the central section of the floor.

The design principle of the inner reinforced crescent floor is as follows: the resultant force of the tube shells on both sides of the main bifurcation and bifurcation on each section of the floor should be as close as possible to the core of the section, so that the floor is mainly subjected to tensile force. The width of each section of the floor should be designed according to the same strength conditions [9]. Due to the pipe diameter of the bifurcation pipe in this project is small, to simplify the calculation, the intersecting line of the main bifurcation pipe and the bifurcation pipe is taken as the contour line of the outer edge of the crescent-rib, and the outer edge of the rib is determined according to the parabolic contour by adding a certain manufacturing margin. The width of each section of the floor can be determined by determining the outer contour and inner edge line of the floor.

The design of the inner reinforced crescent floor includes the following aspects:

1. Angle calculation between three cone two intersecting line and three cone axis: each Angle value is determined by the geometric relationship between half cone Angle $\alpha_i$ of each cone bifurcation pipe and the Angle $\omega_{ij}$ of each cone bifurcation pipe axis. The calculation result is shown in table 3.

Table 3. The Angle between two intersecting lines of three cones and the axis of three cones.

| Name | $\rho_{12}$ | $\rho_{21}$ | $\rho_{13}$ | $\rho_{31}$ | $\rho_{23}$ | $\rho_{32}$ |
|------|-------------|-------------|-------------|-------------|-------------|-------------|
| Number | 79°26′54″ | 79°33′6″ | 72°56′26″ | 73°3′34″ | 27°20′21″ | 27°39′39″ |

(2) Coordinate position calculation of the vertex of the crescent floor: the vertex of the floor is the intersection point of two intersecting lines on the middle surface of the three-cone. The main cone, main bifurcation cone and bifurcation cone coordinate system are set up at Center of the public cut ball when calculation. The coordinate system of the crescent rib bifurcation is as shown in figure 3.

Figure 3. Is a schematic diagram of vertex coordinate calculation of crescent floor.
(3) Floor vertex coordinates in the coordinate system is different. First of all, floor vertex coordinates in the bifurcation cone coordinate $\chi_3c$, $Z_3c$ and branch cone vertex in a circular tube section in the corresponding central Angle $\theta_3c$ should be calculated. Then according to coordinate transformation, the vertex coordinate value $\chi_{1c}$, $Z_{1c}$, $\chi_{2c}$, $Z_{2c}$ in the main cone coordinate system and vertex in the corresponding taper pipe section in the circle the corresponding central Angle $\theta_{1c}$ and $\theta_{2c}$ should be calculated. The calculation results of coordinate value of the crescent floor vertex in each coordinate system are shown in table 4.

Table 4. The coordinate value of the apex of the crescent floor.

| Name | $\chi_{1c}$ | $Z_{1c}$ | $\theta_{1c}$ | $\chi_{2c}$ | $Z_{2c}$ |
|------|-------------|----------|---------------|-------------|----------|
| 02c  | -11.05      | 16.34    | 90°55′58.4″   | 4.46        | -19.21   |
| 03c  | 89°34′29.3″ | 18.29    | -7.36         | 88°27′21.0″ | 91°32′39.0″ |

(4) The horizontal projection length $a$ of the intersection line between the middle surface of the tube shell and the middle surface of the floor, and the distance $2b$ of the top and bottom of the floor: According to the correlation between the coordinates of the top of the floor, the radius of the main spinal canal, the Angle of the top of the half cone and other geometric parameters, the calculated results are as follows:

1# bifurcation tube horizontal projection length $a=1299.0$ mm
Distance between ribbed top and bottom $2b=1357.2$ mm

(5) The floor waist width $BT$ and thickness $tw$: According to the experience curve in the specification, when the Angle of bifurcation pipe of the bifurcation $\beta=55^\circ$, the ratio of the rib width $BT$ to the horizontal projection length $A$ of the middle surface of the shell and the intersection line of the rib $BT/a = 0.41$, so $BT = 0.41a=540$ mm. The thickness of the ribbed slab is determined by the vertical force on the ribbed cross-section, the ribbed width $BT$ and the allowable stress. The thickness of floor plate is calculated as $tw=54$ mm. The inner edge curve of the floor is determined by the following parabolic equation $y^2 = 678.62(759-\chi)/759$.

(6) Calculation of rib outer curve coordinates: calculate the intersection line between the middle surface of the main bifurcated tube and bifurcated tube and the middle surface of the rib, which can be used as the basic contour line of the rib outer edge line. The production margin of 100mm can be added to determine the outer edge curve of the floor [10]. According to the calculation results, the elevation of 1# bifurcation pipe crescent floor is shown in figure 4.

![Figure 4. Elevation of crescent floor.](image)

5.3. *Final Shape of the Bifurcated Tube*

According to the bifurcation tube shape design, structure design and crescent rib design, the final bifurcation tube shape is shown in figure 5.
Figure 5. 1# bifurcation diagram.

6. Conclusion
The key to bifurcated tube design is the shape design. Only after the shape is preliminarily determined, can the structure calculation be carried out, and the result of the structure calculation can be used to verify the rationality of the shape design. In this project, bifurcation pipe type is determined and bifurcation pipe type is preliminarily drawn on the basis of referring to the bifurcation pipe type of a large number of constructed projects. After repeated calculation and comparison, the geometric dimension and structural thickness of bifurcation pipe are finally determined. The bifurcation pipe of the power station has been running well after hydrostatic test and put into operation, which proves that the structure design of the bifurcation pipe is reasonable and the structure design is safe and reliable.

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