Numerical Analysis of Pelton Nozzle Jet Flow Behavior Considering Elbow Pipe

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Abstract. In Pelton turbine, the dispersion of cylindrical jet have a great influence on the energy interaction of jet and buckets. This paper simulated the internal flow of nozzle and the downstream free jet flow at 3 different needle strokes. The nozzle model consists of the elbow pipe and the needle rod which supported by 4 ribs. Homogenous model and SST k-ω model were adopted to simulate the unsteady two-phase jet flow. The development of free flow, including a contraction process followed by an expansion process, was analysed detailed as well as the influence of the nozzle geometry on the jet flow pattern. The increase of nozzle opening results in a more dispersion jet, which means a higher hydraulic loss. Upstream bend and ribs induce the secondary flow in the jet and decrease the jet concentration.

1. Introduction

Pelton turbine mainly manipulate the high velocity jet flow to impulse buckets on the runner. Through the regulation of the nozzle numbers, a multi-nozzle Pelton turbine can be operated under the wide range of output power maintaining high efficiency[1]. While, the secondary flow induced by the bifurcation, elbow and ribs may increase the jet dispersion and deflection, which will reduce the jet concentration and unit efficiency.

Peron et al compared the jet surface at model and prototype heads and conclude that the jet at high head has an increased external thickness of mixed air-water flow, which lead to a more dispersed jet[2]. Zhang et al obtained the jet velocity profile by LDA method and figure out the secondary flow induced by elbow will result in disturbance on the jet surface[3]. Staubli et al compared the efficiency and jet flow pattern for the one nozzle operations in a two-nozzle Pelton turbine, and observe that the larger jet diameter corresponds to the lower efficiency. They also simulate the jet deformation at model scale and predicted a highest values of the secondary flow magnitudes about 3% of the jet axial velocity[4]. Han et al predicted the jet diameter, contraction position and expansion rate of a model jet[5]. Benzon et al parametric investigated the impact of nozzle angle, spear angle, spear tip curvature and injector scaling on injector losses and optimized the injector design using CFD[6]. Zheng et al optimized the nozzle and needle geometry by simulating the one phase water flow[7].

The jet deformation may decrease the efficiency of Pelton unit about 0.4~0.8% estimated by Staubli et al[2]. This paper simulated the free jet flow injected by a nozzle with elbow pipe upstream. The influence of secondary induced by the elbow and ribs on the jet flow patterns were investigated.
2. Simulation model

2.1. Governing equations

This simulation adopted the homogenous model and SST $k-\omega$ model. The homogenous model can be used to predict the interface shape of two immiscible fluids. This model introduces volume fraction of each phases and the interface shape can be obtained from solving the volume fraction of the phases in each control volume. A single group of governing equations is solved throughout the computation domain, which is dependent on the volume fractions of two phases through the properties $\rho$ and $\mu$.

A $k-\omega$ based SST turbulence model with automatic wall function and curvature correction was adopted for high accuracy boundary layer simulations. This model uses the Wilcox $k-\omega$ model in near wall regions and the standard $k-\varepsilon$ turbulence model in the fully turbulent region far away from the wall. The transition between the two models is guaranteed by the automatic near wall treatment. Curvature correction takes the elbow curvature into account\cite{8}.

The continuity and momentum equations discrete using a high resolution scheme with the physical advection terms weighted by a gradient-dependent blend factor. While a second order backward Euler scheme is used for the transient terms.

2.2. Physical model

Figure 1 shows the computational domain which consists of nozzle and downstream space. Diameter of nozzle throat is $D_1$. Inlet diameter is $1.67D_1$. Outlet of downstream space is $9.66D_1$ to the nozzle tip. The elbow angle was 120 degree. This paper simulated three different needle strokes of $0.13D_1$, $0.27D_1$ and $0.46D_1$. Thus, the relative needle strokes ($sn$) were 0.13, 0.27 and 0.46.

![Figure 1. Computational domain](image1)

The computational domain was divided into 4 parts, elbow domain, nozzle domain, jet domain and air domain. Elbow domain was discretized into structured hexahedron mesh. Nozzle domain was discretized into unstructured tetrahedral mesh. The 3D axisymmetric grids of jet domain and air domain were obtained by rotated the 2D mesh\cite{9}. Figure 2 shown the mesh distributions. Total nodes number was 2,145,000 and element number was 2,657,000.

![Figure 2. Mesh distribution](image2)
The total pressure was set at the pipe inlet according the operating water head. Outlet and outer boundary of air domain were set as opening with relative static pressure of 0 Pa. Water volume fraction was set as 1 and 0 at inlet and outlet respect.

3. Simulation results

3.1. Shape and geometric characteristics of jet flow

Figure 3 shows the predicted free jet as an isosurface at the water concentration $c=0.5$. The predicted jet shape deformed along the flow directions and deviates from the ideal conical. There were four buckles on the jet surface. Jet surface of $sn=0.46$ bulged out at the four coordinate directions. While jet surfaces of $sn=0.13$ and 0.27 only bulged out at the negative Y direction and caved in the other three coordinate directions.

(a) Jet shape of $sn=0.13$

(b) Jet shape of $sn=0.27$

(c) Jet shape of $sn=0.46$

Figure 3. Jet shapes of three needle strokes

The predicted jets were projected on the Plane xOy and xOz to obtain the jet outline variations as shown in Figure 4. Jets contracted after flowing out the nozzle and then follows an inflation progress along the flow direction. It clearly depicted the jet inflated much greater at the negative Y direction than the other three coordinate directions. In other word, the predicted jets deflected towards the inner side of the elbow.
Jets’ diameter variations on Plane xOy and xOz were obtained by subtraction of the two jet outlines on each plane, as shown in Figure 5. Jet contraction positions for $sn=0.13$, 0.27 and 0.46 were $1.4D_1$, $1.3D_1$ and $0.9D_1$ to the nozzle tip. Jet inflation angles for $sn=0.13$, 0.27 and 0.46 were 0.64, 1.23 and 1.99 degrees on Plane xOy. It clearly depicted that the predicted jet contracted faster and then dispersed more severe at larger needle stroke.

3.2. Secondary flow patterns analysis
Secondary flow induced by the upstream bend and ribs would influence the predicted jet flows. Surface streamlines on Section 1 were shown in Figure 6. The secondary flow induced by the elbow would results in the fluid near the center of the pipe moving toward the outside and the fluid near the pipe wall moving inwards. Fluid near the pipe wall had a greater velocity magnitude of the secondary flow than the fluid near the pipe center. The maximum secondary flow velocity magnitude can be
about 40% of the main flow velocity. Two secondary circulation flows symmetrical located on two sides of the section and deflected a little to the inner side of the elbow.

Figure 6. Secondary flow on Section 1

Figure 7 shows the secondary flow on Section 2 which is perpendicular to the jet axial direction and not influenced by the needle structure. The maximum velocity magnitude of the secondary flow on Section 2 was smaller than that on Section 1 with the same needle stroke, while the secondary flow distribution changed a lot. These two circulation flows on Section 2 had moved towards the inside elbow wall and became closer to each other than that on Section 1. Thus the fluid moving inward or outward the inner side of the elbow has a greater secondary flow velocity than the other area on Section 2. As the needle stroke increased, the impact area of secondary circulations became closer to the pipe wall.

Figure 7. Secondary flow on Section 2

Figure 8 shows a continued decline velocity magnitude of the secondary flow on Section 3. Because of the four supported ribs, water flow was divided into four parts. The circulations induced by elbow dominated the secondary flow in the two regions corresponding with the inner side of elbow. In the other two regions, new secondary flow characteristic appears. Fluid near the rib on the Y direction flows tangentially toward the rib on the Z direction.

Figure 8. Secondary flow on Section 3
3.3. Jet flow patterns analysis

Jet development in air space can be divided into 2 stages, concentrates at first and then inflates. At the first stage, the jet flow has radial velocity component along the needle surface and the pressure energy was gradually converting into kinetic energy\(^\text{[10]}\). Thus, the jet axial velocity component increases after ejected from the nozzle tip, which results in the jet concentration stage. Because of the dissipation of two phase shear flow, wake flow induced by the needle and secondary flow induced by the upstream bend and ribs, jet average velocity decreased and the jet began to inflate after the contraction position.

Figure 9 chosen 4 positions to show the jet axial velocity distributions on Plane xOz for \(sn=0.13, 0.27\) and 0.46. Distances of the 4 positions to the nozzle tip were \(D_1, 1.5D_1, 3D_1\) and \(6D_1\). The axial velocity distributes nonuniform at each position. After ejected from the nozzle tip, jet flow was free from the nozzle wall, while center of jet flow still subject ed to the needle wall. Thus affected by the wake flow, center of jet flow has the lowest axial velocity. As the needle stroke increased, the needle wall posed less of an effect on the axial velocity at the same position.

![Jet axial velocity variation at sn=0.13](image)

(a) Jet axial velocity variation at \(sn=0.13\)

![Jet axial velocity variation at sn=0.27](image)

(b) Jet axial velocity variation at \(sn=0.27\)

![Jet axial velocity variation at sn=0.46](image)

(c) Jet axial velocity variation at \(sn=0.46\)

**Figure 9. Jet axial velocity variation on Plane xOz**

Figure 10 depicted the surface flow patterns at the position where has a distance of \(6D_1\) to the nozzle tip. Red lines are the predicted jet profiles at the water concentration \(c=0.5\). Black lines are ideal jet profiles calculated from the water volume flow rate and jet axial velocity. Tangential velocity and surface streamlines distributions indicted the secondary flow in the jet flows are similar for the three different needle strokes. Two circulations located at the negative Y directin corresponding to the inner side of the upstream bend. The other four circulations is corresponding to the secondary flow induced by the ribs. Tangential velocity distributions shown that circulations induced by upstream bend were stronger than that induced by the ribs. Also, the strength of circulations induced by the bend were greater as the needle stroke increased. Thus, the jet flows deflected to the negative Y direction more at larger needle stroke as shown in Figure 5. Although the jet diameters inflate little in the other three direction as shown in Figure 4, the three buckles located on the three directions indicated that the circulations induced by the ribs would deform the water jet.
4. Conclusion
This paper numerically simulated Pelton jet flow at three needle strokes. Secondary flow patterns induced by elbow and supported ribs were analyzed. Jet flow structures were discussed to analyze the influence of secondary flow on free jet flow. Main conclusions were as follow,

1. Upstream bend generated circulations at the inner side of the elbow pipe, which deflected the water jet to same direction.
2. Secondary flow induced by the needle ribs deformed the water jet shape at the position corresponding to the ribs.
3. Water jet flow has bigger inflation angle at larger needle stroke which means a greater hydraulic loss.

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