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Effect of Spear Needle Eccentricity on the Pelton Turbine Jet

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Abstract
In a Pelton turbine, the jet is one of the most important factor that impacts the energy generated by the runner. In this study, numerical investigation is conducted to understand the effect of eccentricity of the spear needle on the jet of the Pelton turbine. The results from the study show that the jet diffuses due to the eccentricity in the spear needle-nozzle assembly. The diffusion first increases and then decreases with the increase in the eccentricity. The asymmetrical flow area around the needle head due to eccentricity also affects the circumferential static pressure distribution. The results suggest that eccentricity has an adverse effect on the jet quality of the Pelton turbine. The deviation from a symmetrical jet is more pronounced in micro Pelton turbines that operate on low flow rates.

Keywords
Pelton Turbine, Pelton Turbine Jet, Nozzle, Spear Needle Eccentricity, Jet Diffusion

1. Introduction

In the context of Nepal, renewable resource such as hydropower is a viable option for local generation of electricity in rural and isolated locations. The rivers that flow in the mountain and the hilly regions of Nepal provide a high head due to which the Pelton turbine is best suited for micro-hydropower plants but the efficient extraction of electrical energy requires high performance buckets, runner and injector. In spite of these complications, micro-hydropower plants that generate a power of 1kW to 500 kW prefer Pelton turbines due to their cost effectiveness and flat efficiency curve [1]. The Pelton turbine is a high efficiency impulse turbine that operates on high head and medium flow rate conditions. The Pelton turbine was patented by Lester A. Pelton, patented on October 26, 1880. After the development, many modifications have been made over the years on the design of the nozzle and buckets to enhance its performance. Modern day Pelton turbine consists of the following parts: injector assembly, runner and buckets, casing and breaking jet [2].

The performance of a Pelton turbine depends upon the design of the runner, the buckets, the nozzle, the shape of the jet exiting the nozzle and the operating conditions [3]. Pelton turbine injector accelerates the flow for efficient extraction of the energy by the runner. The defects in the injector assembly of the Pelton turbine results in poor jet quality which affects the overall performance of the Pelton turbine [4]. The velocity profile of a perfectly centered spear needle shows an symmetry about the plane passing through the center of the jet with the minimum velocity located right at the center of the jet. However, the installation of a perfectly centred spear needle is very difficult in practice and errors in the re-installation process, the self-weight of the needle introduce eccentricity in the spear needle and non-uniform erosion of the nozzle.

Spear needle eccentricity in the injector is defined as the off-set of spear needle axis from the centre of nozzle [4] expressed as percentage (Equation 1).

$$e = \frac{s}{d} \times 100\% \tag{1}$$

Where, e is the eccentricity, s is the offset of the needle axis from the nozzle axis, d is the nozzle diameter and ϕ is the circumferential angle of the needle as shown in Figure 1.

Eccentricity in the injector causes mass imbalance which in coalition with high jet flow can cause vibration during operation [5]. Eccentricity also

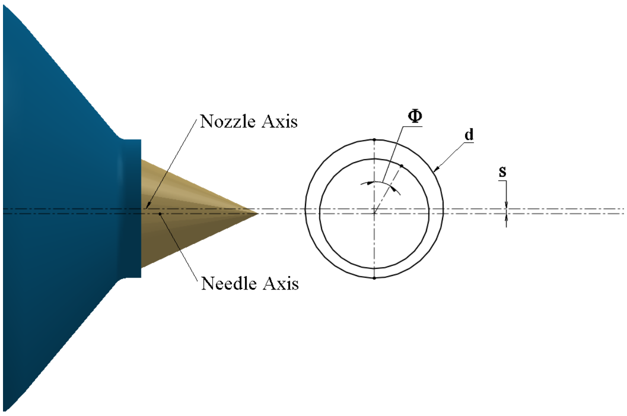


Figure 1: Eccentricity in the injector assembly

results in the axial diffusion of the jet which reduces the efficiency of the Pelton turbine. Jet diffusion severely degrades the performance of a Pelton turbine [6]. The decrease in efficiency due to jet diffusion is seen to be significant for low flow rates for a micro-Pelton turbine [4]. Although, the eccentricity in the injector greatly affects the performance of the Pelton turbine, most previous studies have only focused on the runner wheel and the buckets for the performance improvement of the Pelton turbine [7]. There are only a handful researches conducted to study the effects of eccentricity of the spear needle, thus, a thorough study on the issue of spear needle eccentricity and its effect on jet quality was deemed necessary. The effect of needle eccentricity on the jet quality was studied with the help of computational fluid dynamics (CFD). A CAD model of the injector assembly was modeled using SolidWorks. The model was meshed using ANSYS ICEM and the numerical simulations of the model for different eccentricities and flow rates were carried out on ANSYS Fluent.

2. Pelton Turbine Injector

Pelton Turbine injector assembly is a mechanism which converts potential energy of jet into kinetic energy and regulates the flow of jet in the Pelton Turbine. It receives the water through pen-stock and delivers water to the bucket after suitable regulation. The parts of the Pelton turbine injector are spear needle and injector nozzle. Spear needle sits inside the injector nozzle along the longitudinal axis. Spear needle is provided with a mechanism which provides movement of the spear needle along the longitudinal axis. This is the movement which helps in regulating the flow by altering water exit area.

The main function of the spear needle is to regulate the rotation of the Pelton wheel in response to fluctuating load conditions in order to generate the required amount of energy. During low load conditions, to reduce the energy generated by the Pelton turbine, the spear needle is moved forward, towards the Pelton wheel which decreases the outlet area. This reduces the flow rate, which in turn, reduces the momentum of the jet hitting the Pelton wheel. This decrease in momentum decreases the energy extracted from the jet by the Pelton wheel. During high load conditions, the spear needle is moved backward, away from the Pelton wheel which increases the outlet area. The increase in flow rate increases the momentum of the jet hitting the Pelton wheel which results in the increase of energy extracted from the jet.

The Pelton turbine requires water with high momentum which impinges on the Pelton wheel to generate impulse which rotates the Pelton wheel at the required angular velocity. The potential energy of the water that flows from the reservoir or directly from the river is converted into kinetic energy through pen-stock and injector. The conversion of the potential energy into kinetic energy in the Pelton turbine is explained by the Bernoulli's Equation (Neglecting Friction). The speed of jet is given by Equation 2. The energy transfer from jet to the Pelton wheel occurs with the change in momentum of the jet from the injector. This energy transfer is based on the Newton's second law of motion.

$$C_0 = \sqrt{2gH} \tag{2}$$

Where g is acceleration due to gravity and H is the net pressure head at the inlet of the injector.

3. Flow Study of the Pelton Jet

The geometry of the Pelton turbine injector assembly used for the study is adapted from [8]. The geometry of the needle was traced using dial gauge by mounting the injector assembly on a milling machine during the overhaul process. The CAD model of the spear needle and the nozzle was then designed using SolidWorks. The specification of the geometry dimensions and the operating conditions of the Pelton turbine injector assembly is given in Table 1.

The numerical study of the flow through the Pelton turbine injector assembly at different operating conditions was conducted with the help of ANSYS

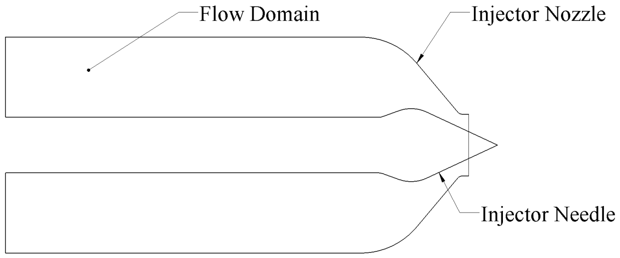


Figure 2: Geometry of the Injector Assembly

Table 1: Injector Geometry and Operating Conditions.

Specifications	Values
Flow Rate	6 kg/s
Pump Rating	6.3 kW
Nozzle Diameter	20 mm
Nozzle Angle	100°
Needle Angle	50°
Pressure	3 bar

FLUENT, a commercial CFD solver. For discretization of the flow domain, ICEM CFD was used. For capturing the viscous layer, inflation layers were used near the surface of the needle and the wall. Figures 3 and 4 show the mesh generation of the flow domain within the Pelton turbine injector assembly. Steady state fluid flow simulations were carried out for various flow rates at different eccentricities after the development of the CAD models and meshing. The realizable k-epsilon model was used as the viscous model. Table 2 provides additional information about the solver settings.

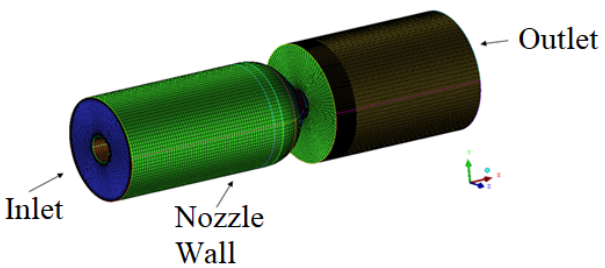


Figure 3: 3D mesh

4. Results and Discussion

4.1 Effect of Eccentricity on Jet Pressure Distribution

The change in flow area in the upper and lower sections of the nozzle due to the effect of eccentricity introduces

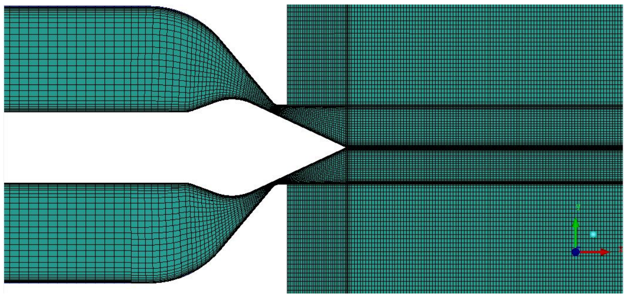


Figure 4: Longitudinal cross-section view of mesh

Table 2: Solver settings.

Parameters	Settings
Solver	Pressure-based
Space-time discretization	2^{nd} order upwind and steady
Viscous model	Realizable k-ε
Pressure-velocity coupling	SIMPLE
Inlet condition	Gauge pressure, 3 bar
Outlet condition	Gauge pressure, 0 bar
Reference pressure	1 bar
Convergence criteria	Scaled residual $<10^{-5}$, absolute

a pressure distribution on the jet which is measured along the circumferential surface of the spear needle at an axial distance of 20 mm from the needle tip. The relative pressure deviation was measured using Equation 3.

$$\delta = \frac{P_s - P_{av}}{P_{av}} \quad (3)$$

Where, δ is the relative static pressure deviation, P_s is the absolute static pressure at the needle wall and P_{av} is the average absolute static pressure at the needle wall.

To study the effect of eccentricity on the jet pressure distribution, the needle pressure distribution curve for various values of eccentricities at 50% flow rate was plotted, which is shown in Figure 5. The relative static pressure deviation is seen to increase as the eccentricity increases. This difference in the static pressure results in unbalanced force in the needle, which is one of the major reasons for the vibration of the needle. The pressure distribution is also responsible for jet diffusion.

Jet diffusion due to eccentricity is significant for low flow rates [4]. Thus, the needle pressure distribution

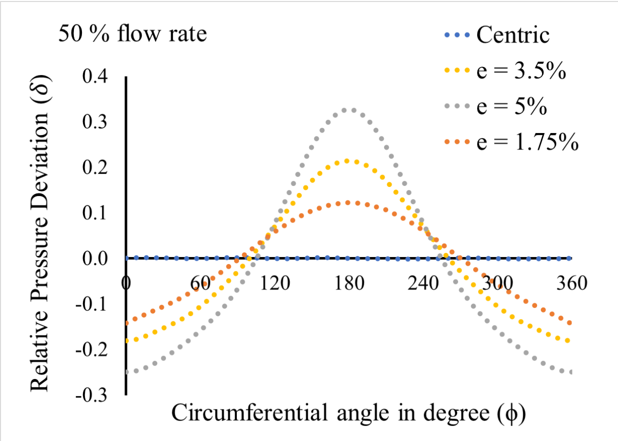


Figure 5: Pressure distribution along the needle circumference for 50% flow

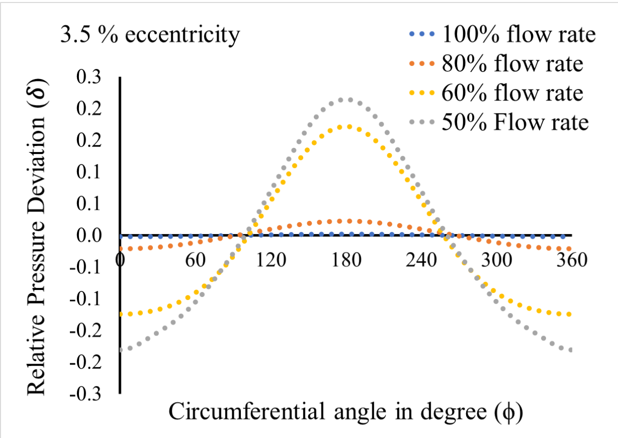


Figure 6: Pressure distribution along the needle circumference for e = 3.5%

at 3.5% eccentricity for various flow rates was generated to study the effect of eccentricity on jet pressure distribution for decreasing flow rates. This is plotted in Figure 6. At high flow rates (100% and 80%), the effect on the needle pressure deviation is seen to be negligible but as the flow rate is lowered (60% and 50%), significant effect is seen on the needle pressure deviation. This verifies that jet diffusion due to needle eccentricity is significant for low flow rates.

4.2 Effect of Flow Rate on Velocity Profile of the Jet

To study the effect of flow rate on the velocity profile of the jet in eccentric condition, velocity contours and the velocity distribution at needle tip generated for decreasing flow rates for 3.5% eccentricity, which is illustrated in Figure 7. The needle tip lies on y-axis and x-axis aligns with the nozzle axis.

From the velocity distribution at the needle tip, a velocity deficit can be seen at the jet core. The development of boundary layer on the surface of the needle is responsible for the formation of a velocity deficit, which shows a distinct boundary limit with the surrounding flow [2].

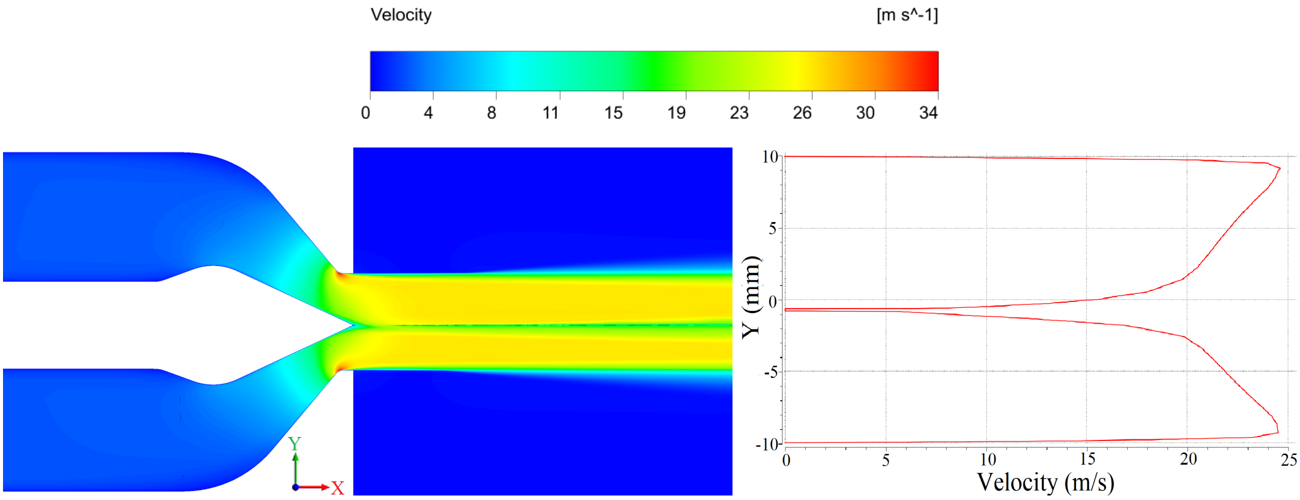
The velocity contours for different openings of the nozzle indicates that the jet becomes unstable as the flow rate decreases. . The upper and lower sections of the jet which are separated by the longitudinal axis of the spear needle show difference in flow characteristics, which is shown by the velocity profile. The maximum velocity of the lower section of the jet is seen to rapidly decrease as the flow rate decreases. This is because the area of flow in the lower section of the nozzle decreases significantly than the area of flow in the upper section, due to the eccentric bias. The velocity profile also shows that at 40% opening of the nozzle, the size of the lower part of the jet is approximately half of the size of the upper part of the jet. The difference in the size of the jet indicates velocity energy imbalance which reduces the efficiency of the Pelton turbine [4]. When the asymmetrical jet impacts on the bucket, it results in unbalanced forces which causes twisting and bending action that promotes vibration in the runner. This compromises the mechanical integrity of the Pelton turbine.

Thus, from this study, it is seen that the radial velocity profile of the jet is affected by needle eccentricity. The asymmetry between the upper and lower sections of the jet are seen to be drastic in lower flow rates, which significantly decreases the performance of the Pelton turbine.

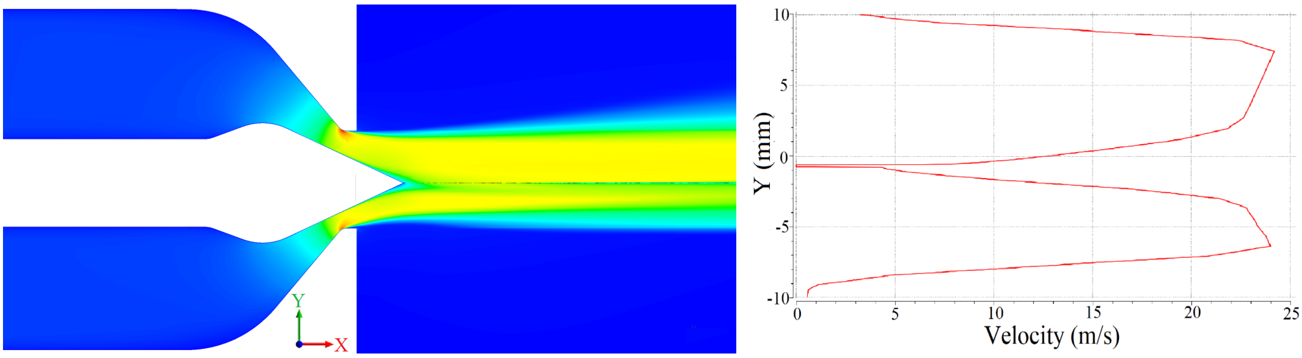
4.3 Effect of Flow Rate on Jet diffusion

The effect of the flow rate on the diffusion of the jet for 3.5% eccentricity was studied by generating the velocity streamlines. The diffusion angles for the upper and lower sections of the jet were measured from the streamlines. The angular diffusion for the upper section of the jet (α) and the lower section of the jet (β) is shown in Figure 8.

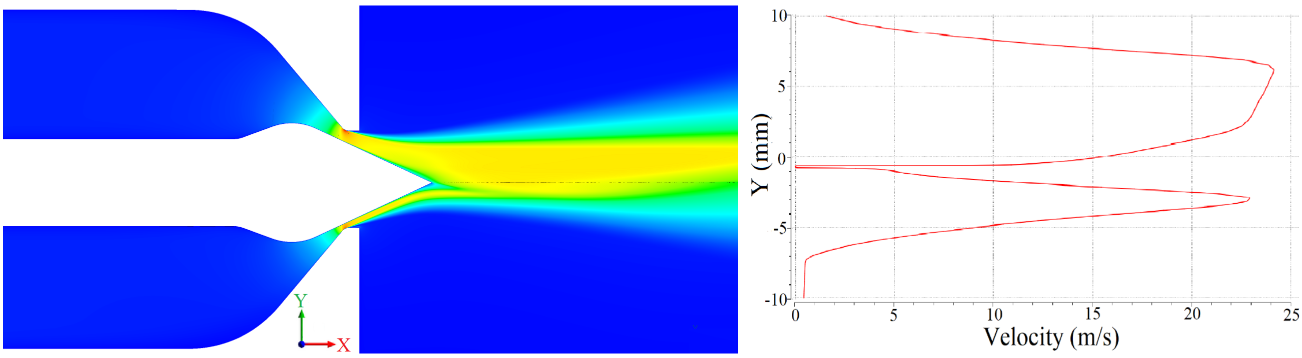
Velocity streamlines were generated using CFD Post and 3D CAD software SolidWorks was used to measure the diffusion angle of the jet. Figure 10 shows the velocity streamlines for various flow rates at 3.5% eccentricity. The upper and lower diffusion angels for various flow rates were plotted, which is



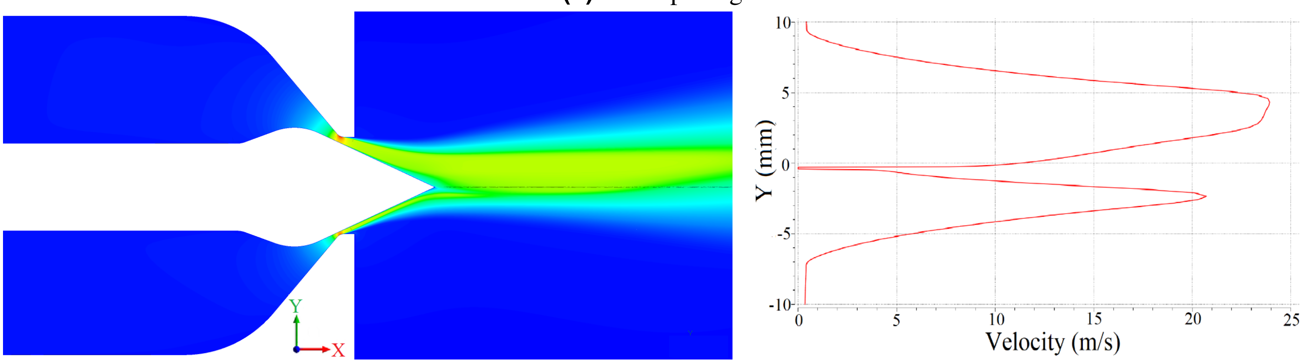
(a) 100% opening



(b) 80%opening



(c) 50% opening



(d) 40% opening

Figure 7: Velocity contours and velocity distribution at the Needle tip for various flow rates at 3.5% eccentricity

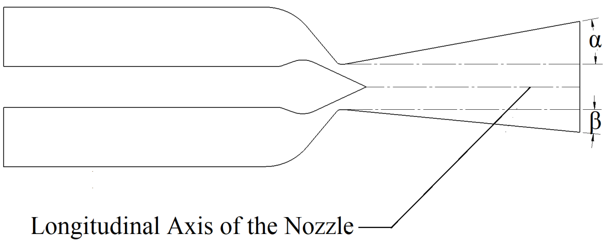


Figure 8: Upper diffusion Angle(α) and Lower Diffusion Angle(β)

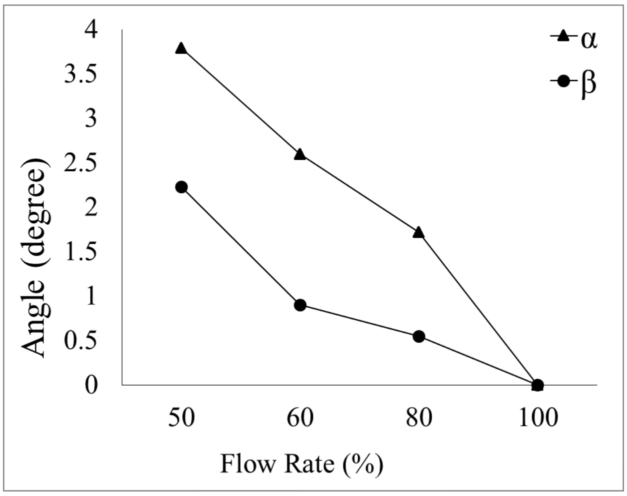
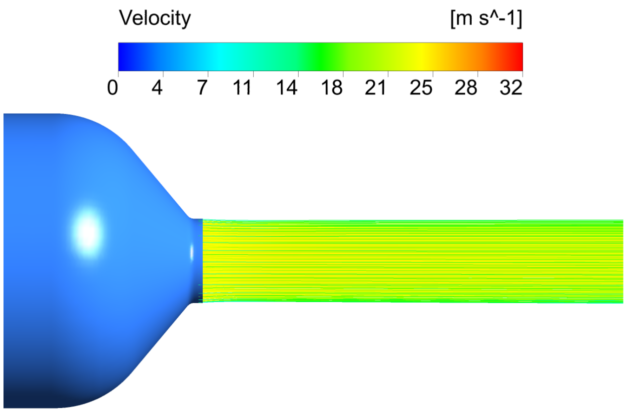
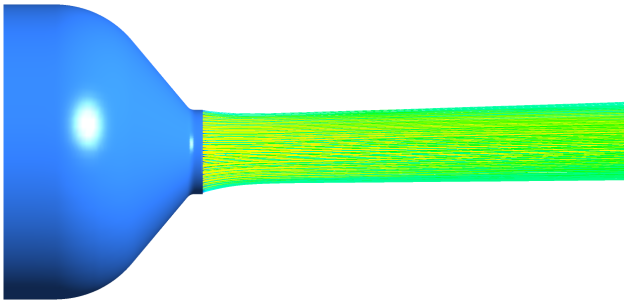


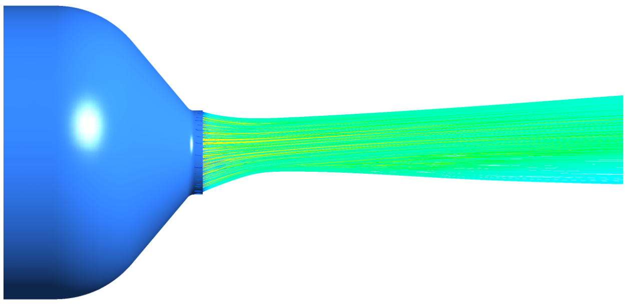
Figure 9: Variation in upper diffusion angle (α) and lower diffusion angle (β) with change in flow rate



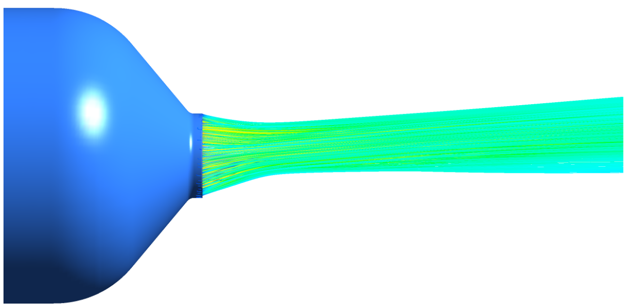
(a) 100% opening



(b) 80% opening



(c) 50% opening



(d) 40% opening

Figure 10: Velocity streamlines for various openings at 3.5% eccentricity

shown in Figure 9. The upper and lower diffusion angles are seen to increase as the flow rate decreases. The change in α is seen to be somewhat gradual but the change in β is seen to be abrupt as the flow rate changes from 60% to 50%. This is due to the abrupt decrease in the flow area of the lower section of the nozzle.

4.4 Effect of Needle Eccentricity on Jet Diffusion

Jet diffusion was seen to significantly increase at low flow rates. To study the effect of eccentricity on the jet diffusion at low flow rates, numerical simulations were conducted for various eccentricities at 50% flow rate. The velocity streamlines for analysis of jet diffusion for various values of eccentricity for 50% flow rate is shown in Figure 12. It is seen that jet diffusion increases as the value of eccentricity increases. As a result, the upper section of the jet has a greater area than the lower section of the jet.The upper and lower diffusion angels for various flow rates were plotted, which is shown in Figure 11. α increases linearly with variation in the eccentricity. However, this is not the case for β, which is seen to increase abruptly as the eccentricity increases. This is also is due to the abrupt decrease in the flow area in the lower section of the nozzle.

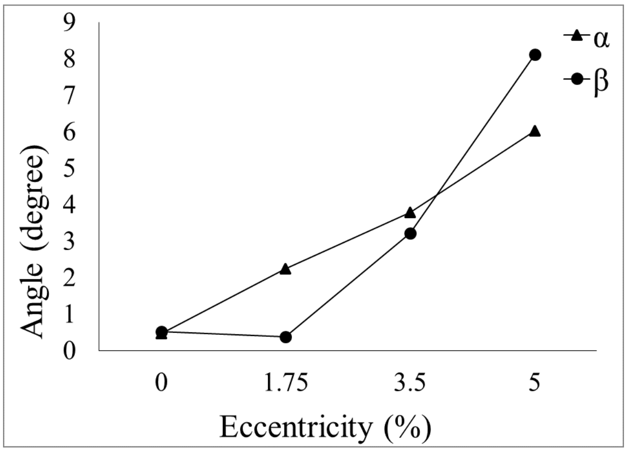


Figure 11: Variation in upper diffusion angle (α) and lower diffusion angle (β) with change in eccentricity

5. Conclusion

Numerical investigation of the jet was carried out to determine the effect of needle eccentricity on the jet quality. From the numerical investigation, a relative change in the static pressure along the circumferential angle of the needle was observed for eccentric needles. This change in the static pressure results a force in the needle which may be one of the major reasons for vibration of the needle. This change in the relative static pressure was also found to increases abruptly with lower flow rates and higher eccentricities. The diffusion of the jet from the normal condition was also observed from the fluid flow simulations. This diffusion occurs due to the change in relative static pressure and velocity across the circumferential angle. The diffusion in jet is seen to increase as the flow rate decreases an the value of eccentricity increases. This results in a poor jet quality that reduces the efficiency of the Pelton turbine.

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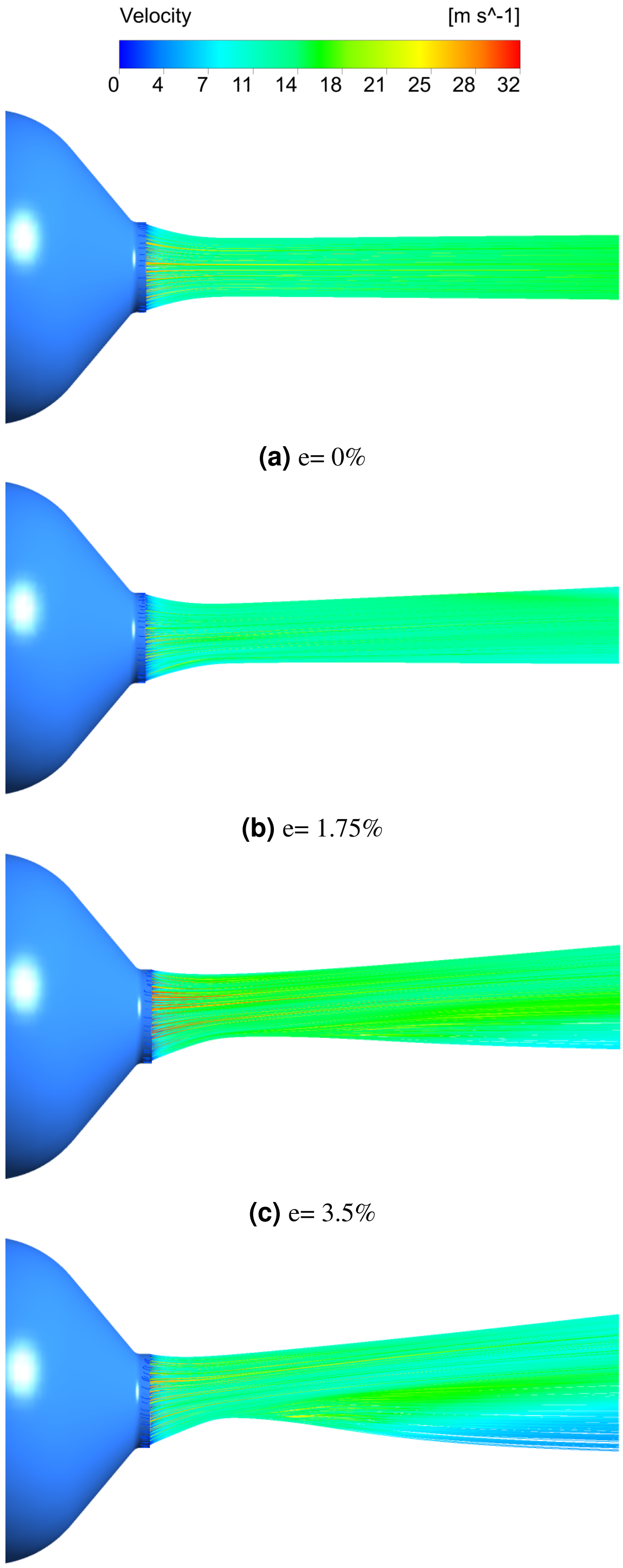

(a) e= 0%

(b) e= 1.75%

(c) e= 3.5%

(d) e= 5%

Figure 12: Velocity streamlines for various openings at 3.5% eccentricity

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