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Numerical modelling of the sand particle flow in pelton turbine injector

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Abstract

Pelton turbine is commonly employed high head impulse type turbine. Pelton turbine injector is an integrated part of the Pelton turbine machine which serves the purpose of converting entire pressure energy of water to kinetic energy and also regulates the water flowrate, with partial opening hence governing the power production. Severe erosion in Pelton turbine injector is reported from field setting research studies. Since the jet is atmospheric pressure jet, there is few chances of occurrence of cavitation hence it can be understood that impact of sand particles is the major cause of erosion. Furthermore, with turbine operating in partial flow condition, more erosion is reported in the needle of injector. For a long spear type injector, this study explores the cause of erosion by modeling the motion of the sand particle flow in steady state jet. For numerical modeling of the flow, the realizable k-epsilon model is used and for modeling the particle flow, the Discrete Phase Model (DPM) is used. Three different operating condition of the injector is considered and 77000 particles were injected to the flow domain. It is observed from the numerical simulations that the more sand particle hits the nozzle-needle surface with partial opening of the injector.

Keywords: *Injector, needle, pelton turbine, sand particle motion.*

1. Introduction

One of the operational problems being faced by South-Asian hydropower plants is the heavy flow of sediments through the generating units causing severe erosion of the hydro mechanical parts (Thapa, 2004). The main cause of this heavy sediment inflow during a particular season (May–October) is the weak and fragile geometry of the Himalayas and its hills (Bajracharya et al., 2008). The heart of the power plant, the turbine's performance deteriorates thus affecting the overall efficiency of the power plant as it erodes. The erosion is thus not only associated with financial losses due to less efficiency but also with increase in maintenance cost (Felix et al., 2016).

There are many perineal water sources, the rivers in Nepal and it is estimated that the economically feasible power potential of Nepal from these fresh flowing rivers is about 43,000 MW (Thapa, 2004). However, the rivers are loaded with enormous sediment during May-October season, due to heavy rainfall and the weak and fragile geometry of the Himalayas. The incessant and stochastic nature of the monsoon rain in the mountainous catchment area of these rivers are also responsible for the generation of an enormous amount of sediment in these rivers (Pandit, 2005; Poudel et al., 2012). A specific case study (Chhetri et al., 2016) of sediment loading of the Langtang river, one of the rivers located in central Nepal, reveals the sediment loading data as follow:

- Pre-monsoon: 37.69 tons per day
- Post-monsoon: 11.52 tons per day,
- Monsoon: 872.86 tons per day
- Lowest value: 5.54 tons per day (winter season)

The sediment loading is composed of minerals like quartz, feldspar, mica, granite, tourmaline, clay, organic matters etc. Detailed mineralogical analysis of the sediment content reveals the domination of hard minerals (hardness > 6 on Moh's scale) like quartz and feldspar (Bajracharya et al., 2008; Neopane & Sujakhu, 2013; Poudel et al., 2012). Generally, the hardness of turbine material is about 6 on Moh's scale. Hence, these hard minerals possess higher erosion potential. In addition, the sharp nature of their particles further adds up the erosion potential. Hydropower projects have well engineered desanding (or desilting) arrangements like gravel trap, settling basin. Despite such arrangements, sand particles of size < 2 mm (maximum size) passes through the turbine parts causing severe erosion. Despite heavy investments of time and finances to understand the erosion mechanism and its prevention techniques, the phenomenon is not yet clearly understood. It is well understood that beforehand prediction of such failures due to eroded parts will help engineers to predict the optimal repair time thus preventing damages, hazards and ensure operational safety of hydropower projects.

Solid particle erosion is a term in tribology referring to the loss of solid materials containing fluid flow due to impingement of suspended solid matters in the flowing fluid. Among several variables affecting the solid particle erosion of slurry erosion, Javaheri et al. (2018) has classified the variables to four headings and have constructed a fish bone diagram (Javaheri et al., 2018). Broadly speaking, the erosion due to sand particles in hydro turbines are due to following causes (Brekke et al., 2010)

- Turbulence erosion: Erosion due to high turbulence in the boundary layers
- Accelerated flow: Due to flow acceleration, particles are separated from flow and collide with the walls.
- Vortex erosion: Formation of vortices due course of flow will trap particles within it thus causing erosion in region of vortex formation due to repeated impact on the wall

Pelton turbine holds special place in Nepal for its application in both major hydropower plants as well as in micro hydro schemes for rural electrification. Review of field setting researches of Pelton turbine erosion reveals that the erosion prone areas in Pelton turbine are:

- Needle surface
- Needle seat in nozzle
- Bucket Surface
- Bucket Splitter

Fig. 1 summarizes the erosion from two hydro power plants.

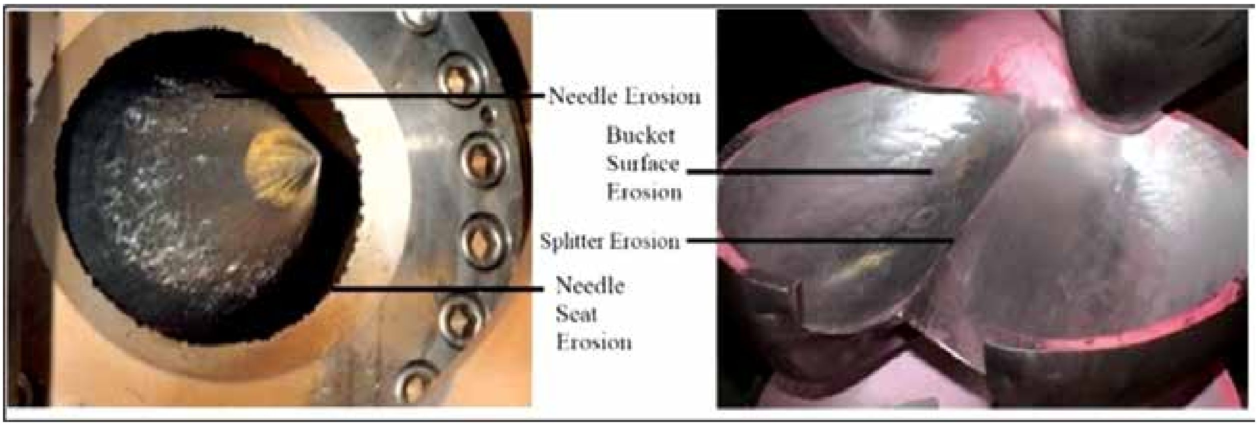

Figure 1: Typical erosion in Pelton turbine parts (On left: Mel Norway On Right: Bucket of Khimti Powerplant, Nepal) Image Courtesy: Neopane et al. 2011.

1.1 Erosion Studies of Pelton Turbine Needle

Bajracharya et al. (2008) did a field setting research and laboratory research to reveal the empirical relation between loss of efficiency due to sand particle led erosion of Pelton turbine. The authors measured the eroded needle profile after fixed operational hours of the runner (see Fig. 2).

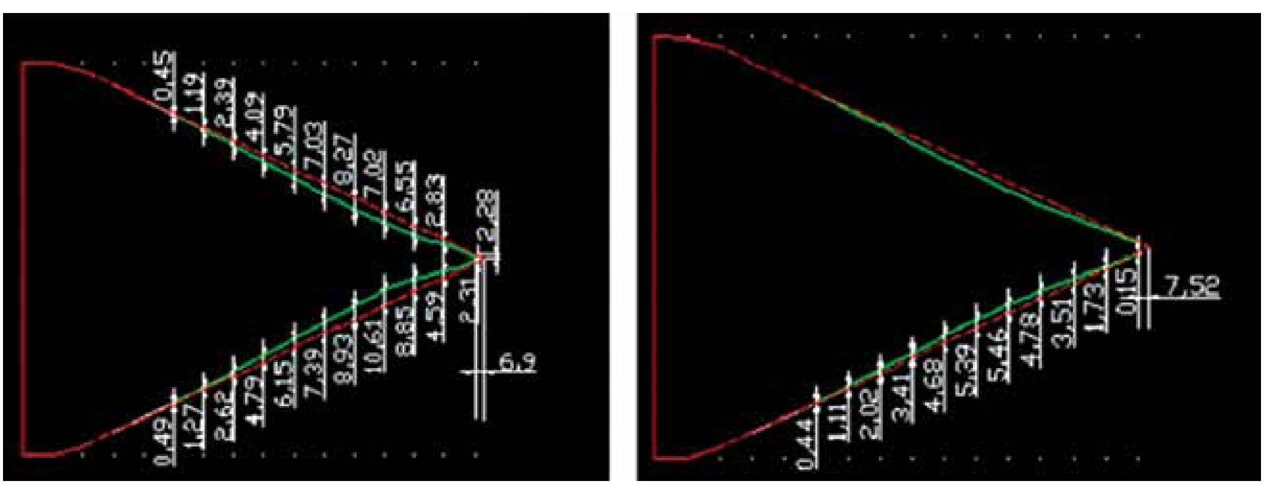

Figure 2: Erosion of Pelton turbine needle at Chilime HPS, Nepal (Adapted from Bajracharya et al. 2008)

The authors observed that the needle erodes more between the nozzle exit and needle tip. Needle tip itself is free from erosion. The authors explain the observed phenomenon based on relation between erosion and particle velocity (ε_{α} α V_p^3). The authors explain that with the decreasing cross-sectional flow area, the flow velocity increases (continuity equation) thus increasing the rate of erosion as flow approaches the needle tip and near the tip, the force on the needle surface is low and jet flows under atmospheric pressure hence needle tip doesn't erode much. The actual eroded needle is shown in Fig. 3. The eroded needle is seen to be have in depth erosion.

Figure 3: Needle damage due to erosion at Chilime HPS, Nepal

Neopane et al. (2011), in review of erosion of hydraulic turbines have revealed the images of eroded nozzle and needle of Andhikhola HPS and Khimti HPS of Nepal. From the Fig. 4, it can be observed that there is uniform wear of the nozzle (in the needle seat) and scaly erosion is seen in the Needle surface.

Figure 4: Erosion in nozzle and needle (On left, erosion in nozzle ring of Andhi Khole HPP, Nepal and needle erosion in Khimti HPP, Nepal (Adapted from Neopane et al. 2011)

Morales et al. (2017) experimentally studied about the erosion of Pelton turbine injector of Chivor hydroelectric plant, Columbia. The authors have also developed a test rig to study and develop empirical relation of nozzle-needle coatings and wear. The needle erosion of Chivor hydropower station has in depth erosion and is similar to that observed by Bajracharya et al. 2008. ANDRITZ hydro (Karandikar, 2015) performed the field test of HVOF Coatings to combat hydro abrasive erosion. The study reveals images (see Fig. 5) of coated and uncoated needles in a two nozzle Pelton turbine and concludes that the coated needle has four times longer life than the coated needle.

Figure 5: Erosion study in coated needle (Image Courtesy: Andritz Hydro)

The nature of erosion observed in injector is not similar as large scale erosion is seen in the needle surface and there is breakage of the needle tip. As classified in literature, all types of erosion are observed in the needle. It can be understood that the difference in erosion nature is due to site specific condition of the sediment, operating condition and of course the injector design.

The Pelton turbine injector not only converts the pressure energy of the water to the kinetic energy but also controls the flowrate of the water, the governing action. Among the turbine components, the first one to interact with the sediment-laden water is the injector which thus suffers from erosion wear. The direct effect of the erosion is change in shape of the nozzle and needle thus altering the jet dispersion, jet velocity thus the energy content of the jet. In an experimental investigation about the jet dispersion, it has been concluded that poor jet quality is major cause of cavitation in bucket. In this study, the motion of sand particle in the jet is modeled using a commercial computational fluid dynamics package for correlating the motion of sand particle and erosion prone areas as observed from field setting researches.

2. Methodology

The flow region (flow domain) is modeled in Three-Dimensional Computer Aided Design (3D CAD) software and then discretized (meshed) using ICEM. The structured mesh was then exported to a commercial CFD code where, the boundary condition and solver settings for fluid and flow properties, convergence criterion were defined. The numerical simulation was carried out using SIMPLE algorithm for pressure velocity coupling, realizable k epsilon model for modeling turbulence. The realizable k epsilon model is modification to the traditional k epsilon model by giving a benefit of better performance in simulation of planar and round jets (ANSYS Inc, 2013), rotation, recirculation and streamline curvature (Wasserman, 2021). The Pelton turbine jet has streamline curvature in at nozzle exit and is expanding jet (Bajracharya et al. et al., 2019; Zhang, 2016).

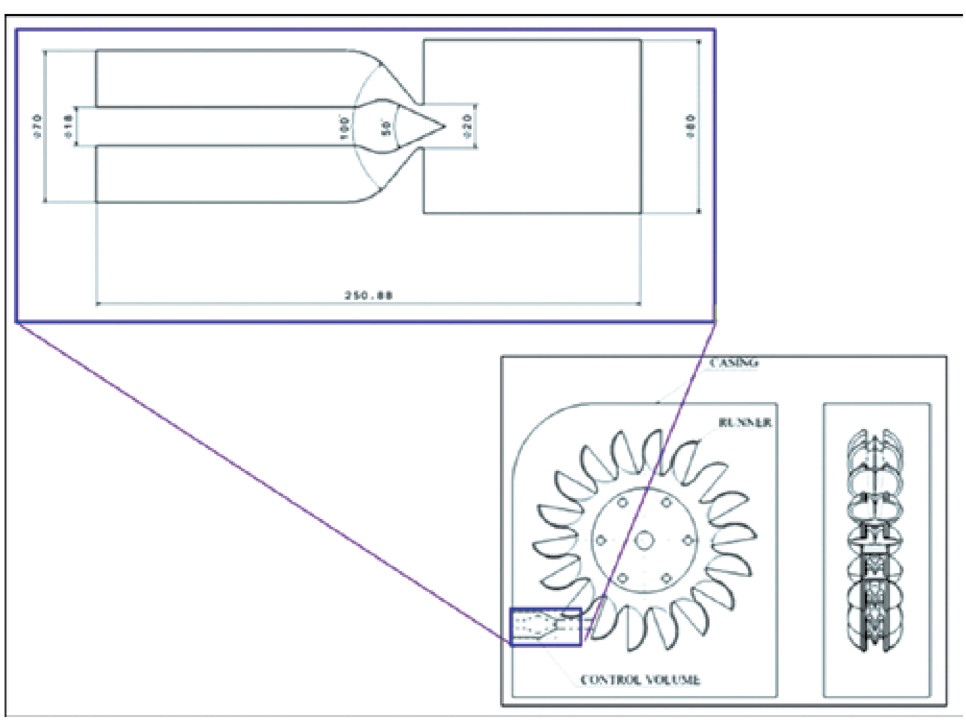

Figure 6: Flow domain.

Fig. 6 is the flow domain, the dimensions of the injector are those of a 2 kW model Pelton turbine test rig (Bajracharya et al., 2007) located at Center for Energy Studies, Institute of Engineering. To better capture the viscous layer effects, the fine mesh was used in the needle wall and in the nozzle wall. The axially symmetric nature of the flow domain made the choice of O-grid optimum in this case. Fig. 7 and 8 give the boundary conditions and longitudinal section of the mesh.

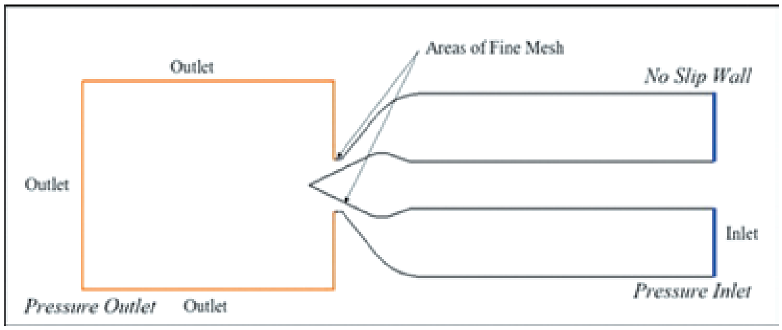

Figure 7: Boundary and boundary conditions

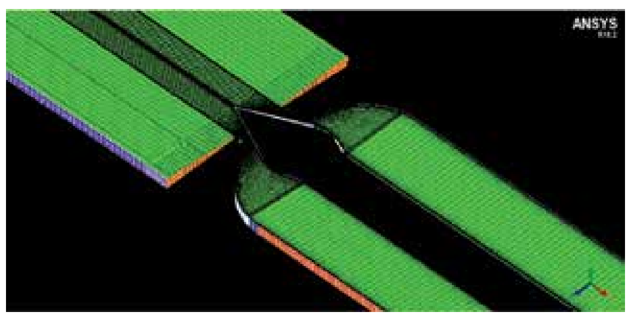

Figure 8: Meshing details

The numerical value at pressure inlet was set at 3 bar (gauge) while the pressure outlet was assigned value of 0 bar (gauge). The boundary values were chosen based on the measured value from Pelton turbine test rig at Center for Energy Studies (Bajracharya et al., 2007). The solver settings used is summarized in table 1.

Table 1: Summary of solver settings

Solver	**Three-Dimensional, Steady State, Pressure Based**
Time discretization	Steady State
Discretization scheme	Second Order
Turbulence model	Realizable k-epsilon
Flow	Single Phase, Discrete Phase Modeling for Modeling Particle Flow
Convergence criteria	RMS, Scaled residual target = 10–6
Hardware	Processor: Intel Core i7 @ 3.6 GHz (8 CPUs). Memory: 32 GB

As the flow simulation results were converged, then 77000 sand particles from were introduced normally from inlet to the flow. In the validated flow model, particles with maximum diameter 2 mm were introduced and nature of its flow along with the jet was studied for three different condition. The particle size distribution of the sand sample used for the study is shown in Fig. 9.

- Fully-open injector
- Quarter-closed injector
- Half-closed injector

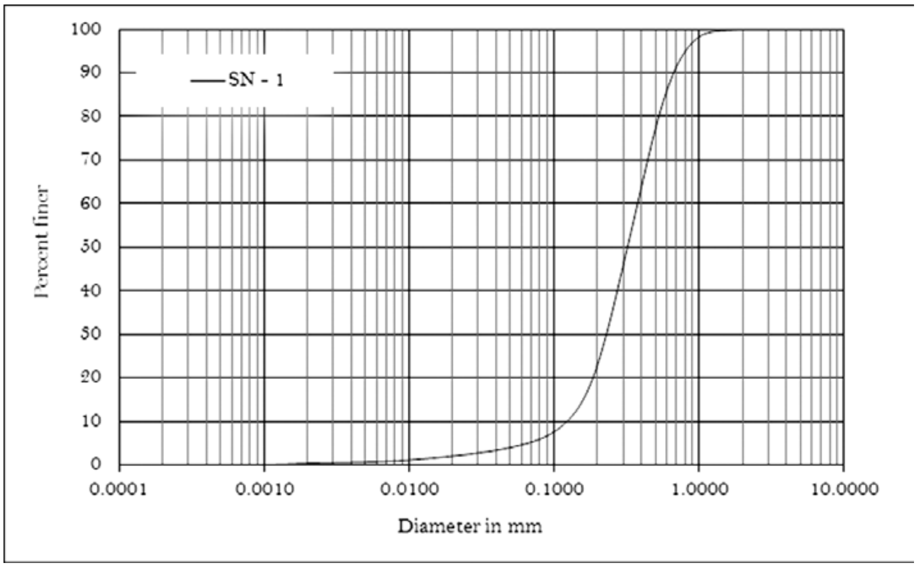

Figure 9: Particle size distribution of sand sample (Rosin Rammler Fitted Curve)

For different injector openings, the motion of sand particles was studied. For estimation of the number of particles that hit a particular wall, the wall was set to trap the particles and number of particles that were trapped were counted and subtracted with the number of particles trapped with wall set to rebound condition however after detailed observations of the particle flow, it was seen that few numbers of particles were rebounding after hitting the nozzle and then hitting the needle in partial opening condition.

3. Results and Discussion

3.1 Flow Modeling

The steady state jet was modeled and the flow velocity, velocity profile and jet geometry are compared with experimentally observed one (Fig. 10). The details are published in Bajracharya et al. (2019) and is briefly summarized here.

3.1.1 Velocity profile

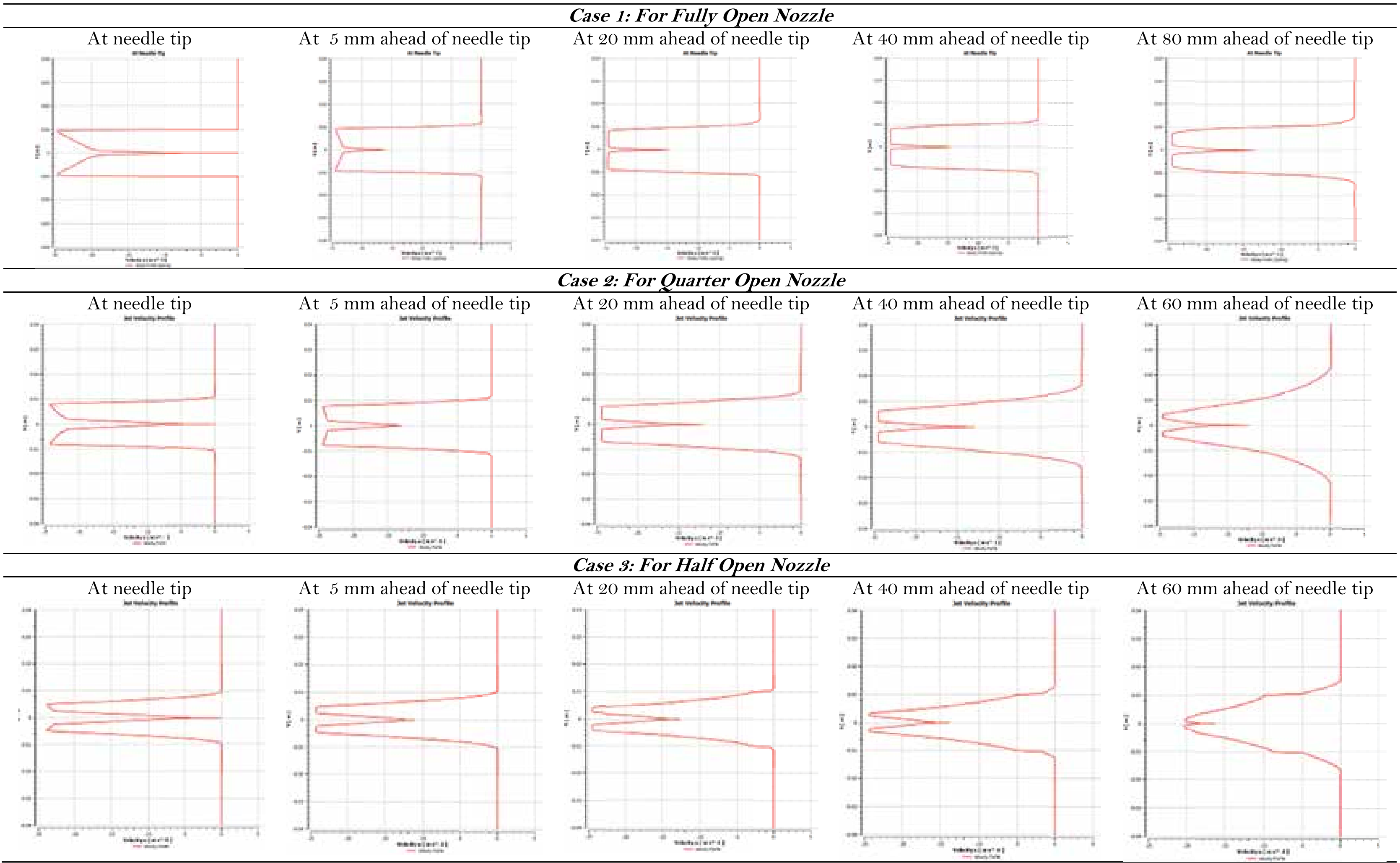

Figure 10: Velocity Profile (Detail Image Attached in Appendix Section)

The obtained velocity profile (summarized in Fig. 10) reveals that at needle tip, the jet velocity is zero and as the jet moves forward the velocity in the region ahead of the tip increases. The jet velocity is maximum between the needle tip area and jet surface making the overall velocity profile of "B" shape.

Zhang et al. (2016) experimentally studied the jet velocity distribution (using Laser Doppler Anemometry. The jet velocity obtained from computational simulations and experimental modeling are in good agreement

3.1.2 Jet geometry

An ideal jet is supposed to have uniform velocity distribution in each cross section and the jet diameter is constant without any contraction or expansion (Zhang, 2016). Experimental investigations of the jet (Staubli & Hauser, 2004; Zhang & Casey, 2007) reveal that the real jet deviates from this ideal form. The real jet first contracts after it exits from the nozzle and then it expands. The geometry of jet flow obtained also matches with the experimental observation. Fig. 11 shows the jet geometry for half open injector. The jet contraction ahead of the nozzle exit can be seen. This contraction is associated with jet energy loss.

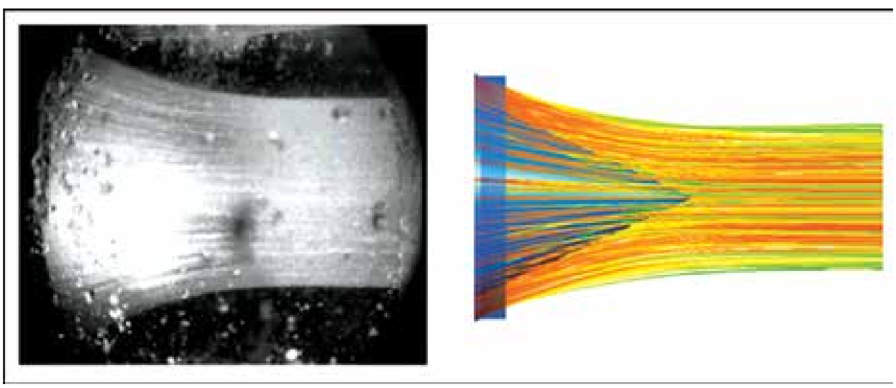

Figure 11: Jet geometry for half open injector (Right image courtesy of Staubli et al. 2004)

3.2 Particle Flow Modeling

3.2.1 Fully-open injector

Fig. 12 shows the motion of the sand particles in fully open injector. A close observation of the nozzle exit area reveals none particle interacting with the needle surface while few particles exiting near the nozzle surface are hitting the needle seat area. Hence, the direct impingement of the particles in the needle seat causes its wear. Further, it can be said that the uniform hitting of the particles will cause even wear of the needle seat. The simplified representation of the trajectories is presented in Fig. 13.

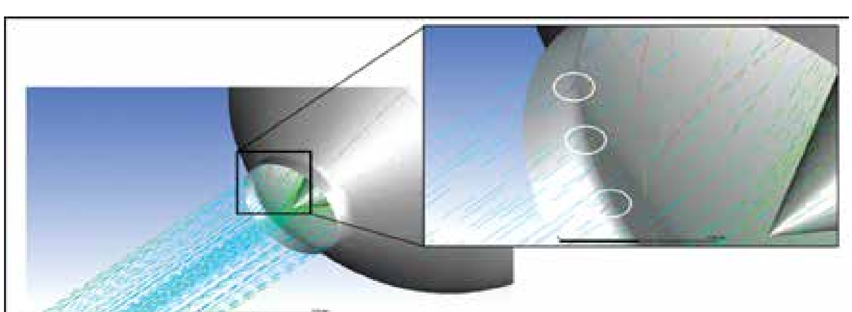

Figure 12: Particle motion for fully open injector

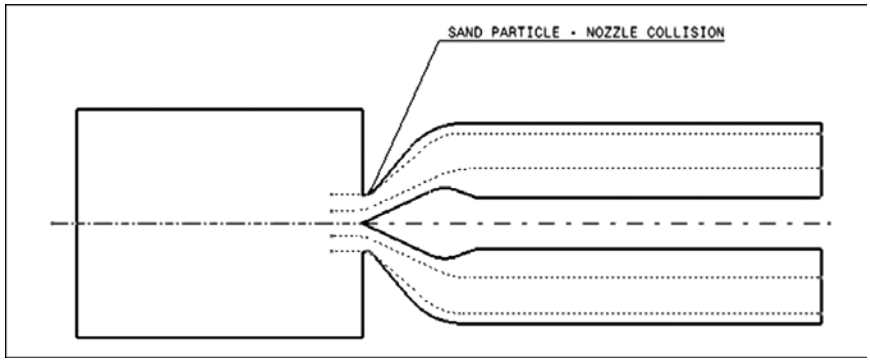

Figure 13: Particle Trajectories for fully open injector

3.2.2 Quarter-closed injector

Fig. 14 shows the motion of the sand particles in quarter closed injector. The particles in addition to hitting the needle seat partly hits the needle surface just upstream of the tip. The impingement angle is seen to be between 0 to 20 degrees. The simplified representation of the trajectories is presented in Fig.15.

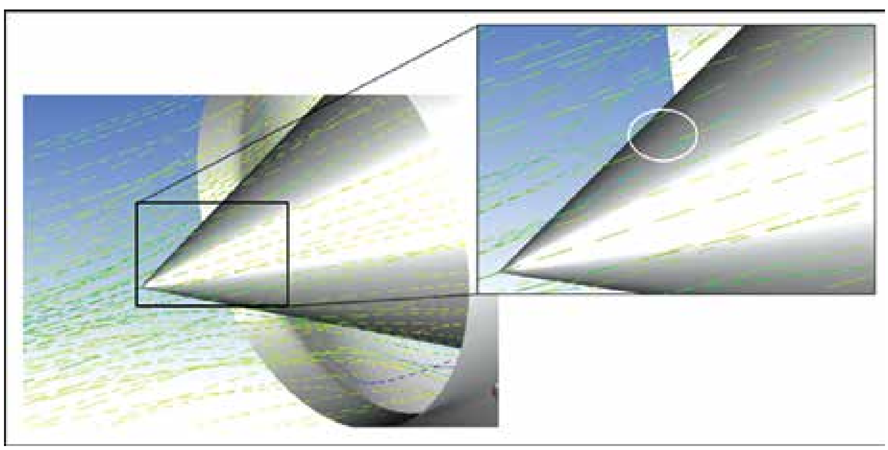

Figure 14: Particle motion for quarter closed injector

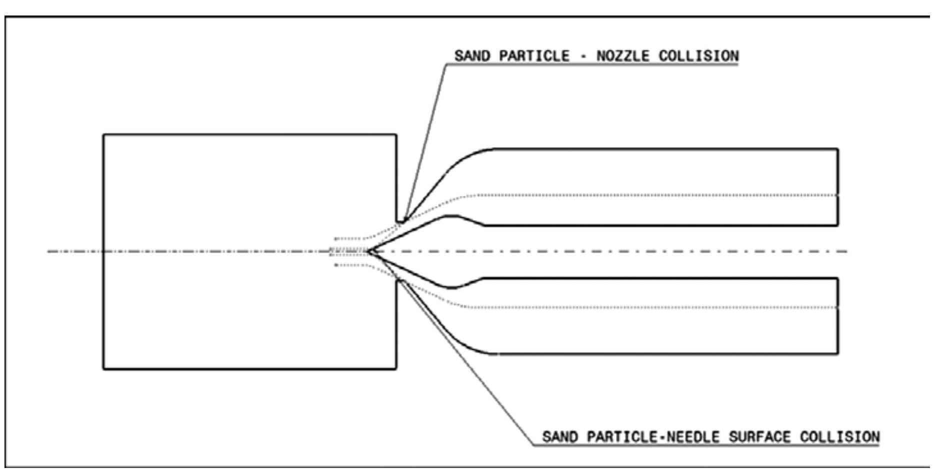

Figure 15: Simplified particle trajectories for quarter closed injector

3.2.3 Half-closed injector

In case the injector is half closed, the particle strikes in region between the needle tip and nozzle exit not uniformly but randomly on a specific region (see Fig.16 and 17). The needle surface-sand particle interaction increases more in comparison to the quarter closed condition. This shows that more erosion can be expected if the turbine is operated on partial load. This supports the findings of Bajracharya et al. (2008) who stated that erosion is directly related to the loading condition of the machine and it is dangerous with regards to erosion to operate the machine in part load.

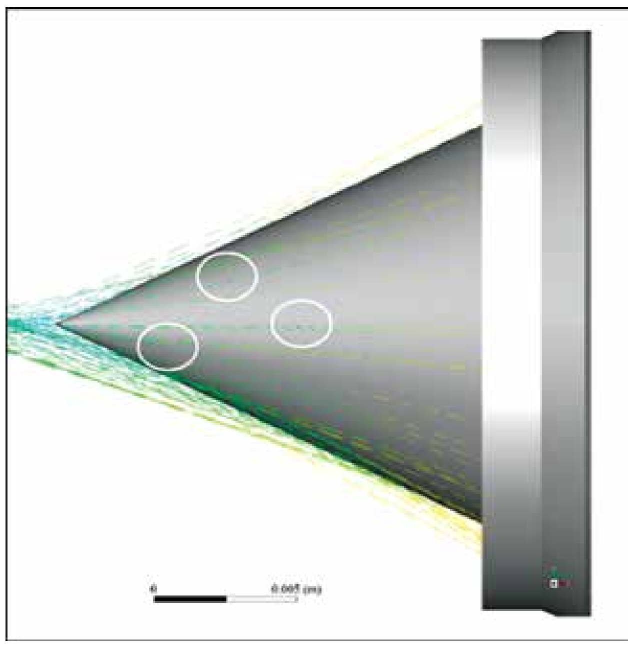

Figure 16: Particle motion for half-closed injector

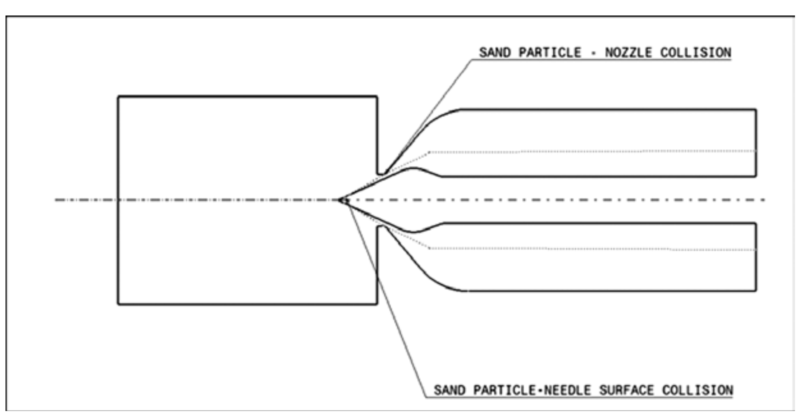

Figure 17: Simplified particle trajectories for half-closed injector

The detailed flow of the particle in the flow domain along with flow region classification is shown in Fig.18. With manual counting, it was seen that among 100 particle trajectories, 19 particles hit the nozzle wall and among these 19, 12 particles were hitting the needle after rebound and 10 particles were hitting the needle wall without rebound from the nozzle exit.

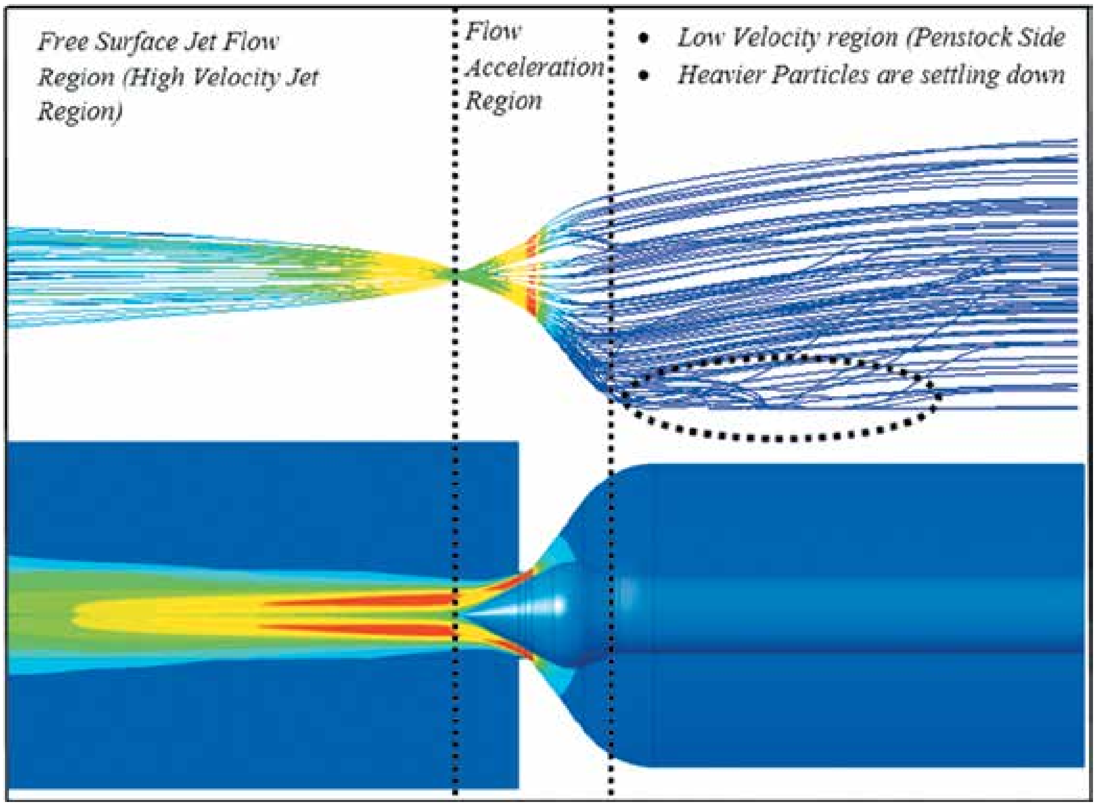

Figure 18: Flow velocity and particle motion

As seen from the Fig. 18, The heavier particles are settling in the low velocity region just upstream of nozzle beginning. The particle motion converges to a point ahead of the needle tip then disperses.

Table 2: Summary of particle – wall interactions for different cases

S.N.	Case	Number of Particles hitting (among 100 particles)		
		Nozzle	Needle	Needle-Nozzle
1.	Fully Open Injector	15	-	-
2.	Quarter Open Injector	17	-	14
3.	Half Open Injector	19	10	12

3.3 Erosion

Erosion models are deduced by either theoretically by energy balance for particle-target wall collision or experimentally by formulating empirical relations or by dimensional analysis (Bajracharya et al., 2020). The first proposed erosion model to evaluate progressive loss of material was by Finnie in 1960 (Finnie, 1960). The erosion model proposed by Finnie is more suited for ductile materials, where the major variables are impact angle and velocity. Among several theoretical erosion models proposed thereafter, impact angle and velocity are those variables which are mostly considered for evaluation of progressive loss of material. Figure 19 shows the erosive behavior of ductile and brittle material. The Pelton turbine injector is manufactured by steel, a ductile material. From Fig. 12-17 it can be observed that the impact angle of most particles hitting either the nozzle or needle is 10 to 30 Degrees for which Fig. 19 shows maximum erosion.

Fig. 18 shows the particle trajectories for half open injector. As observed from field setting research there is asymmetrical nature of erosion of the needle (Bajracharya et al., 2008) i.e., needle erosion is mostly not uniform and less erosion is seen in the back side of the needle (the part attached to the needle stem). It can be deduced from the particle motion that a greater number of particles (also heavier) travel from the downward side of the needle causing more erosion on the downward part of the needle. Upon division of the flow domain on the basis of flow velocity (hence particle velocity), it can be seen that the backward side of the needle lies in low velocity region hence few or less erosion is observed in the backward side. In addition, the impact angle of particles is near to right angle thus causing minimal erosion damage.

Table 2 summarizes the number of particles (among 100 particles) that hit selected surfaces. For fully open injector, the particles hit only the nozzle at exit only. The region is also maximum velocity region (see Fig. 18), these high speed particles when hit the nozzle at the exit, cause mass of nozzle to erode. Among 100 particles, 15 particles hit the nozzle at exit area. The number of particles hitting nozzle is fairly constant for other two cases with slight increase for partially open injectors. For the case of needle, no particles hit the needle for fully open injector while with partial opening, some particles that hit the nozzle and rebound towards needle were hitting the needle before leaving the injector domain. The number of particles hitting the needle has increased with partial opening and for half open injector, 22 particles were found to be hitting the needle. The hitting area was area ahead of nozzle exit. The impact angle of the particle was around 10 to 30 Degrees for region near tip and was greater than 30 Degrees for region farther from the tip. Hence as seen from field setting researches (Neopane et al., 2011; Thapa, 2004) more erosion can be expected at near tip region with less erosion upstream of the needle tip.

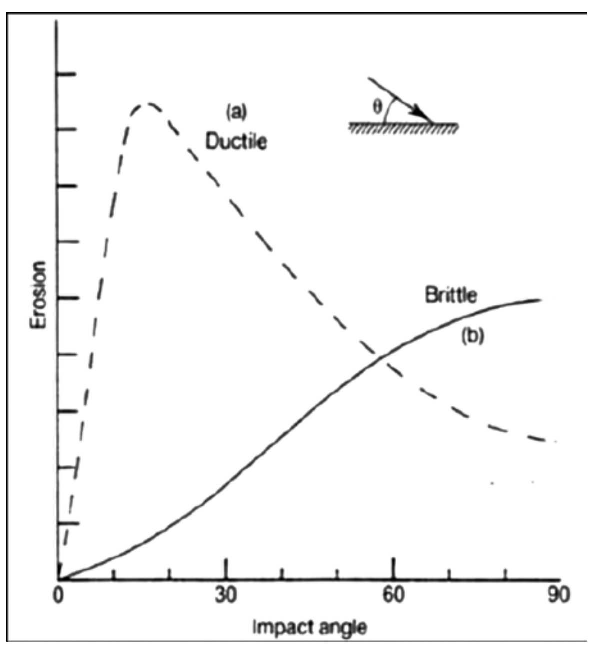

Figure 19: Erosion behavior of materials (Hutchings, 1981)

4. Conclusions

With single phase steady state approach, the motion of sand particles as it passes from long spear type Pelton turbine injector is studied with DPM Model. The major objective was to study the trajectory of particles to understand erosion behavior of the injector. With nozzle and needle combining to form an injector assembly, as seen from field setting research, there is ring type erosion around the periphery of nozzle and for needle, more erosion is seen towards the tip with decreasing erosion rate in upstream region.

It was seen that number of particles hitting the nozzle exit is uniformly distributed hitting with fairly constant (15, 17 and 19 for fully open, quarter open and half open injector respectively) and the impact angle is 10 to 30 degrees. From velocity distribution, it was seen that the nozzle exit is the maximum velocity area. Hence for nozzle erosion is relatively constant no matter of operating position.

For needle, it was observed that number of particles hitting the needle surface in increasing (0, 14 and 22 for fully open, quarter open and half open injector respectively) and the impact angle is 10 to 30 degrees for particles near the tip area and more than 30 degrees for upstream area. From velocity distribution, it was seen that the nozzle exit is the maximum velocity area. Hence for nozzle erosion is relatively constant no matter of operating position. Further heavier particles were flowing from the downward part of the injector which may cause much erosion damage on downside thus asymmetrical erosion of the needle.

The present work is only limited to numerical modeling of the particle flow and relating the motion of particles seen and erosion behavior from field setting research studies. Further studies should consider secondary flows, and particle-particle interactions for better modeling of particle trajectories. Experimental modeling of the particle flow shall further enable to better understand the particle motion. Conclusions from present study shall form a base for further advancement of studies relating to particle motion modeling and geometrical modification and optimization of injector.

Acknowledgements

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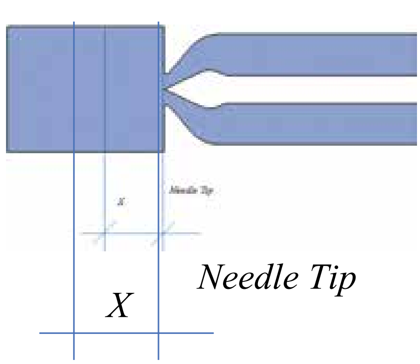
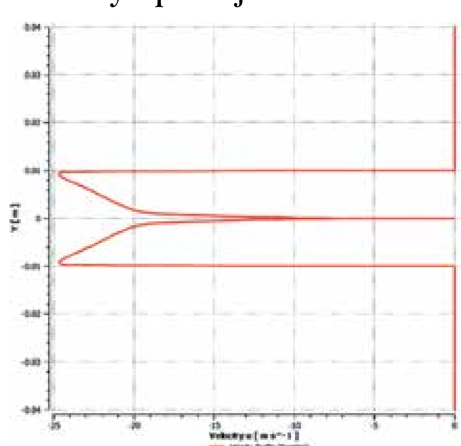
Conflict of Interests

Not declared by authors.

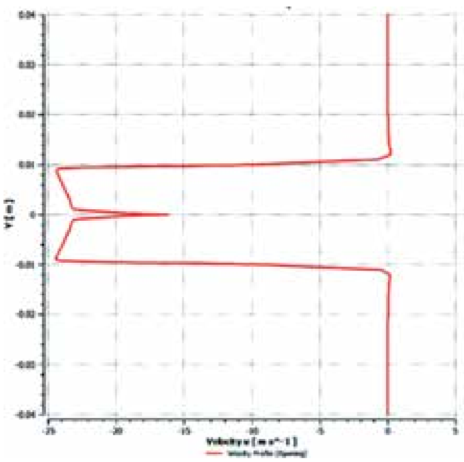
Appendix: Velocity Profiles for Different Position of Jet

Development of Axial Velocity of Jet for Fully Open Injector

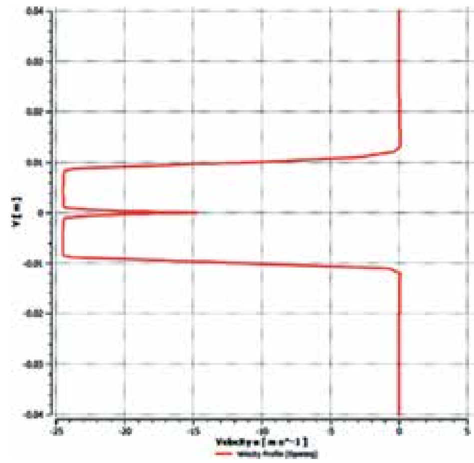




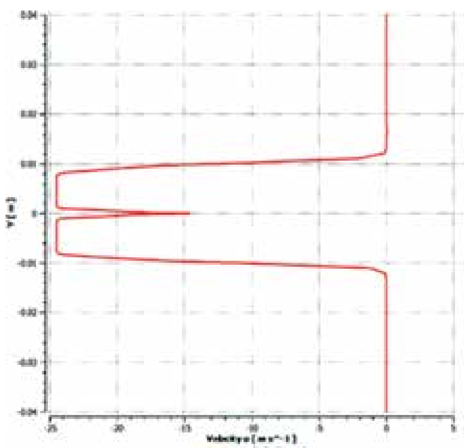
At Needle Tip



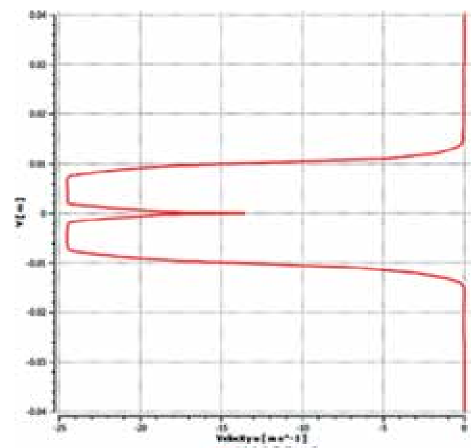
At 5 mm Ahead of Needle Tip



At 20 mm Ahead of Needle Tip

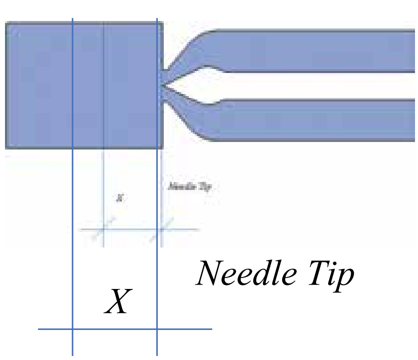


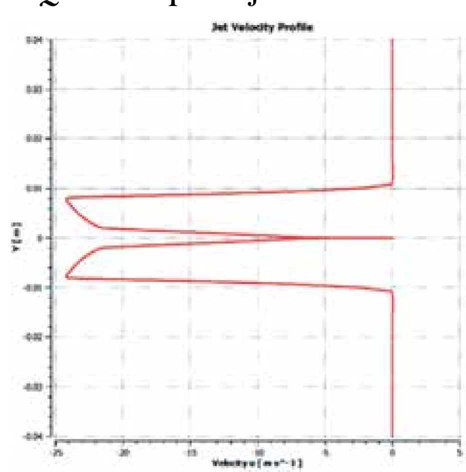
At 40 mm Ahead of Needle Tip



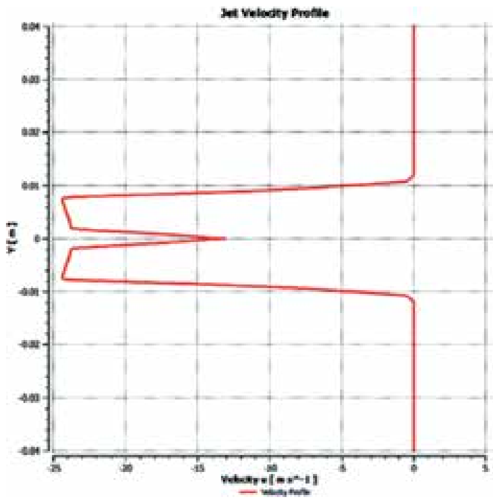
At 80 mm Ahead of Needle Tip

Development of Axial Velocity of Jet for Quarter Open Injector

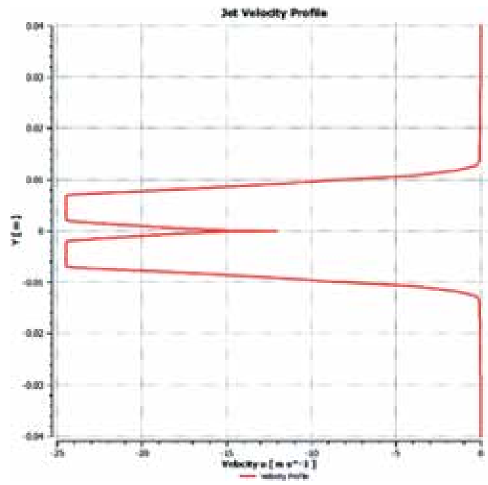




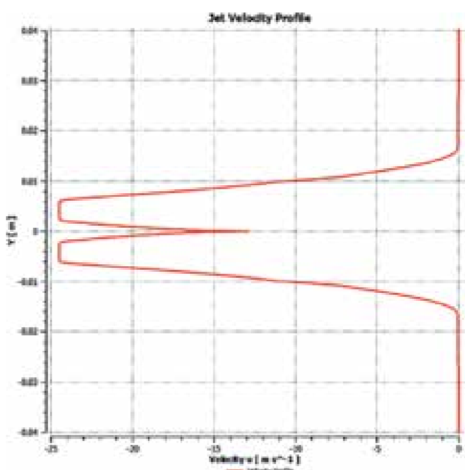
At 5 mm Ahead of Needle Tip



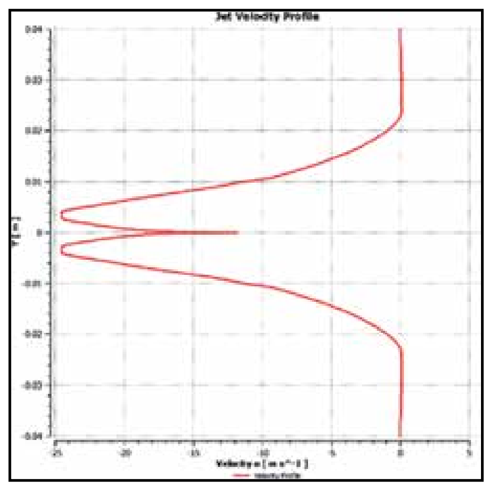
At 5 mm Ahead of Needle Tip



At 20 mm Ahead of Needle Tip

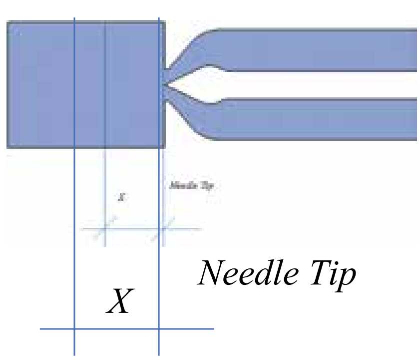


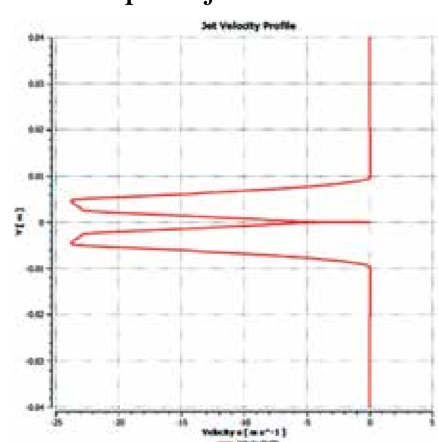
At 40 mm Ahead of Needle Tip



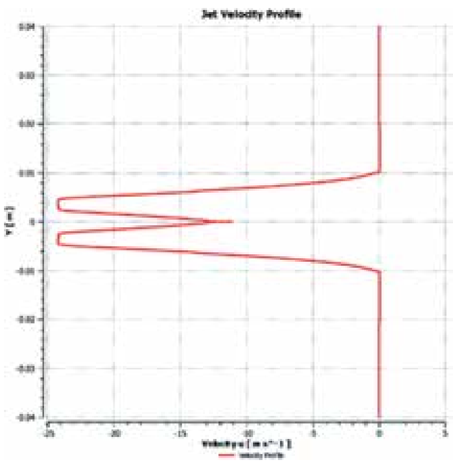
At 80 mm Ahead of Needle Tip

Development of Axial Velocity of Jet for Half Open Injector

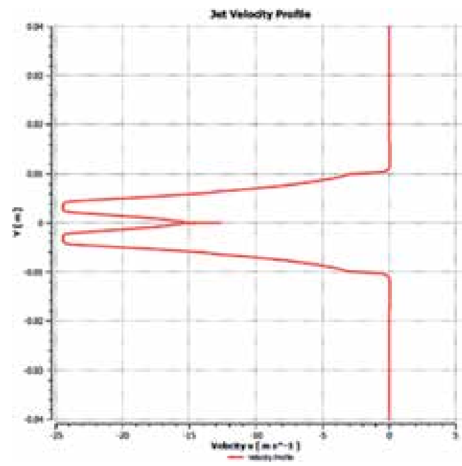




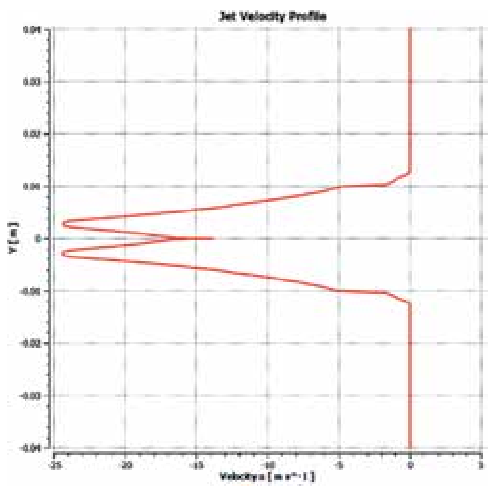
At Needle Tip



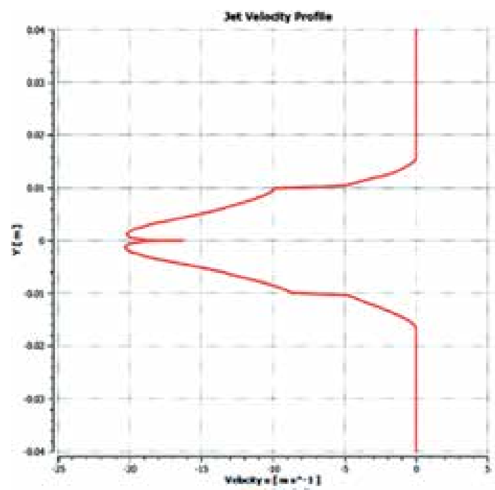
At 5 mm Ahead of Needle Tip



At 20 mm Ahead of Needle Tip



At 40 mm Ahead of Needle Tip



At 80 mm Ahead of Needle Tip

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