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Hydro-abrasive erosion in Pelton turbine injectors: A numerical study

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A B S T R A C T

Numerical simulations were performed to investigate how the design and the operation conditions of a Pelton turbine injector affect its vulnerability to hydro-abrasive erosion, alongside with its flow control capacity. Use was made of a Volume Of Fluid (VOF) model for simulating the free nozzle jet, a Lagrangian particle tracking model for reproducing the trajectories of the solid particles, and two erosion models for estimating the mass removal. The comparison against earlier studies and the experimental evidence, integrated with a careful sensitivity analysis, gave strength to the reliability of the numerical model. Nozzle seat and needle were the injector components most vulnerable to erosion. As the valve was closing, the erosion of the needle strongly increased, whilst that of the nozzle seat remained broadly constant. The influence of the injector design was also explored, suggesting that a reduction of the needle vertex angle is likely to enhance the risk of erosive wear. Finally, it was found that the possibility to condense the effects of the needle stroke and the needle vertex angle in a single parameter (i.e. the effective opening area) is no more allowed when hydro-abrasive erosion is considered, thereby assessing the need for case-specific wear prediction analyses.

1. Introduction

In a Pelton turbine, the proper interaction between the water jet and the blades is fundamental for the efficiency of the device. In this context, an important role is played by the injector, which is used both for generating the high-speed jet and regulating the flow rate. Particularly, a needle valve throttles the flow in the injector, and the control of the flow is achieved by adjusting the needle stroke, s, in the nozzle. Fig. 1 shows the main geometrical parameters of the needle-nozzle system, namely the constant aperture diameter of the nozzle, D_0, the needle vertex angle, γ_n, and the contraction angle of the nozzle seat, γ_{ns}.

When investigating the regulation characteristics of the injector, is it a common practice to make reference to the discharge coefficient, φ_{D_0}, which is defined as:

$$\varphi_{D_0} = \frac{4Q_{\text{jet}}}{\pi D_0^2\sqrt{2gH}} \tag{1}$$

where Q_{jet} is the water flow rate through the injector nozzle, g is the modulus of the gravitational acceleration, and H is the net head at the injector entrance. At a certain distance from the plane of the injector outlet, the jet has a minimum area where all the streamlines are parallel. Such narrow section was referred to as "waist section" by Zhang [1], who demonstrated that, under the assumption that the head drop in the injector is negligible compared to H, φ_{D_0} represents the ratio of the jet diameter in the waist section to the diameter of the nozzle aperture. The trend of φ_{D_0} versus the dimensionless needle stroke, s/D_0, is usually called "injector characteristics".

A certain number of studies were reported in the literature regarding the fluid dynamic behavior of Pelton turbine injectors. With the exception of few studies entirely based on physical experiments [1–3], most investigations relied, in part or in full, on Computational Fluid Dynamics (CFD) simulations. For instance, in their upgrading and refurbishment of the injector nozzles of a Pelton turbine for the water power plant of Tillari in India, Veselý and Varner [4] assessed the effect of the design modifications on the injector characteristics via CFD and experiments on a prototype model. Koukouvinis et al. [5] proposed a numerical technique based on Smoothed Particles Hydrodynamics (SPH) as a tool for injector design based on the predicted inherent characteristic curve. Benzon et al. [6] employed two commercial CFD codes to investigate the influence of the injector geometry on its dissipation characteristics based on 2D axi-symmetric simulations, and suggested

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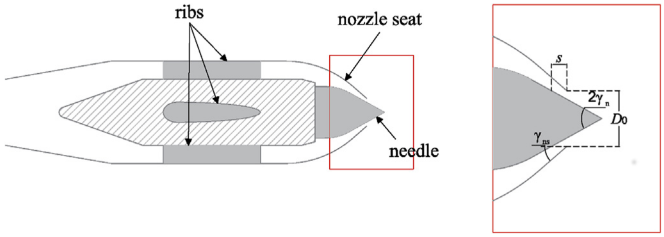

Fig. 1. Sketch of a Pelton turbine injector.

two values of γ_n and γ_{ns} which reduce the energy consumption required to produce a given flow rate. In a later study [7], the same researchers gave strength to the obtained results by performing more complex 3D simulations of the injector installed in Turgo and Pelton turbines. Jo et al. [8] combined CFD and laboratory tests to assess the effect of the nozzle contraction angle upon the discharge coefficient of the injector, the quality of the jet, and the overall Pelton turbine efficiency. Zeng et al. [9] numerically investigated how the fluid dynamic characteristics of the jet are affected by the elbow pipe upstream the device and the inner ribs for different needle strokes. Finally, a result of considerable impact for injector design was reported in Zhang's book [1], and it consists in the possibility to unify the influences of γ_n and s/D_0 on the discharge coefficient into a single parameter, called “effective opening area”. This variable is defined as the ratio between the opening area, A_D, calculated as follows

$$A_D = \pi\left(1 - \frac{s}{2D_0}\sin 2\gamma_n\right)D_0 s \sin\gamma_n \tag{2}$$

and the nozzle area, $A_{D_0} = \pi D_0^2/4$.

In hydro turbines, the presence of solid particles carried along with the flow is a concern to engineers because, when the solids hit the turbine surface, they can produce material removal. This phenomenon, referred to as hydro-abrasive erosion, is particularly significant in some world regions where the natural water is seasonally rich in silt, which is difficult to remove [10]. The erosion by silt sediment could have negative influence on the produced power due to the decay of the efficiency and to the growth of extraordinary maintenance. In their reviews of hydro-abrasive erosion of hydraulic turbines, Padhy and Saini [11] and Felix et al. [12] listed the parts of Pelton components mainly affected by this phenomenon, namely needle tips, seat rings and injector nozzles, runner buckets, jet deflector, protection roof of injectors, casing, and grating below runner. However, the majority of the studies focused on the hydro-erosion of buckets. M.K. Padhy and R.P. Saini carried out extensive research on this topic based on experiments on a small-scale Pelton turbine. In a first work [13], they proposed an interpolatory formula for the mass loss of Pelton buckets as a function of the silt concentration, the silt size, the jet velocity, and the operating hours. Later [14], they correlated the erosion of Pelton buckets to the efficiency reduction of the turbine, and developed another empirical formula which, starting from the same input parameters, estimates directly the percentage efficiency loss. Finally [15], they discussed the main erosion mechanisms occurring at various locations of Pelton buckets for different sizes of the abrasive particles. Abgottspon et al. [16] investigated the erosion of Pelton buckets based on a case study of the Fieschertal hydropower plant, and concluded that the loss of material and the reduction in efficiency correlate only to a minor degree with the sediment load, whilst an important role is played by local conditions (such as particle properties), the design characteristics, the mode of operation, and, very important, the status of the runner at the beginning of the sediment season. A series of measurements on two Pelton turbines in the Toss hydropower plant in India, performed during the period May–October 2015, allowed Rai et al. [17] to make a detailed analysis of hydro-abrasive erosion in Pelton buckets, identifying five different erosion categories. During the same period, the authors constantly monitored the sediments entering the turbine, observing that, whilst size and concentration underwent significant variation, the shape of the grains remained substantially unchanged. In another study, Rai et al. [18] developed a simplified model for the estimation of the particle velocity and inclination angle relative to the rotating Pelton buckets, which were identified as the key parameters affecting erosion. The model was applied to a considerable number of real-case scenarios, leading to recommendations for the design and operation of Pelton turbines in order to reduce their vulnerability to hydro-abrasive wear. A similar approach was followed by Zhang [1], who derived a simplified model to numerically track the particle motion in the water-sheet flow within the Pelton buckets.

Fewer papers specifically concerned the hydro-abrasive erosion of the Pelton injectors. Bajracharya et al. [10] investigated the erosion of the needles of the Pelton turbines installed in the Chilime hydroelectric plant in Nepal, reporting some photographs and wear profiles. The authors estimated the penetration rate (that is, the rate at which the erosion depth increases) and the efficiency reduction experienced by the turbines, and they suggested an interpretation of the needle erosion based on fluid dynamic considerations. The particularly severe erosion of the needle was ascribed to the combined effects of hydro-abrasive erosion and cavitation, which were supposed to be enhanced when the injector operated in partial opening condition. Evidence of the synergistic effect of the two phenomena in Pelton needles had been previously reported also by Thapa et al. [19] and discussed in the review paper by Gohil and Saini [20]. Recently, Morales et al. [21] estimated the erosion behavior of the needle at Chivor hydroelectric plant in Colombia by measuring the evolution of its surface roughness, and developed a setup to reproduce the phenomenon at the laboratory scale. The authors found that, after an incubation period, a fast increase in roughness occurred, and the enhancement in the mass removal was attributed to the fact that the hydro-abrasive erosion promoted the onset of cavitation erosion.

Nowadays, CFD has high potential for the analysis of critical working conditions in hydraulic machinery such as turbines and pumps, including cavitation, solid particle erosion, and flow-induced noise (e.g. Refs. [22–24]). The numerical approach, in fact, allows attaining detailed information and it is substantially free from several difficulties inherent in experimental and field testing. Particularly, a well established methodology is available for CFD-based wear estimation, and it consists of two steps in sequence [25]. First, the fluid-particle flow field is simulated by means of an Eulerian-Lagrangian two-phase model [26], in which the fluid flow is represented in a Eulerian, cell-based framework, whilst the solid phase is represented in a Lagrangian framework by following the trajectories of a certain number of particles. Afterwards, a single-particle erosion model is applied to estimate the loss of material produced by each particle-wall collision and, in turn, the overall erosion of the walls.

A single-particle erosion model is an algebraic equation relating the erosion ratio of a particle-wall collision, E_{coll} (i.e. the ratio between the mass of material removed, W_{p}, and the mass of the particle, m_{p}) as a function of several parameters, including the modulus of the particle velocity at the impact stage, $|\boldsymbol{v}_{\mathrm{p,imp}}|$, the particle impingement angle, $\theta_{\mathrm{p,imp}}$, some particle-related quantities, such as its shape and size, and some mechanical properties of the target material, such as its hardness (Fig. 2). The effectiveness of