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IMPORTANCE OF JET QUALITY ON PELTON EFFICIENCY AND CAVITATION

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ABSTRACT

The quality of water jets on the performance and behaviour of Pelton turbines is of high importance. Circumferential Shape, velocity distribution and dispersion of jets are heavily influenced by nozzle and distributor geometry. This paper discusses the current state of the art of jet patterns, underlined by two typical rehab projects for jet improvement in large hydro power plants. Even though our understanding of jet phenomena was widely improved during the last years, the need for further experimental and numerical developments, relying on a proper understanding of water jet physics, is still not depleted.

1 PELTON JETS

In the field of Pelton turbines, as shown with a 2 jet horizontal axis unit at Figure 1, the understanding of the physics of the flow and the sources of loss was till now relatively weak. The main reason for this is that the flow patterns and the hydraulic losses are very difficult to observe and to quantify separately. Indeed, the jet is directly influenced from the distributor geometry, possibly the upstream penstock geometry and the net head. It is now established that the jet can be characterized by its shape deformation and deviation, induced from flow topology in the distributing pipe, and by its dispersion that is mostly related to turbulence, e.g. head.

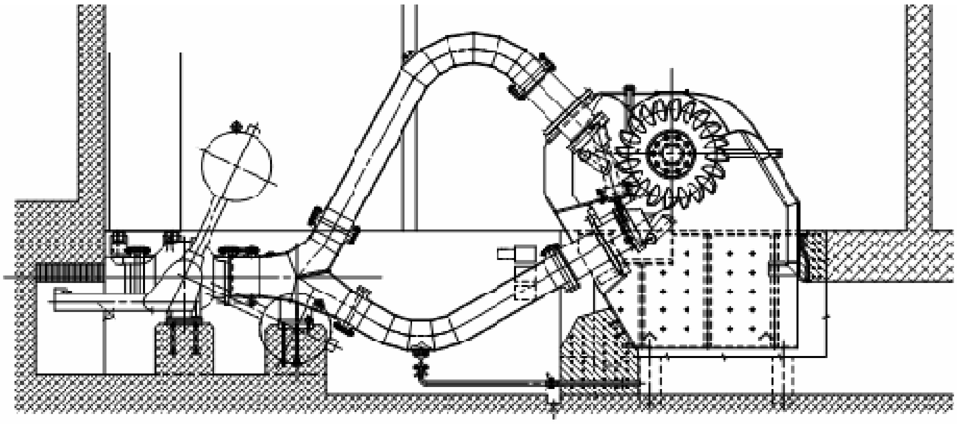


Figure 1: Typical layout of a horizontal shaft 2 jet Pelton turbine

These patterns have a direct impact on the jet “quality”, influencing the efficiency and the potential risk of cavitation.

Following a discussion on recent theoretical and experimental studies on jets, two representative projects at large power plants are discussed in the paper to illustrate the impact of this jet “quality” on the operation of Pelton turbines.

2 JET DESCRIPTION

As mentioned above, the jet of a Pelton turbine is more and more seen as a major influence parameter for the performance of a Pelton turbine. A water jet in a Pelton turbine shows large variations of length and time scale. Within very few centimetres between the internal region of the nozzle and the first jet diameter downstream of detachment, the physical properties are strongly varying and subsequently singularities appear in the flow. With an example head of 800 m, velocities and relative pressure range from lower than 10 m/s to 125 m/s and from 78 bars in the nozzle to 1 bar (ambient pressure) in the casing of the turbine. As discussed in [Parkinson, 2006], shape deformation and deviation of a jet are directly defined from the flow topology in the nozzle. Bends and obstacles that may generate vortices in the flow have hence a direct impact on the jet topology and consequently on the turbine performance. These effects can be assessed with multi-fluid CFD analysis that include both the distributing pipes and the water jets as shown in Figure 2. An optimisation of static components is therefore a profitable option for Pelton turbines. This becomes clearest in the project HPP BORDOGNA which will be discussed in the next chapter.

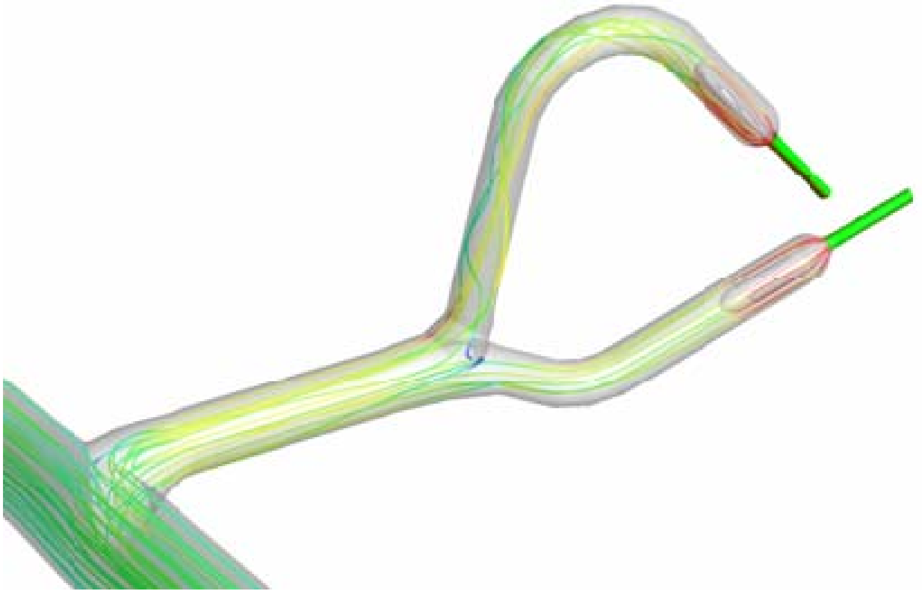
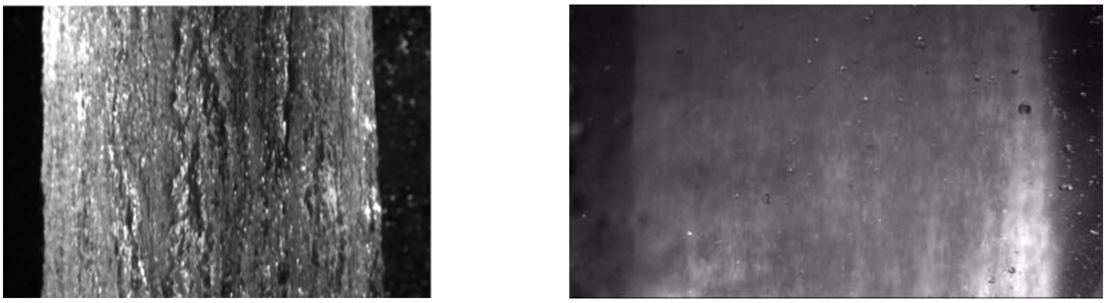


Figure 2: Secondary flows in a Pelton distributor

It must be noted that the usual Froude homology as recommended by IEC is not applicable in hydraulic homology between model and prototype for the subject of jet behaviour.

This difference in behaviour is indeed clear when one compares, for identical nozzles, the discharge / needle position characteristics measured on model and prototype. The discharge reduction observed on the prototype for the same relative needle opening and for the same Froude number is directly related to the head value. The difference in discharge can be of the order of percents for very high head Pelton turbines. This influence also varies with the relative needle position.

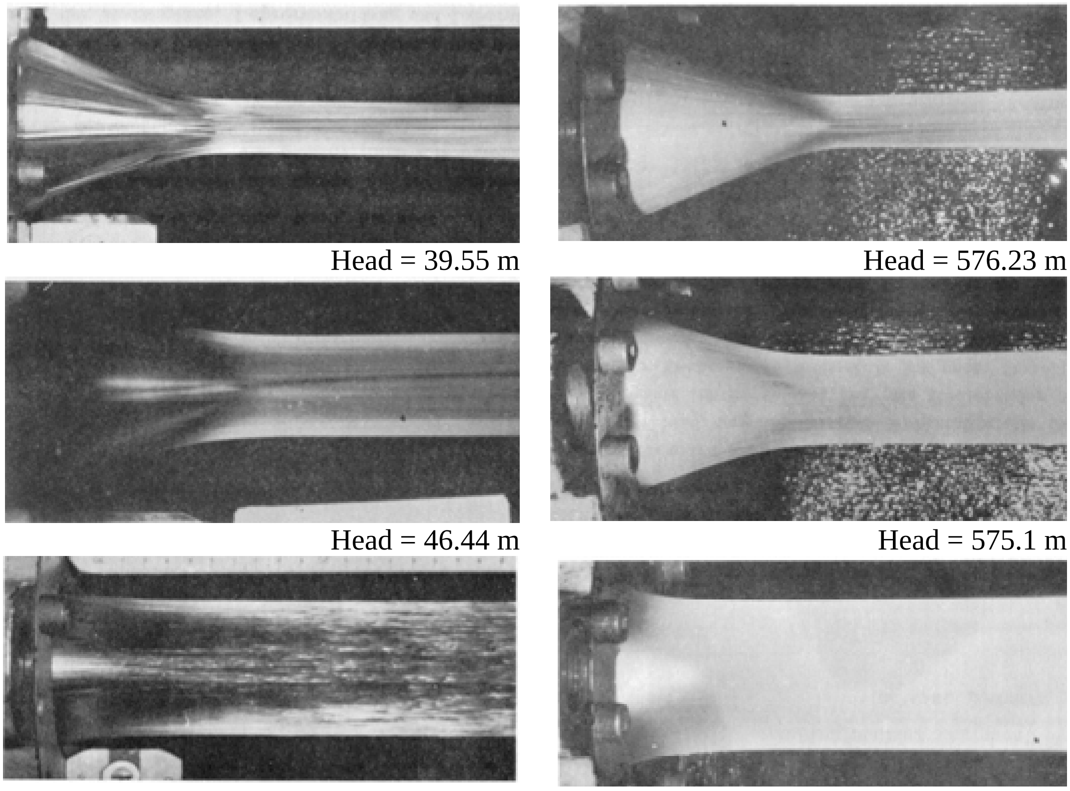
Since the Reynolds homology is not fulfilled, there are some minor differences in the secondary structures of the flow, e.g. on the jet deformation and deviation. The situation is even more complex when considering dispersion as experience shows that dispersion indeed heavily depends on the head, see Figures 3 and 4, with quite different patterns observed on the jet visualisations achieved at model and prototype scales.



Model	Head:	153 m	Prototype	Head:	588.4 m
	Nozzle opening:	80%		Nozzle opening:	80 %
	Jet diameter:	34mm		Jet diameter:	182 mm

Figure 3: Dispersed area around the jet at 1.5 diameters downstream of the nozzle exit [Weibel, 2008]

The jet at high head is less transparent, with an increased external thickness of mixed air-water flow. Non-linear phenomena such as turbulence, instabilities [Itoh, 2004] and gaseous germs developments [Sallam, 1999] occur in a Pelton jet.



Nozzle opening		
4.6%	Head = 39.55 m	Head = 576.23 m
15.45%	Head = 46.44 m	Head = 575.1 m
63.1%	Head = 42.74 m	Head = 535.31 m

Figure 4: Jet surface at model and prototype heads [Villacorta, 1972]

These flow patterns result in a dispersed phase which has a direct impact on efficiency and, possibly for high heads with droplet erosion, on longevity of the turbine.

This is mostly related to the Reynolds difference that implies different turbulence intensity, resulting in different boundary layers characteristics at nozzle exit, see Figure 5. This has a direct consequence on the jet surface disturbances, which feed the droplet extraction process, e.g. the dispersion. This process is emphasized where large scale jet surface deformations occur.

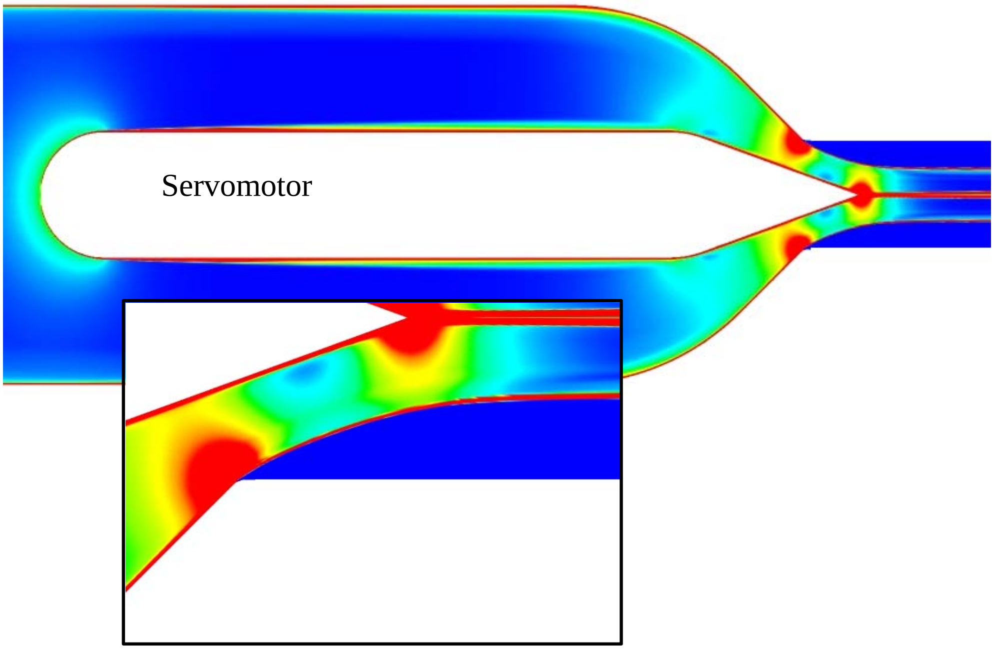


Figure 5: Pressure gradient map at nozzle exit (red: max, blue: min)

With dispersion, the jet diameter “seen” by the runner is larger than its theoretical value. It will modify the pressure map on the bucket and has a direct negative influence on the runner torque and consequently on efficiency. The industrial example of FIONNAY HPP is a perfect illustration of this dispersion influence on efficiency, as discussed further below.

Predicting jet dispersion with CFD is still at a research level. Indeed, the numerical simulation of the jet dispersion has to take into account many interfering physical phenomena (such as multiphase interactions, compressibility, turbulence, impinging droplets). The time and length scales involved are also of an order of magnitude below the currently considered values, leading to computational efforts that require specific methods and algorithms. The need for prototype experimental data is also clear in order to document the transposition effects between model and prototype behaviours. On-going activities in this field are discussed within the JISPP project presentation at the end of the paper.

3 INFLUENCE OF JET SHAPE: BORDOGNA HPP

This first example deals with the hydro power plant BORDOGNA. Owned by ENEL Produzione S.p.A., it is located north of Bergamo, Italy, in the resort of the high Brembo Valley. The HPP is equipped with three units. The following discussion applies to Unit #3, built in 1947, and detailed in Table 1.

Name:	BORDOGNA HPP	Net Head:	525 m	Number of jets:	1
Owner:	ENEL Produzione S.p.A.	Discharge:	3.80 m^3/s	Pitch diameter D1:	2230 mm
Location:	Bordogna	Speed:	428.6 rpm	Bucket width B2:	680 mm
	Italy	Output:	17.15 MW	D1/B2:	3.28

Table 1: BORDOGNA HPP Unit #3 rated characteristics

In 1996 ENEL awarded VA TECH HYDRO with the replacement of a runner for Unit #3, which was installed in February 1999. During commissioning the turbine showed the expected performance and behaviour, but also a particular noise above 12 MW. The noise level was not critical, but the owner worried since he regarded it as a symptom of cavitation.

Noise analysis tests were carried out by ENEL specialists in order to find out if the noise was caused by incipient cavitation. The noise originated from the zone where the shaft passed the turbine casing and the phonometer was positioned at this zone. The tranquillity of the casing gave the impression that the noise might come from the rotating parts, namely from the runner. Noise spectrums at different output powers were jointly analysed by ENEL and VA TECH specialists, who assessed that the noise was mainly broadband nature with few insignificant peaks and an interposed continuous spectrum growing with the power. Therefore it was likely that the noise which arose from the excitation of all possible frequencies, was produced by higher quantities of water sprays crashing into the runner at greater discharges and jet dimensions. Within only three months of exploitation, asymmetric damages on the external surface of the bucket cut-outs were observed, as shown in Figure 6. They were located at the internal side of the injector bend, having its plane orthogonal to the middle plane of the runner.

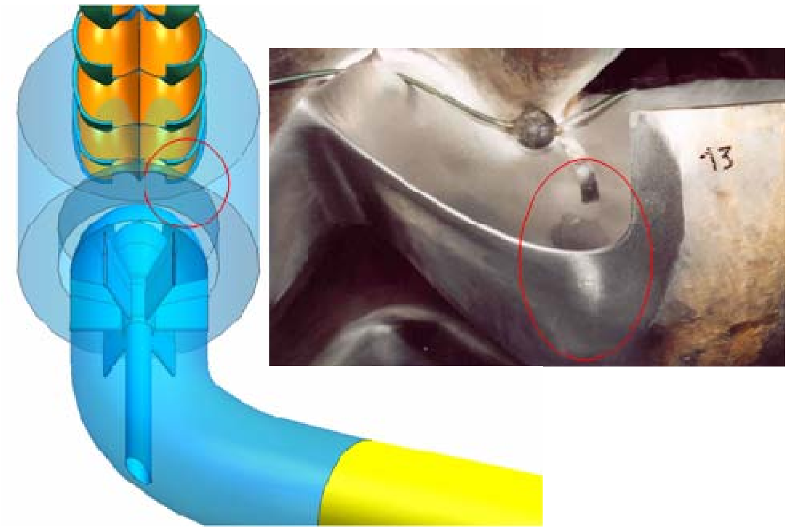


Figure 6: Cavitation damages on the external right cut-out section

This cavitation pattern, located outside of the theoretical jet diameter, was expected to be caused by the jet deformation induced by the vortices developing in the bends found in the complex piping system of BORDOGNA, see Figure 7. It was possible with a multi-fluid CFD simulation of the jet to establish that damages are indeed exactly positioned where a strong deformation of the jet exists as seen in Figure 8. The jet is not at all axis-symmetric because of the superposition of all vortices induced by the various upstream bends, not forgetting those related to the servomotor shaft.

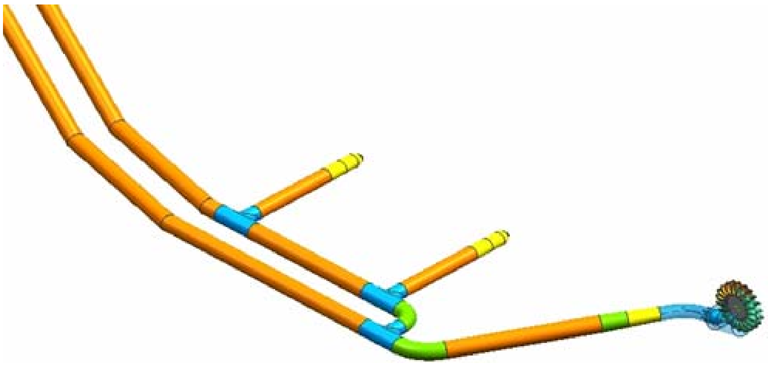


Figure 7: Layout of the considered unit within the hydro-plant

When cavitation is caused by a bad jet quality, it is often possible to avoid a progression by enlarging and lowering the buckets cut-outs. This strategy is easy to perform and was carried out at Bordogna in April 2003. The cut-outs where lowered by 4 mm, but the modification was still too weak to improve the damage measurably.

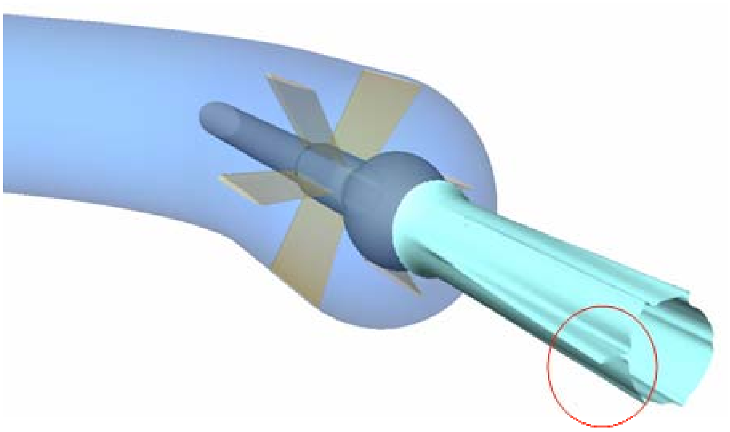


Figure 8: Initial jet shape of BORDOGNA HPP (strong deformations)

During an inspection in November 2003, VA TECH followed the idea to intervene at the origin of the problem, e.g. reducing the formation of vortices in the injector. A flow guidance in the injector bend would have been the best solution, but due to the injector design, it was not possible to insert a guiding vane through the whole curved zone. The only possibility was a strong rectification of the flow in the last part of the bend and in the nozzle. ENEL accepted this compromise and was interested in a guiding structure which could be inserted through the nozzle flange. The vortices produced in the first part of the bend had to be eliminated by the guiding vanes in order to recover a good jet quality and thus avoiding cavitation damages in the runner.

VA TECH could formulate an offer including a flow calculation and, in case of positive results, deliver a guiding structure. CFD analysis, see Figure 9, confirmed a decisive improvement of the jet quality without the previous deformations. This led to the expectation that the cavitation inconveniences should be eliminated by an application of the new design.

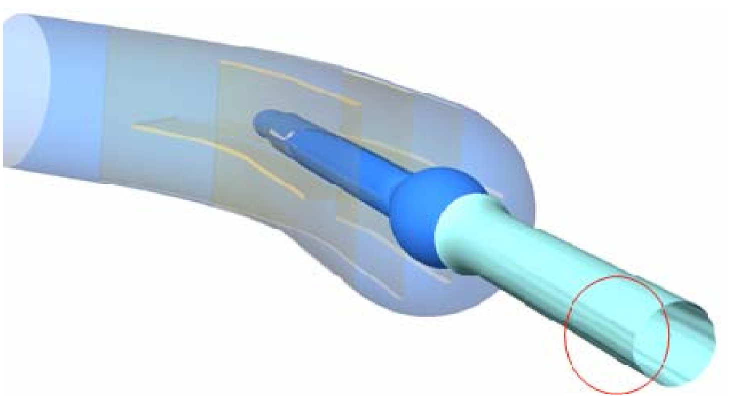


Figure 9: Modified jet shape of BORDOGNA HPP (no major deformations appear)

After weld repairing of the cavitation zones on the runner in January 2005, a new guiding structure was installed in April. At this moment, the runner had cumulated 18’491 operation hours in its lifetime. The commissioning with the new guiding structure showed a first positive result since the unusual noise had disappeared.

After the agreed six months operation with the new guiding structure, ENEL performed an inspection on October 26th, 2005 to assess the cavitation condition. In this lapse of time, Unit #3 had cumulated 1’414 operation hours after the last weld repair and showed no cavitation damages, as stated in the ENEL inspection report. The good condition of the runner was confirmed at the following inspections, regularly performed approximately every six months in the low discharge periods in winter and in summer.

The disappearance of noise and cavitation confirms that their root cause is the deformation and dispersion of the jet. Since cavitation and noise was resolved, efficiency should be enhanced too. The efficiency test performed by ENEL specialists in January 2000 (before this rehab) gave results within the guaranteed range. It is most probable that the sub-optimum jet quality during this test, producing cavitation and noise, also induced some efficiency loss, as known from experience and model test results, and shown in the following example. This was however not checked on the prototype after installation of the new guide structure

4 INFLUENCE OF JET DISPERSION: FIONNAY HPP

This second power plant, see Table 2, is also a one jet horizontal shaft turbine in Switzerland. In this project, a performance increase was obtained by improving the nozzle geometry. The nozzle design was modified in the frame of a refurbishment project.

Name:	FIONNAY HPP	Head:	872 m	Number of jets:	1
Owner:	Grande Dixence S.A.	Discharge:	3.75 m^3/s	Pitch diameter D1:	2650 mm
Location:	Fionnay	Speed:	428.6 rpm	Bucket width B2:	635 mm
	Switzerland	Output:	25 MW	D1/B2:	4.17

Table 2: FIONNAY HPP rated characteristics

As observed by camera during prototype operation, see Figure 10, the nozzle modifications had a direct impact on the jet dispersion. The dispersion angle was clearly reduced by the new nozzle geometry.

Figure 11 shows the jet diameter measurements (from the images) before and after the nozzle modification and compares the measurements with the theoretical jet diameter, which is calculated from the discharge and the theoretical jet velocity. This reduction of jet diameter had a direct positive outcome on the efficiency which increased in the entire operating range, see Figure 12.

The influence of dispersion was analysed and confirmed with CFD simulations, which showed that the bucket loading, respectively the bucket flow pattern depend on the jet dispersion intensity. In case of higher dispersion, the induced pressure field is distributed over a wider area, which deviates from the hydraulical optimum and thus has a negative impact on the runner efficiency.

Figure 10: Camera and strobelights for jet visualisation

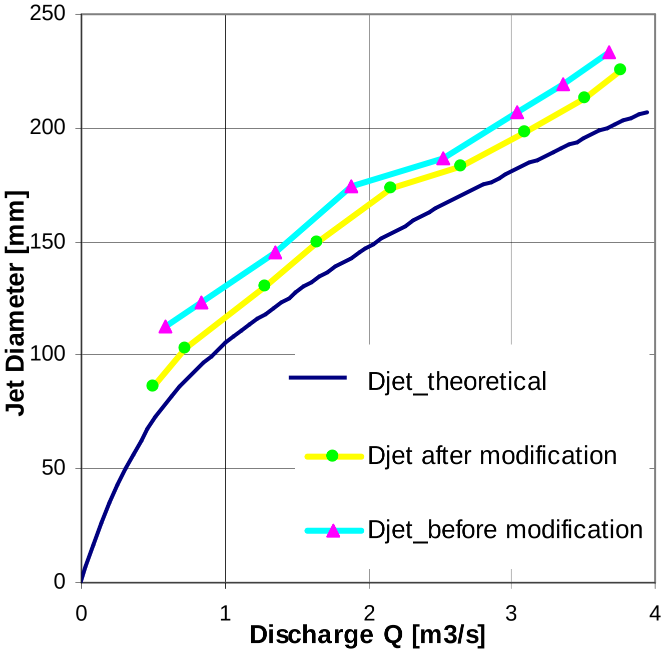


Figure 11: Optical jet diameter measurement before and after prototype modification [Staubli, 2004]

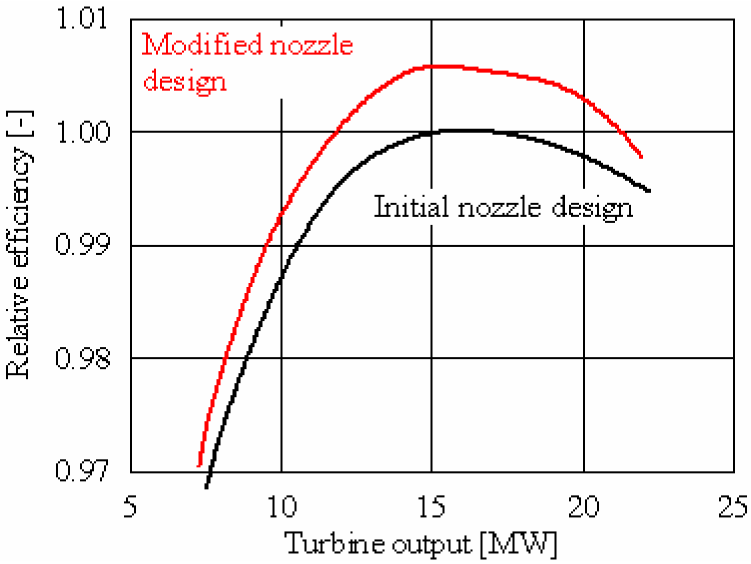


Figure 12: Comparison of initial and new efficiencies for FIONNAY HPP

5 JISPP INITIATIVE

As shown above, it is important to gain experience with prototype jet behaviour and patterns to consolidate transposition knowledge and prediction methods, such as CFD. A research initiative in this field was launched in 2005 in Switzerland [Weibel, 2008].

The objectives of this project, under the acronym of JISPP (Jet Improvement for Swiss Pelton Plants) are to establish best practice guidelines for Pelton refurbishment projects with respect to jets and to analyse the potential of "jet refurbishments" on representative prototypes with the aid of model and prototype measurements plus CFD developments.

This can be achieved by extensive analysis on prototype hydraulics, based on visualisations of prototype jets, accompanied by efficiency measurements. This allows finding a correlation between jet patterns, such as dispersion, deviation and deformation, with performance. This should consequently clarify the performance upgrade potential of a turbine.

The project partners are Swisselectric Research (www.swisselectric-research.ch), the Lucerne University of Applied Science and Arts (LUASA) in Switzerland, the Laboratory of Fluid Mechanics and Acoustics (LMFA) at Ecole Centrale de Lyon (France) and VA TECH HYDRO.

6 CONCLUSION

Pelton jets depend on complex phenomena related to both upstream piping geometry and operating head, as illustrated from the above industrial examples. In both cases, the analysis of the prototype behaviour beyond sole performance measurements was of high importance and value. This includes jet visualisations, CFD analysis and analytical methods.

The successful issue of these projects lays in the optimum combination of model testing, prototype assessment and advanced CFD analysis tools during expertise in Pelton technology. It requires a continuous investment in scientific and technical research in the field of Pelton jets, as followed by VA TECH HYDRO with the support of scientific partners such as LUASA and LMFA.

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