FLOW VISUALIZATION - A DIAGNOSIS TOOL FOR PELTON TURBINES

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ABSTRACT

A series of video sequences of the jet development taken within one of the Pelton turbines of the Moccasin power plant, California, were quantitatively analyzed and compared to the theoretical jet dimensions. The results showed considerable divergence of the jet before entering the buckets of the Pelton runner. In addition unsteady flow structures on the jets surface were observed. These result in suboptimal interaction with the runner and lead to reduced efficiency. One of the sources of the jet's poor flow quality was identified in the injector design. Subsequently the nozzle geometry was modified. Efficiency measurements before and after the modifications showed considerable enhancement of performance, verifying the diagnosis as well as corroborating the measures taken to improve jet quality.

1 INTRODUCTION

The quality of a jet of a Pelton turbine has major impact on the overall efficiency of the turbine. Jet disturbances ensue primarily from upstream flow conditions in the distributor, the injector and the nozzle. The resulting secondary flows and non-uniformities in the velocity distributions of the exiting jet are inherently connected with energy losses. More important, however, is the suboptimal energy conversion of the disturbed jet in the runner buckets.

Downstream of the nozzle exit internal flow disturbances immediately build up surface deformation of the jet. Parts of these deformations are steady while vary with time. In the worst case the jet may be deformed in a way that some of the water does not even touch the Pelton buckets, but bypasses the runner.

For example typical steady deformation of the jets surface arises from the secondary flow induced by an upstream bend, as was shown with laser velocimetry on a model jet by Zhang and Parkinson, 2002. Vortex stretching creates longitudinal structures on the jet surface as do local mechanical defects of the nozzle surface, which leave "scratches" on the jet's surface.

Furthermore, there are a series of different origins of unsteady surface variations. For instance, the momentum exchange involved in a jet's internal turbulence directly leads to small-scale surface variations propagating at the jets velocity. Large-scale unsteady effects may arise from large-scale swirl fluctuations of the incoming flow or from unsteady flow separation at one of the upstream hydraulic structures.

Shear layers of jets are highly unstable. Instability starts to growth of instability starts immediately at the orifice. However, due to the high Reynolds numbers and the accelerated flow in the nozzle these shear layer instabilities play a secondary role, even though typically such jet instabilities are enhanced by noise and vibrations.

When comparing jets with different geometrical and different upstream flow boundary conditions Reynolds and Weber numbers should be identical to allow comparison.

$$\mathrm{Re} = \frac{\sqrt{2gH}\,D}{\nu} \qquad (1)$$

$$We = \frac{\rho D 2gH}{\sigma} \qquad (2)$$

Especially for model testing flow visualization proves to be a simple and valuable tool to analyze of the jet bucket interaction and to investigate the water deflected from the bucket, which can lead to droplet erosion in prototype plants (Bachmann et al. 1990). Within the housing of a prototype machine it is far more difficult to perform flow visualization than on model turbines, but nevertheless flow visualization also proves to be also a good tool for diagnosis of noise and efficiency problems for prototypes (Staubli, Humm, 1998).
Installation of equipment for prototype visualization is tricky since the best positioning of camera and lighting can not be found on the basis of trial and error but must be based on experience. Furthermore, the mechanical forces of possible water impingement on the camera and lights call for a rigid mounting system. Housings of camera and lights have to be waterproof and measures must be taken to avoid condensation building up on the lenses.
The high Reynolds and Weber numbers (for the present investigation both were in the order of 10^7) lead to a further complication since they are responsible for the formation of small droplets and fog in the housings of a prototype. In order to achieve acceptable image quality under these adverse circumstances special equipment is needed.

2 MOCCASIN POWER PLANT

The Moccasin Powerhouse of Hetch Hetchy Water & Power, California, has two six-jet Pelton type turbine generators, each rated 57.5 MW and designed to operate at a net head of 350 m. The Moccasin units are used mainly for peaking, and the average load during operation is about 38 MW. Index efficiency tests before and after a first replacement runner was installed in 1999 indicated improved but less than predicted efficiency throughout the normal operating range. At full load, the efficiency improved by only 0.3 percent (Gass, 2003).
To ensure that no experimental uncertainty was present, measurements were repeated after a careful inspection of the unit by means of thermodynamic efficiency testing. Unfortunately, previous the measurements of performance were verified. In the following discussions attention focused on the jet performance and a poor jet quality was suspected. To achieve certainty one decided to visualize the jet.

3 INSTRUMENTATION

Figure 1 shows the mounting of the equipment. The photograph displays the welded steel construction on which the camera housing and the strobe lights were mounted. The camera is seen in the center, while the two strobe lights are mounted on the sides. The welded housings of the strobe lights have acrylic glass windows in front of the bulbs, which are sealed with O-rings. A slight overpressure prevents humidity entering the housing - which would be detrimental due to the high voltage operation of the light bulbs.
In front of the camera housing a vortex generator device, which worked with compressed air, was installed. This vortex was created by four carefully adjusted air nozzles in front of the camera window and kept the window free of water droplets.
All instruments were connected with cables through plastic hoses with the outside instrumentation being securely fixed with a steel cable. The outside instrumentation included the camera control with short-time digital image memory, the strobe light control, a triggering device, and a digital video recorder.
The camera was mounted in the shelter of the injector and cut-in deflector and could be adjusted at different angles for observation of the jet. In the study presented three different angles were chosen (minus 11, 0, and plus 11 degrees). Video sequences were taken at the exits of two different nozzles, which were nozzle one and five, to guarantee reliable results.

Figure 1 - Mounted instrumentation within the turbine housing in the shelter of the injector five and its deflector

4 IMAGE SEQUENCIES

The best image quality was achieved in the shelter of the cut-in jet deflector of nozzle five. Figure 2 provides three sample images taken from the video at a nozzle opening of 5 percent. The jet is compact, however white in color, indicating that cavitation and degassing of water occur in the low pressure zones of the jet on the needle surface. Three still frames are reproduced to show that the amount of elapsed time is irrelevant for the development of the surface structures. Minor mechanical defects of the seat ring surface show as "scratches" on the jet's surface and always remain at the same position from frame to frame.

5%

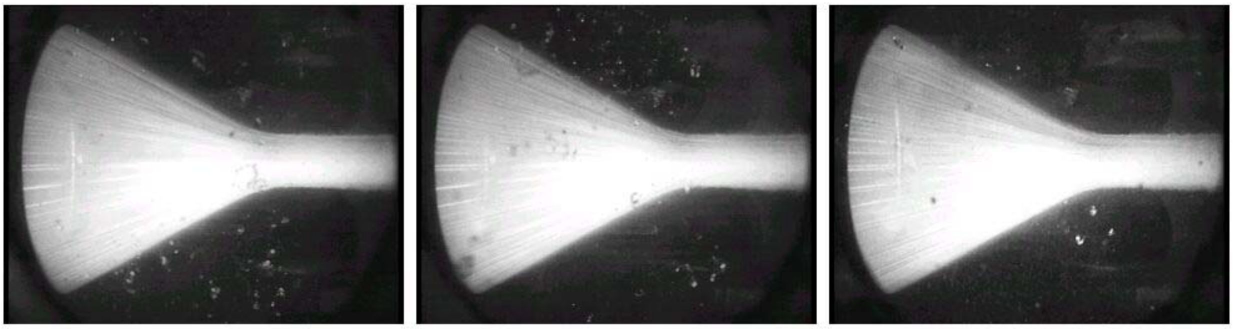

Figure 2 - Jet at the nozzle exit at 5 percent needle opening

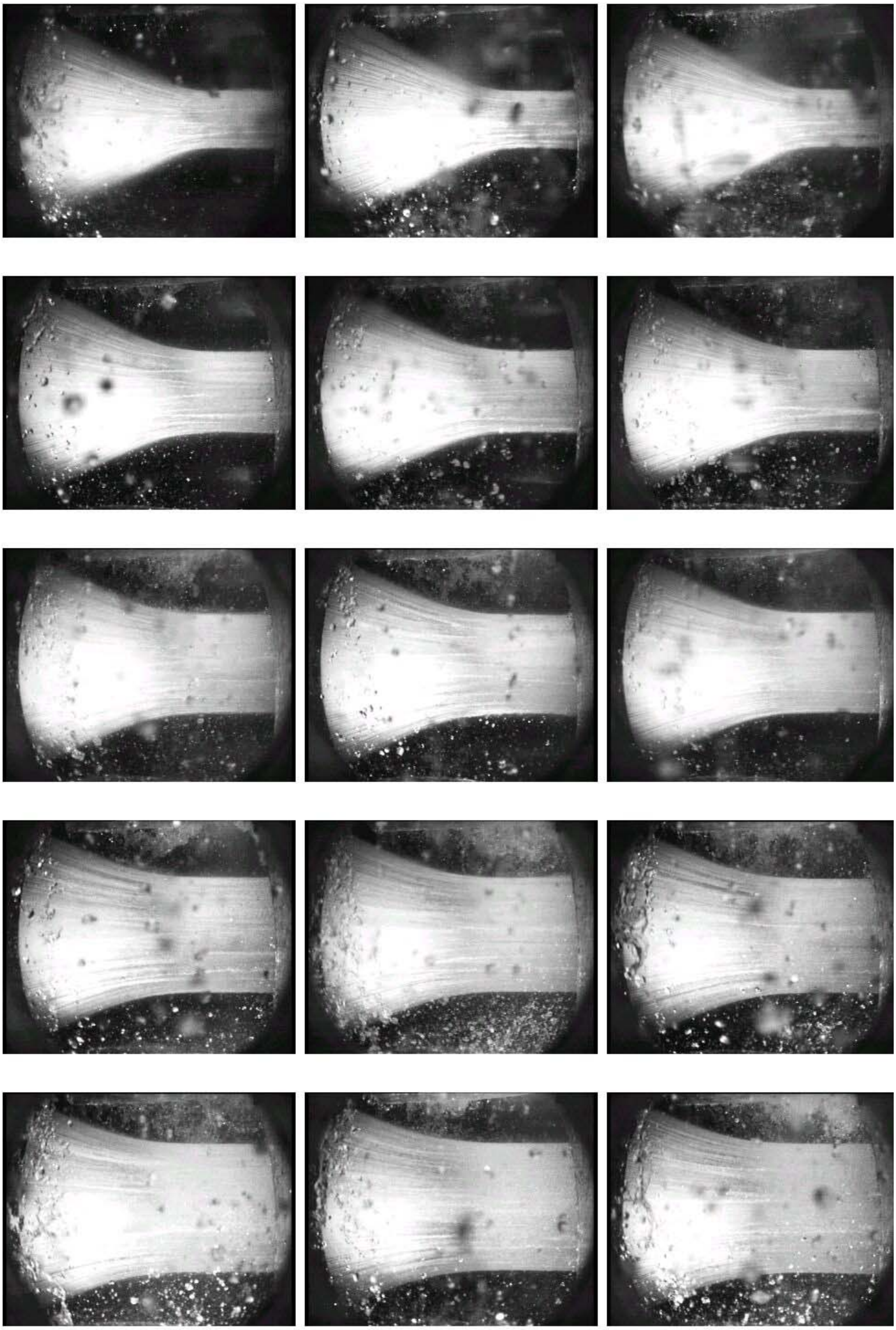

Figure 3 - Jet at the nozzle exit at 10 - 50% needle opening

Figure 3 displays jet development when the needle opening is further enlarged. In these sequences time starts to gain importance with respect to the development of the surface structures.

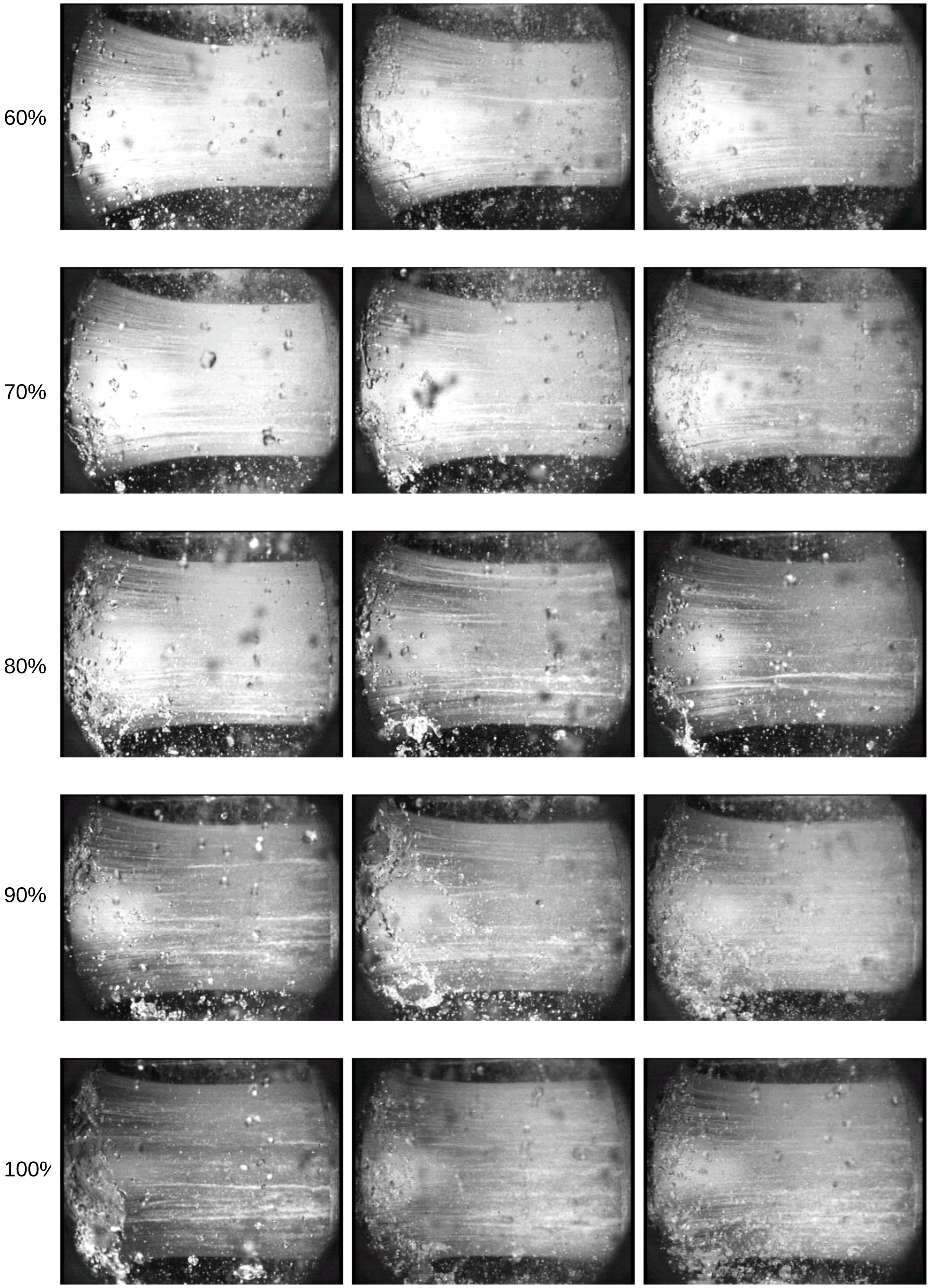

Figure 4 - Jet at the nozzle exit at 60 - 100% needle opening

From 60 % needle opening to full load the surface deformations increase in size and become increasingly unsteady, as can be observed in the video.

5 QUANTITATIVE ANALYSIS

Quantitative measurement of the jet's diameter from the images is possible, but since the contours of the jet are not always clearly visible, this measurement is not very accurate. At the nozzle exit measurements of the jet diameter correspond well to a theoretical value which was determined based on discharge and exit velocity. Further downstream, in the observation area of figure 8, the scatter of the measurements increases and accuracy is less than ± 10%. However, since a large number of frames were analyzed, clear and repeatable trends of the data could be established for the measurements at nozzle 1 and 5. It was clearly shown that the outer limit of the jet is considerably larger than the theoretical diameter for all needle openings.

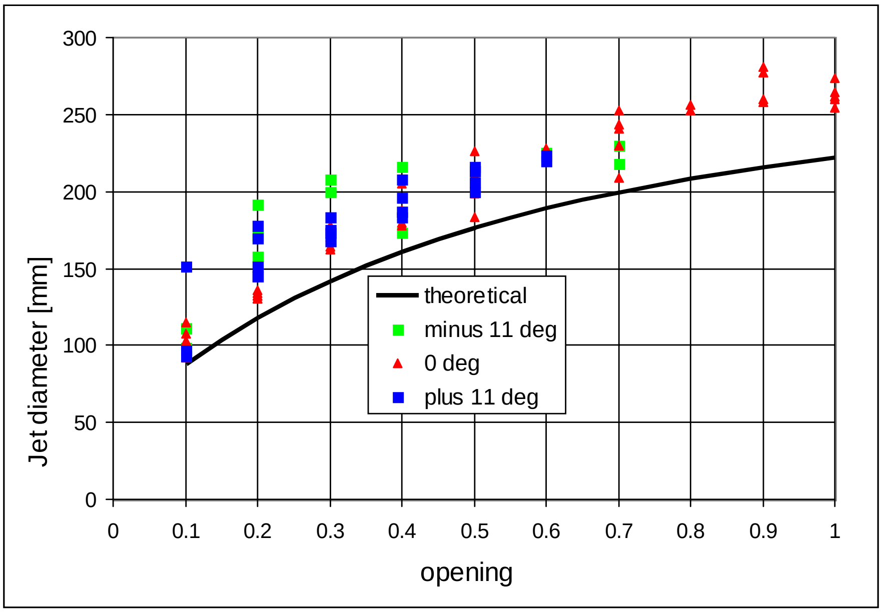

Figure 5 - Jet diameter in the observation area of nozzle 1 measured from the images at three observation angles

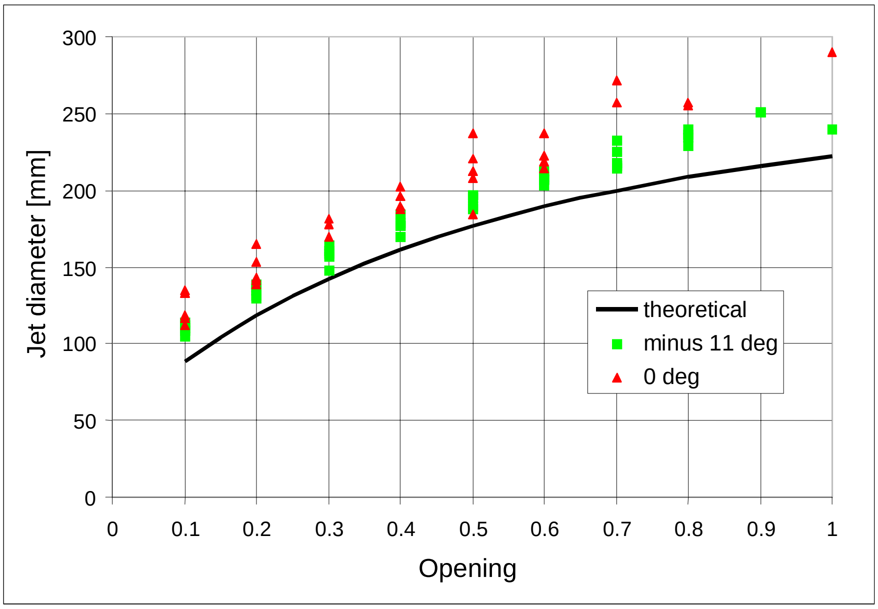

Figure 6 - Jet diameter of nozzle 5 measured in the observation area from the images at two observation angles

A second means of determining the jet diameter using the images is to measure the position where the bucket splitter tip appears on the image when cutting through the jet. Position can be determined quite accurately using this method. An example of such an image of the bucket splitter break-through is provided in Figure 7.

On the basis of these measurements the positions could be entered in the CAD system and the jet diameter at the position of the break-through could be determined. The results of this evaluation are depicted in Figures 8 and 9. Again there is clear indication that the jet diameter diverges considerably. Both methods lead to the same results, within the scatter.

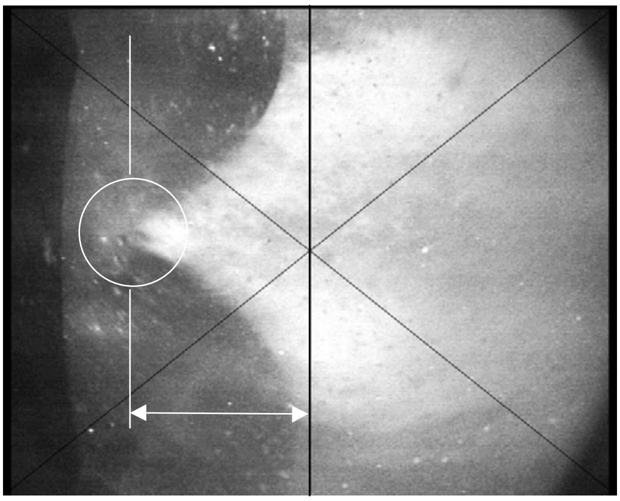

Figure 7 - Measurement of first bucket splitter tip appearance

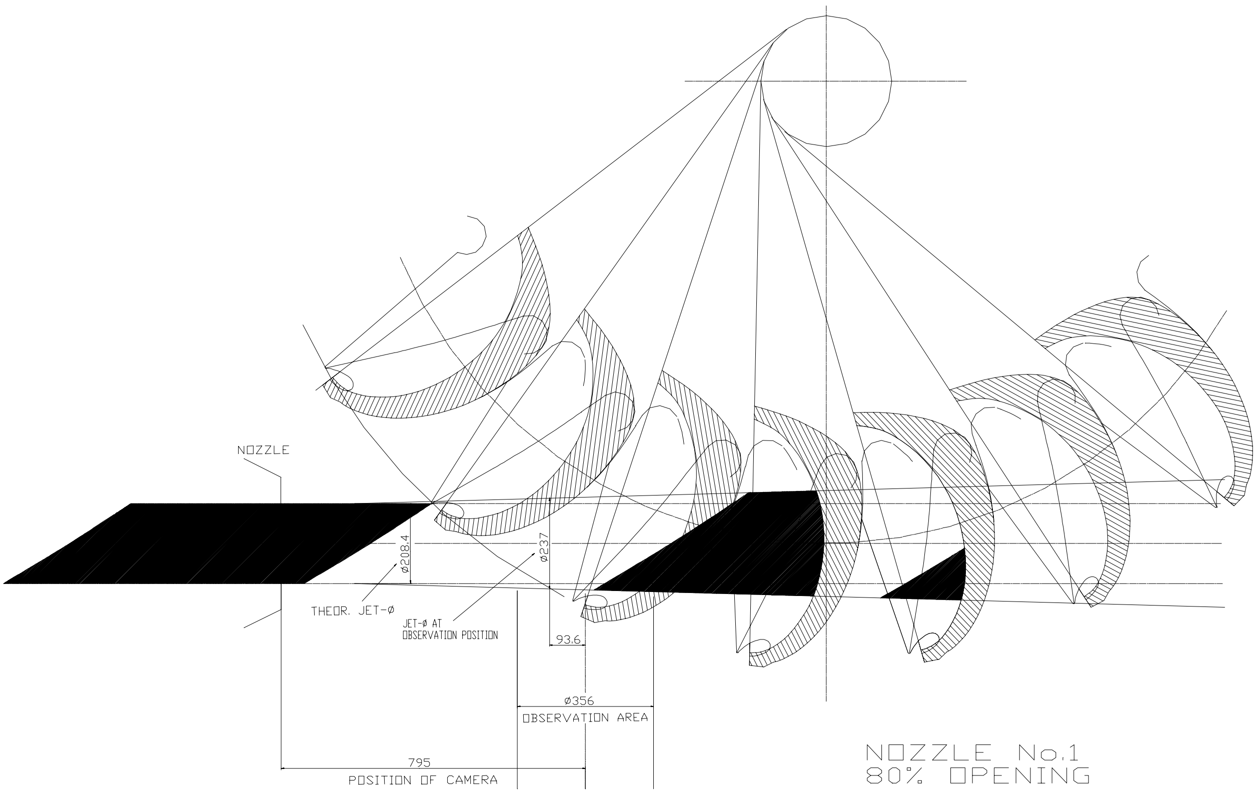

Figure 8 - Jet divergence at nozzle 1 at 80% needle opening with camera position at 0 deg

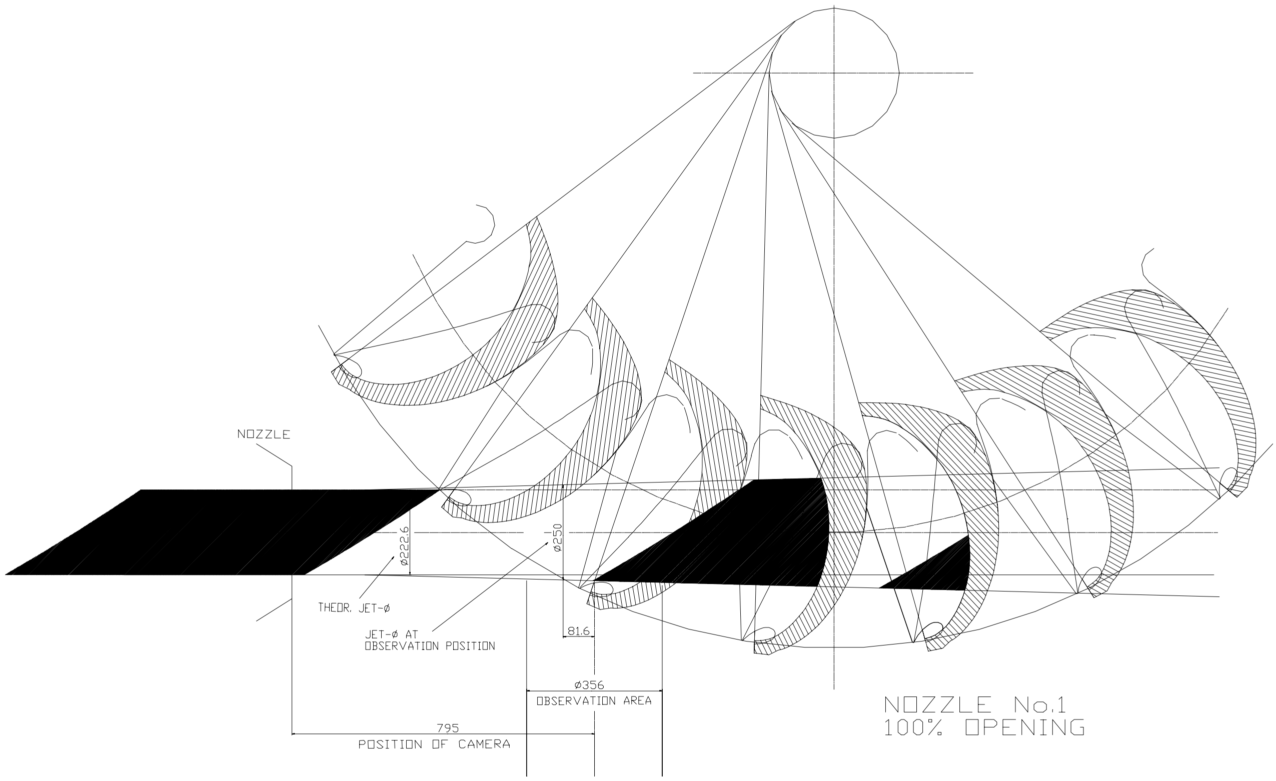

Figure 9 - Jet divergence at nozzle 1 at 100% needle opening with camera position at 0 deg

6 MODIFICATIONS

The original needle and injector design of 1968 does not conform to design criteria commonly applied today. The angle of the needle was found to be too obtuse, while the angle of the seal ring was too acute. For this reason Hetch Hetchy decided to decrease the angle of the needle tip to 50 degrees from 60 degrees and to increase the needle seat ring to 90 degrees from 80 degrees (see figure 10).

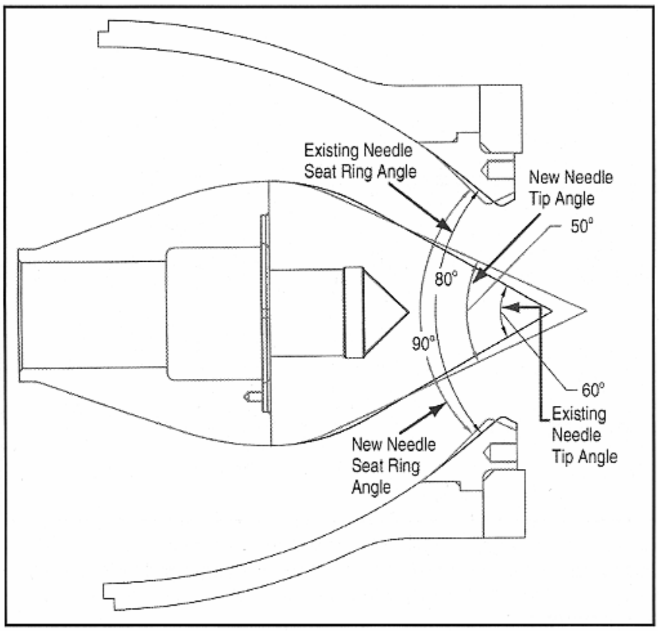

Figure 10 - Jet needle tip and nozzle seat ring modifications for jet quality improvement (Gass, 2003)

Designing the modified seat ring was complicated by the need to fix the new curvature in the existing nozzle body. The nozzle tip was modified in form to properly match the new seat ring without reducing the available stroke. Nevertheless, these measures decrease the maximum throughput and, accordingly, the seat ring diameter had to be slightly increased as countermeasure.
Of course this will not eliminate eventual disturbances being caused by flow conditions further upstream. In general, smooth surface quality should be attained in the injector by carefully painting the surfaces. Such improvements will lead to higher efficiency. Visual confirmation of these secondary improvements is only possible when the quality of the exit portion of the jet is improved beforehand. From previous experience it is known that efficiency can be improved by installing a runner with enlarged bucket width and runner outside diameter in cases where optimum jet quality cannot be achieved.

7 CONCLUSION

Visual observation of the jet on the video sequences showed unsteadiness of the jet's surface structures, which appear to develop directly at the nozzle exit. These structures entrain air, whereby precise jet observation becomes impossible further downstream. However, the jet's contours can still be determined and measured on the images. The resulting data clearly show a jet diameter considerably larger than the theoretical values. A second means of determining the jet's diameter is by measuring the position of the first appearance of the bucket splitter tip when cutting through the jet. This procedure also demonstrated that the jet diverges.
With nozzle modifications the quality of the jet could be improved, which showed an increased turbine efficiency. At full load a 1.2 percent higher efficiency was measured after the modifications.

ACKNOWLEGEMENT

They authors thank Matthew Gass from Hetch Hetchy Water & Power, California, for his support and for making the measurements in the Moccasin Powerhouse possible.

NOMENCLATURE

H	head	(m)	ν	kinematic viscosity	(m^3/s)
D	jet diameter	(m)	ρ	density	(kg/m^3)
Re	Reynolds number	(-)	σ	surface tension	(N/m)
We	Weber number	(-)			

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