Modification Of Nozzles For The Improvement Of Efficiency Of Pelton Type Turbines

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Abstract

The latest units in a program of turbine upgrades and efficiency improvements fell short of the expected efficiency after modification. Two units had only their runners replaced but the tested turbines failed to meet expected performance improvements. After an exhaustive study and testing the lower than expected measured efficiencies were traced to the poor jet quality of the turbine due mainly to the existing nozzle geometry and waterway condition. An improved prototype nozzle was designed, manufactured, installed and tested. The preliminary results showed an over .5 % efficiency improvement at 60 % of full load and .9 % improvement at 100 % needle opening.

Introduction

Hetch Hetchy Water and Power is the municipal power supplier for the City and County of San Francisco. The bulk of the system's power comes from the seven Pelton type turbine generators that comprise the majority of the hydroelectric system. Up to this point, the turbine upgrade program has largely consisted of power upgrades, modernization, and unit changes to increase the efficiency of the Pelton turbines in the system. Previous improvements have consisted primarily of runner replacements, selected nozzle enlargements of the existing injectors, and other minor upgrades. The last major system improvements were the runner replacements for the Moccasin Powerhouse.

Background

Moccasin Powerhouse consists of two, six jet Pelton type turbines designed to operate at a net head of 349.6 meters. The units were installed in 1968 and the turbine supplier was Hitachi. The actual turbine output is 56.7 MW with a theoretical jet diameter of 218 mm. The pitch diameter (D_1) of the units is 2.41 m and the unit speed is 300 RPM. The bucket width (B_2) of the original runners was 754 mm and there were 22 buckets. The original D_1/B_2 ratio for these units was a very low 3.195. The capacity factor of these units is very low and with peaking service, the average load on each unit when in operation, is about 36 MW.

Hetch Hetchy studied the concept of increased performance by replacing the existing runners with runners having higher D_1/B_2 ratios (smaller buckets). In theory, this would move the peak efficiency point to more closely match the normal lower operating level of these units. The only load point guarantee of turbine efficiency in the purchase request was the 38 MW output point. It was expected that a new modern runner design with a higher D_1/B_2 ratio designed for this 38 MW load would favor the machines normally lower output and still maintain high efficiency at full load.

In the documentation sent to bidders, most major components of the existing turbine were shown on drawings for the spiral distributor, nozzle components and wheel pit. The bidders were also provided the normal operating parameters. After a competitive bidding process, the award resulted in new runners being built with a much smaller bucket width of 680mm and with 21 buckets. The resultant D_1/B_2 ratio of the new runners was 3.54. The same manufacturer of the new runners had recently supplied runners for similar machines at Hetch Hetchy that performed very well. These units had comparable D_1/B_2 ratios of 3.74. Prior to the supply of the similar runners the manufacturer performed six jet model tests to optimize their design in the laboratory.

Before the installation of the new runners, both machines were index tested to determine their relative efficiencies at different load levels. The testing was performed using recently installed high accuracy pressure transducers and an existing four-path acoustical flowmeters. A separate test was performed to measure the generator output at 100 % needle opening. Since Hetch Hetchy did not intend to replace any of the nozzle components with the installation of the new runners, a direct test could be done to compare the maximum outputs of the turbines with old verses new runners. After the first new runner installation and full load index testing, the new unit's efficiency appeared to only improve slightly when measured at full load. The measured efficiency improvement at full load was approximately .3 %. The measured efficiency was also less than expected throughout the normal operating range and it was much lower than predicted at the higher loads. Since the turbines with the new runners did not perform as expected, the purchase contract allowed for damages to be assessed if the efficiency of the turbines fell below a set value. Moreover, there was a provision in the contract that thermodynamic testing would be the final determination of the measured efficiency of a turbine. It is important to note that only the runner was supplied but it was the efficiency of the whole turbine that was measured.

Discussions continued with the runner manufacturer identifying several items that could be investigated in an attempt to determine the reasons for the low efficiency of the unit. These included a complete crawl through of the spiral distributor, visual inspection of the nozzles, and dimensional checks of the new runners. After these investigations the first unit was then slated for a code thermodynamic test. The results of the thermodynamic testing verified the earlier performance testing results using the acoustical flowmeter and assumed generator efficiencies determined from initial commissioning tests. The results are shown in figure 1.

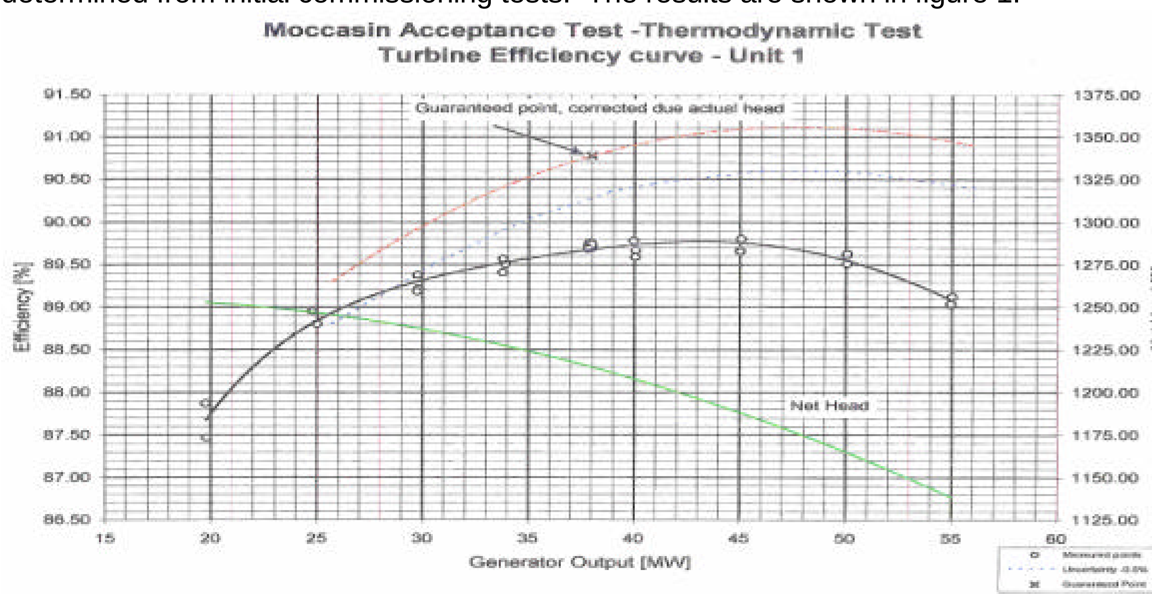


Figure 1

Given the difference of expected performance verses what was measured, there was a joint sense of frustration shared by both the manufacturer and Hetch Hetchy. This performance shortfall was contrasted with recent successes of other supplied runners for similar configured machines. After much discussion and additional testing by Hetch Hetchy and the manufacturer, the focus of the investigation turned to the potential for the jets to be adversely affecting the performance of the unit.

The existing nozzles for these units use a somewhat different configuration than what is considered common practice today. The nozzle seat ring had a final discharge angle of 80°. The nozzle tip has an angle of 60°. It was then questioned that this combination might produce a good quality jet in a model test but not produce a high quality jet in the size required in the prototype. An agreement was struck between the manufacturer and Hetch Hetchy to jointly fund an investigation of the prototype jet in operation. The Swiss researcher Thomas Staubli was contracted to perform a jet visualization study on one of the Moccasin Units. High-speed video images from inside the wheel pit were taken separately on two of the jets in operation from 0 % to 100 % needle opening. The conclusion of this testing was that the jets are of poor quality and the jets diverge from the theoretical diameter towards a diameter much larger in size. The estimates of this divergence are upwards of a 20 % larger jet diameter at the point of contact with the center of the rotating bucket. This jet divergence occurred more at openings greater than 20 % of needle stroke. A drawing showing the old verses new bucket sizes and estimated jet divergence is shown below in figure 2. Strobe video stills of the operating jets are shown in figure 3.

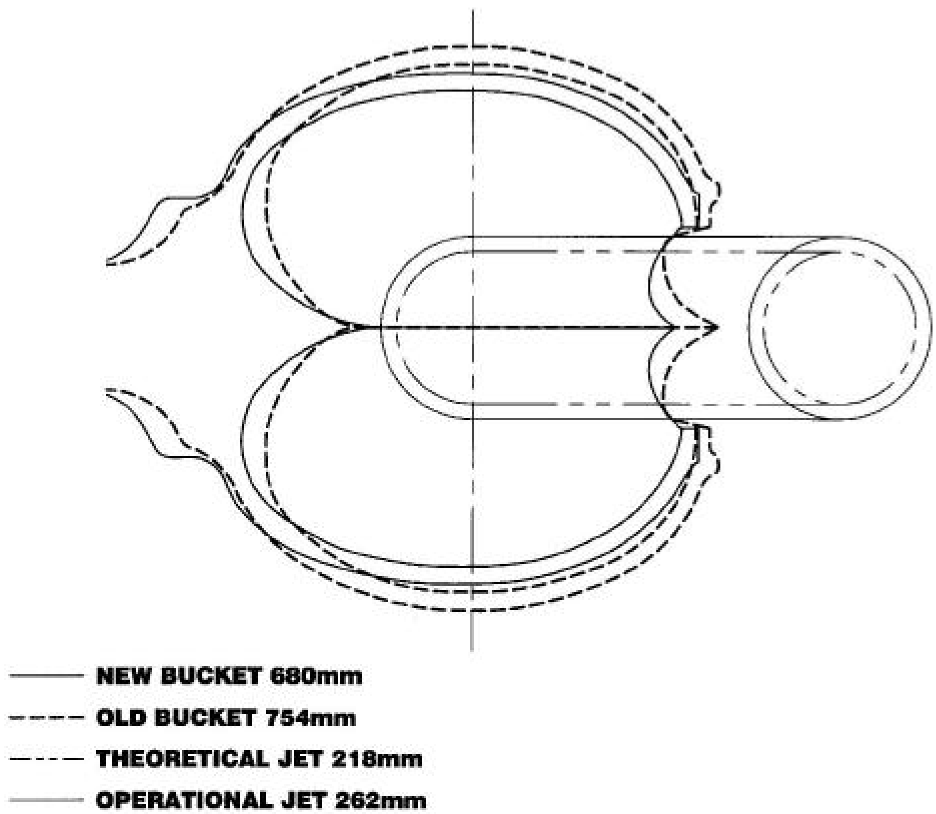
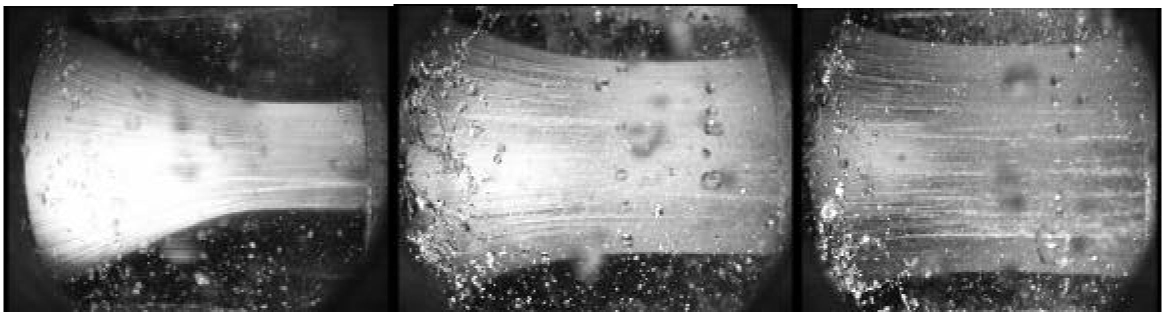


Figure 2

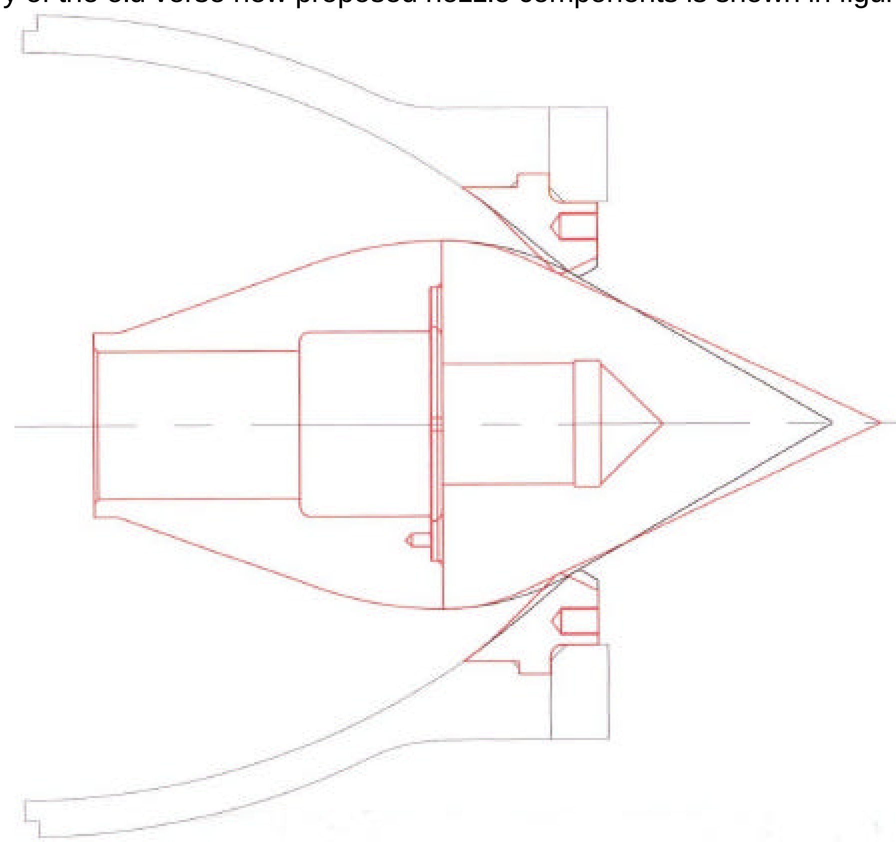


20 % Needle stroke **40 % Needle Stroke** **90 % Needle Stroke**

Actual video stills of single jet in operation

Figure 3

Since the geometry of these jets do not follow modern design convention having a steeper outlet geometry, it was Thomas Staubli's and the manufacture's recommendation to modify the existing housing and/or other components to increase these angles. Their recommendation was to change from the existing 80° needle seat ring and 60° needle tip to a 90°/50° combination. The geometry of the old verse new proposed nozzle components is shown in figure 4



Black 80° seat ring 60° needle tip

Red 90° seat ring 50° needle tip

Figure 4

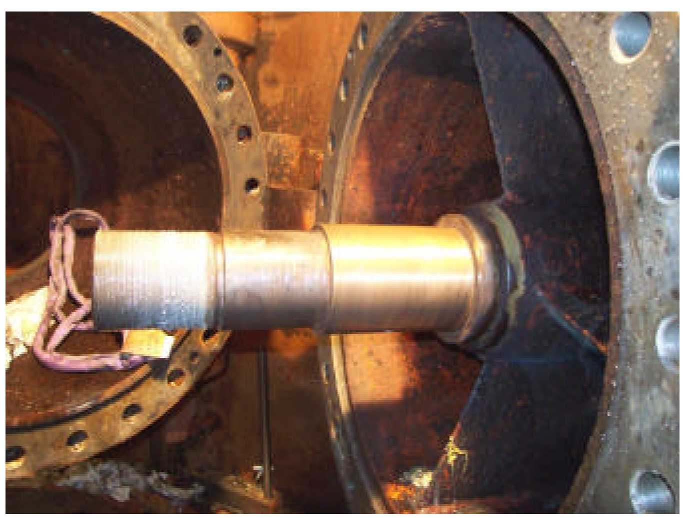
Before Hetch Hetchy launched into a potentially expensive program of component modifications it was decided to test any modification and performance improvement on the prototype. It was further decided to design and manufacture only one nozzle seat ring and needle tip and to test its ease of fit and performance in actual use. If this angle change could not be accomplished without major compromises, it would be necessary to purchase completely redesigned nozzle housings. If this change were required, the economics of the modifications would then not be economically justifiable. The design of the new nozzle components were complicated by the need to fit the existing curvatures and waterway transitions in the existing nozzle body. A design compromise was struck where the curvature of the existing nozzle body would be extended into the design of the new nozzle seat to increase this component's water passage angle from 80° to 90°. There would be less straight section of nozzle seat ring prior to the discharge opening. The seat ring diameter was increased slightly to compensate for the lower discharge resulting from the steeper angle of discharge and the new lower nozzle tip angle. The nozzle tip was modified in form, to properly seat and match the newly designed seat ring geometry without sacrificing any of the available stroke of needle stem. It was discovered that the turbine governor could be modified to extend the existing needle stroke to help compensate for the lower discharge coefficient of the new nozzles' expected flow. Since the Moccasin units rarely operate at full output, it was decided to compromise on providing a slightly lower output in favor of the increased efficiency expected by minimizing the final nozzle seat diameter.

The installation went as planned without incident, until it was discovered that the longer nozzle tip would not allow the nozzle housing and seat ring to easily clear on installation. Final installation required the crew to unhinge the nozzle housing to clear the longer needle tip.

Installation of prototype nozzle seat ring and needle tip
Figure 5

Prior to the single nozzle component change-out, a performance test was done on the unit. With some opposition from the Operations Department, the governor was modified to allow for single jet operation. Their concern stemmed from the anticipated increase in the turbine bearing loading and higher vibration of the unit during single jet operation. To perform the index test a constant forebay elevation was held. Each turbine jet was tested using only one jet at a time while at 100 % needle opening. The flow verses MW was correlated for the 6 different single jet test runs. The flow was measured using a 4-path acoustical meter on the supply penstock which appeared to index the performance well. The results of the testing showed that the relative MW/Flow was approximately the same for all six jets. Jet #1 had the best efficiency with Jet #6 the worst. All six jets indexed to within .3 %. The most stable flowmeter performance was obtained when the unit is allowed to operate for an extended period of time stabilizing the reading before recording the results. Another means of data improvement is to switch from one needle in operation to another in such a way as to minimize the pressure surges and flow changes in the unit's penstock. During single jet testing the turbine bearing metal temperatures rose up to 15 °C above normal and the vibration amplitude as measured at all three bearing doubled.

After the nozzle modification was made, the single-jet index tests were repeated. The results of the jet modification with the new geometry showed a preliminary efficiency improvement of over .5 % at 60 % load and .9 % at full load. If the improvement for the one jet were applied to all the unit's jets, then this would be enough to meet the efficiency guarantee in the runner purchase contract. With the promise of this measurable performance improvement, (2) complete sets of nozzle components are now being manufactured for the Moccasin Units. At another powerhouse in the Hetch Hetchy system there are two other similar Hitachi turbines, which share the same nozzle geometry as the Moccasin units. A complete set of replacement components has also been ordered for these units as well. The installation of the first set of components for Moccasin is scheduled for April of 2002. During the upcoming nozzle installation it is hoped that the corroded nozzle guide vanes and the contraction sections of the nozzle housings can be refinished and recoated to further improve the quality of the resultant jets.



Existing housing and guide vanes. Note: Poor existing surface finishes
Figure 6

Conclusion

The quality of the jet in a turbine should be thoroughly investigated as part of a unit upgrade or runner replacement. The efficiency of these units seems to improve measurably with the modification of the nozzle components to increase the jet exit angle. It is suspect that there are a lot of machines that might share this condition of low jet quality and divergence due to poor existing nozzle geometry. It could be a matter of scale that the performance of a model jet might not accurately represent its' performance on the prototype. More study of Pelton turbines jets should be done on the quality of jets on existing prototype machines that have less than optimum geometry. Machines that operate at high loads or have high capacity factors or bucket loading might benefit from nozzle improvements as part of an upgrade program. The widespread use of computer-aided design has greatly simplified the retrofit of new nozzle components in existing housing while maintaining design clearances and providing proper hydraulic transitions. The use of real time monitoring and acoustical flowmeters greatly simplifies the process of efficiency testing for investigating the relative effects of small trial performance improvements on prototype units. This author would like to thank Thomas Staubli and the personnel at IMPSA /HUGAL who worked through this difficult problem to a successful conclusion.

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