Efficiency testing in Tai An (Shandong China) PSPP reversible units by means of thermodynamic method

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Abstract

The TaiAn Pumped Storage Power Station is located approx. 2 km west the town of Tai An City in Shandong province (China) and approx. 100 km south/west of Jinan, the capital city of the province. The station pumps and uses the water, through twin penstocks, between the upper reservoir on TaiShan mountain and the wide lower reservoir about sixty meters higher than the units' centerline.

The power plant is erected inside the mountain where four pump turbines are installed, two for each penstock.. The units are equipped with francis type pump/turbines made by Voith Siemens Shanghai in China and with Fuji Voith Siemens motor/generators.
A test campaign has been performed with the purpose of acceptance tests on the one of the units in order to verify the behaviour both in turbine and in pump mode with different head levels. Unit Nr. 2 has been choosen as unit to be tested. Thermodynamic method has been adopted as stated in the contract.

S.E.P.R.I.(Jinan-China)/W.E.S.T.(Milan-Italy), has been delegated from the parts to carry out the efficiency test on the unit.
The efficiency tests have been carried out in accordance with IEC EN 60041/11-91 (and revisions).
Some simplification were adopted in the temperature/energy distribution both in high pressure side and low pressure side by using two sampling vessel at the entrance and three sampling vessels at the outlet. The connection between sampling probes and vessels in the low pressure side had quite long insulated pipes embedded in concrete.
Despite these simplification reliable and accurate results were obtained. The paper describes test results.

Unit's characteristics

The machines installed are vertical Francis pump/turbines with 7 blades runner and 24 wicket gate with independent controlled servomotors.

The following values in turbine mode have been guaranteed:

Net Head [m]	Parameters		LOAD						
			50% Pr	60% Pr	70% Pr	80% Pr	90% Pr	100% Pr	110% Pr
250	Weighted factor		1	1	2	2.5	2	1	0.5
	Prototype efficiency	%	xx	xx	xx	xx	xx	xx	xx
	Lower res.water level	m	154.00	154.00	154.00	154.00	154.00	154.00	154.00
240	Weighted factor		1	2	4	8.5	7	6	0.5
	Prototype efficiency	%	xx	xx	xx	xx	xx	xx	xx
	Lower res.water level	m	156.56	156.34	156.11	155.82	155.48	155.29	155.09
230	Weighted factor		1	2	4	9	8	7	0
	Prototype efficiency	%	xx	xx	xx	xx	xx	xx	xx
	Lower res.water level	m	158.65	158.49	158.30	158.07	157.79	157.64	157.48
225	Weighted factor		05	1.5	4	8	6	5	
	Prototype efficiency	%	xx	xx	xx	xx	xx	xx	xx
	Lower res.water level	m	159.87	159.73	159.56	159.36	159.11	158.97	
215	Weighted factor		0.5	0.5	1	2	1	0	
	Prototype efficiency	%	xx	xx	xx	xx	xx	xx	xx
	Lower res.water level	m	160.85	160.75	160.62	160.43	160.24	160.12	

All load values are expressed as ratio of the rated output Pr=255.1 MW

(when the rotation speed is 300 rpm)..

The following values in pump mode have been guaranteed

Parameters		Pump head			
		230 m	240 m	250 m	260 m
Weighted factor		15	36	41	8
Prototype efficiency	%	xx	xx	xx	xx
Discharge	m^3/s	108.68	102.62	96.19	89.17
Power	MW	261.06	257.08	251.28	243.17
Gate opening	mm	268	268	238	208
Lower res.water level	m	158.80	156.70	154.00	154.00

All data refer to the rotation speed of 300 rpm

The maximum performances in pump mode correspond to head of 235.3 m and 105.5 m^3/s discharge. At the minimum pump head of 223.58 m the flow shall not be less than 112.36 m^3/s. at the maximum pump head of 259.60 m the flow shall not be less than 89.45 m^3/s.

The maximum pump input including tolerance shall not exceed 274.00 MW.

Test principle

The thermodynamic method derives from the application of the principle of energy preservation to the transfer of energy between the machine and the water passing through it.

This application, in case of real operation, gives the possibility to express the energy that is transmitted to the water starting from the measured quantities (pressure, temperature, speed, etc.) and from the thermodynamic properties of the water.

Therefore, the efficiency and the net head can be calculated from the measurement of the specific mechanical and hydraulic energy. The measurement of the consumed power taking into account the motor/generator losses obtained during official tests and the bearing losses allow determining the mechanical power at the runner and the consequent discharge.

In this case, the pump/turbine mechanical losses are the sum of the turbine guide bearing losses and a portion of the thrust bearing due to the hydraulic thrust . All other mechanical losses have been assigned to the generator.

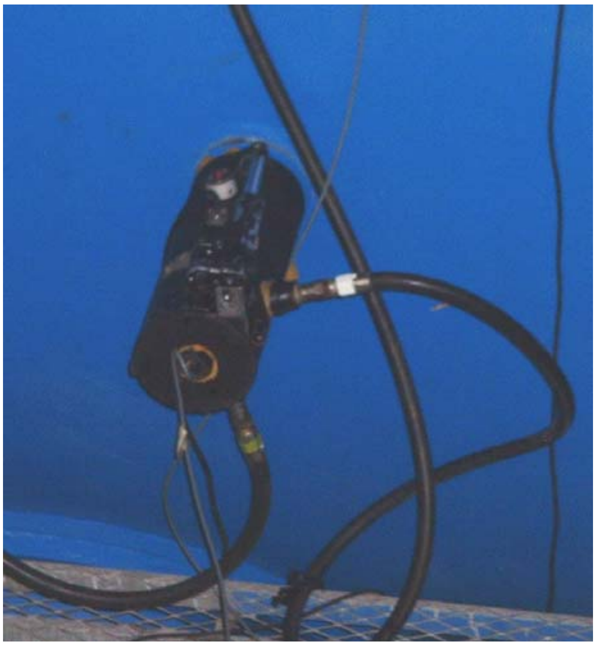
Installation

Four taps have been used at high pressure side for performing the average measurement of the $\mathbf{p_1}$ pressure and connected with high pressure pipes to an high accuracy pressure transducer.

The high pressure side has been also equipped with two sampling vessel for measuring the upstream mechanic energy . They have been placed on the horizontal axis between the spiral case and the unit main valve. The pressures and the temperatures measured inside the sampling vessels have been identified with the symbol **1'**.

Considering the penstock dimensions and in accordance with the international codes, a sampling probe that allowed a net sinking of 400 mm has been utilized.

Four taps have been used at low pressure side for performing the average measurement of the $\mathbf{p_2}$ pressure and connected with high pressure pipes to an high accuracy pressure transducer.

The low pressure side has been also equipped with three sampling vessel for measuring the upstream mechanic energy . Two of them have been placed on the horizontal axis and the third on the ceiling of the measuring section. The pressures and the temperatures measured inside the sampling vessels have been identified with the symbol **2'**.

Considering the dimensions and in accordance with the international codes, a sampling probe that allowed an approximate net sinking of 500 mm has been utilized.

During the tests, the vessel flow has been changed in order to verify the quantity of heat coming from the surroundings that resulted to be absolutely negligible thanks to the adopted insulation and the scantiness of the thermal gradient; therefore no measurement adjustment has been considered necessary.

The not-uniformity of both upstream and downstream sections has also been evaluated by calculating the difference in terms of energy between maximum and minimum energy values.

Calibration of pressure probes

The pressure transducers utilized during the tests are subject to functional check and periodical control of the calibration, in accordance with the ISO specifications.
A check has been performed at the beginning of the official efficiency tests using as primary instrument the Budemberg dead weight manometer, provided with calibration certificate, for the pressure transducers and the Thommen micro-manometer for the level transducers. These calibrations are periodically verified.
It has also been possible to compare the transducer reading with the upstream and downstream reservoir static levels during the first run with the unit standstill for the time necessary to stabilize the pressures in the system and verify the consistency of results

Calibration of temperature probes

The temperature detectors utilized for determining the efficiency with the thermodynamic method have been calibrated in thermostatic bath with 0.5 mK° stability and with a primary reference instrument, before and after the test campaign..
At site two different calibrating procedures are normally adopted.
The first consisting in stabilizing the thermometric probes at the same temperature into a Dewar pot. In this case Tt and Ts are assumed to be equal and then by simultaneously measuring Rt and Rt/Rs ratio both ***Rs=f(Ts)*** and ***Rt=f(Tt)*** relationship are checked.
If Tt=Ts the measurement of the ratio Rt/Rs (instead of Rs) allow to refer all measurements to the same probe Rt and reduce errors during the tests. When systematic errors due to temperature variations occur, The only effect is a common shift of all equations being this offset the same for all probes.
Special care must be taken on the contrary to ensure that Tt=Ts during the calibration. Normally a soft movement of the water inside the pot prevents from stratifications.
This calibration has been repeated at different water temperatures between 0.2°C and 20°C since the test water temperature is approximately 2.5 °C.
A second calibration by means of an expanding device (see IEC EN 60041) is normally performed if some odd values are found in the previous checks . The two vessels (normally installed in the high pressure section during the efficiency tests) are connected in serial and to the penstock so that the same water passes through both vessels. The flow in the vessels is fixed at the value normally used during tests
Every heat exchange with environment has to be prevented. A regulating valve is installed between the two vessels. The losses of the valve due to the flow (p12<p11) inside an adiabatic system cause a rise of the temperature (T12>T11) according to the equation

a (p11-p12) + Cp (T11-T12) = 0

Measuring by means of a differential pressure transducer (p11-p12), p11 and T11 (with the purpose of calculating a and Cp) it is possible to calculate the difference of temperature.

Probes are connected to the bridge so that T11≡Ts and T12≡Tt by simultaneously measuring Rt and Rt/Rs ratio both ***Rs=f(Ts)*** and ***Rt=f(Tt)*** relationship are checked also in the case of Ts≠Tt

Actually, it is necessary to underline that the efficiency measurement requires the measurement of the machine upstream and downstream temperature difference and then it isn't strictly necessary to know the absolute temperature with the prescribed accuracy. It should be noted that a ΔT error of 1% implies an approximate error of 0.1% on the efficiency.

The coefficients obtained during the site check of the calibrations do not show any significant difference from the ones obtained during the official calibrations in ISO laboratory

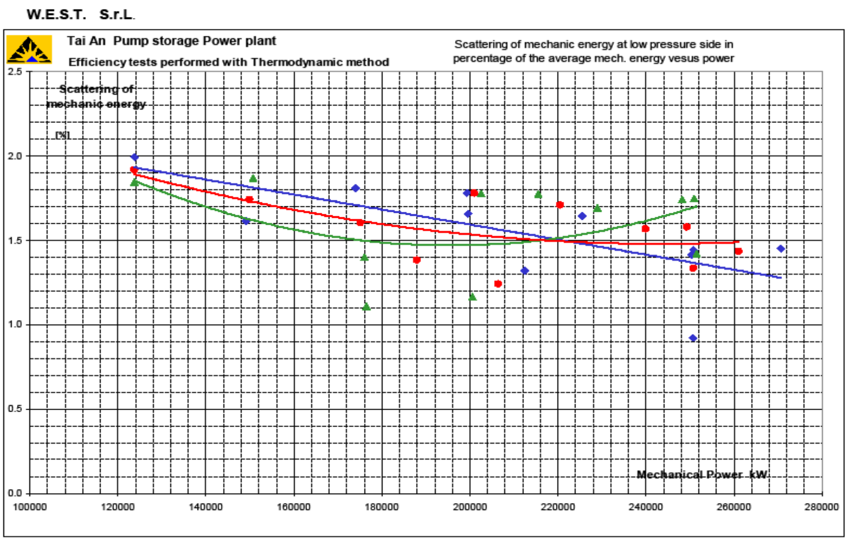
Analysis of measurement errors

The measurement errors can be divided in two different categories, systematic (or bias) errors and random errors. Both types of error shall be calculated from systematic and random errors of all measured quantities.

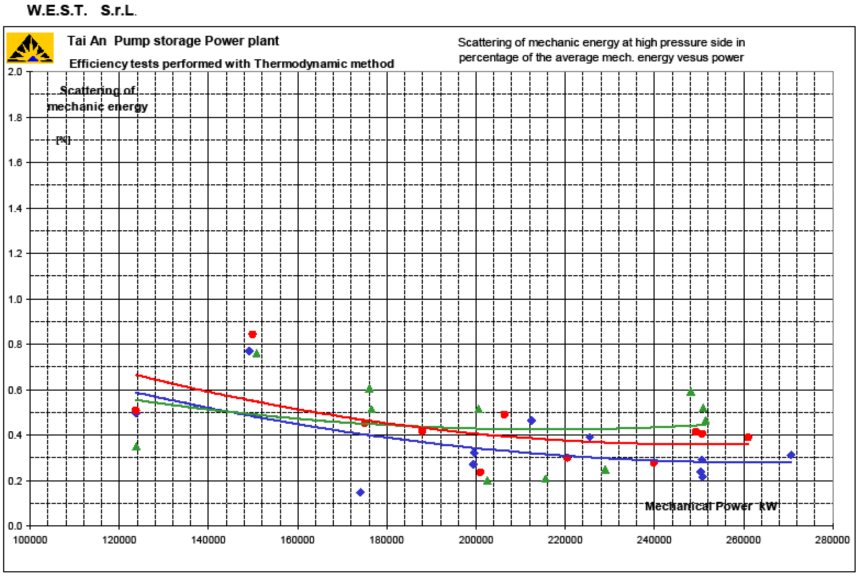
We derive the systematic errors of each transducer from the calibration errors while from data acquisition we calculate the standard deviation of each measurement and consequently the random error.

Major sources of error are linked to temperature measurements in the low pressure side. The three probes (six holes withdrawal) meet the requirements of the international codes, however, is unrealistic to assume that the section of measurement has been adequately explored in order to have a correct value of average temperature.

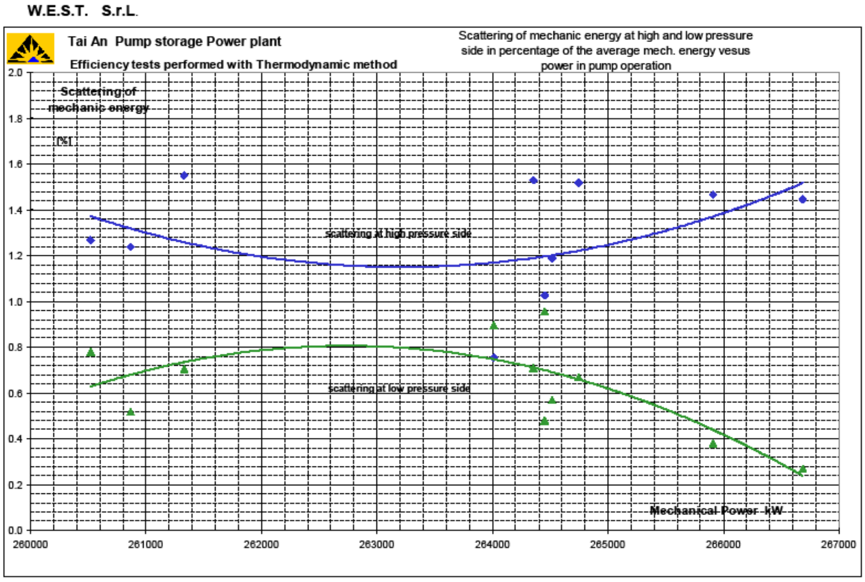
In this sense the evaluation of differences in energy between the different sensors installed looks very useful. The graph shows the greatest divergence between the various probes in the various loading conditions and for different measured heads.



It is noted that the deviations are included in the range between 1 and 2 percentage points with an average of approximately 1.50%. It is possible to denote a trend of decreasing values with the load, this would assume that the differences are related to the conditions disrupted the exhaust typical at partial load. In these circumstances it is likely that the measurement uncertainty due to asymmetries exhaust is more than ±0.60% provided by the codes, even if the installation is fully in accord with the requirements.
A similar graph is available for high-pressure section



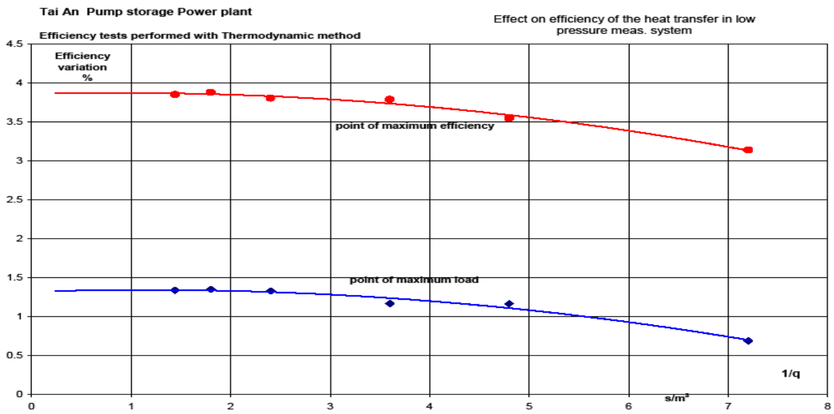
In this case the average deviation is about 0.40%. Again, there is decrasing trend with the load. Under these conditions the measurement uncertainty caused by asymmetries in the side high pressure is probably close to ±0.25% provided by the codes.
Similar results are obtained in pump operation where there are major differences between the high pressure probes while the situation is more homogeneous in aspiration (low pressure)



In this case the average deviation is about 1.40% at high pressure outlet and 0.7% at low pressure entrance. There is no appreciable trend related with the load. Also in these conditions the measurement uncertainty caused by asymmetries looks higher than the values provided by the codes.

The pipeline linking the sampling probes and the measuring tank (where temperature and pressures are measured) have a length of 8 meters and are equipped with double thermal insulation and are embedded in concrete. We can assume in this case that the heat transfer significantly influences the measure temperature.

The analysis of heat exchange performed on two different load conditions leads to corrective terms not negligible but not sensibly affecting the results.
The graph shows the trend of the efficiency curve versus 1/q.



Then following the code we have:
Error on mechanical energy

$$f_{Em} = \frac{e_{Em}}{E_m} = \frac{(e^2_{Ep_m} + e^2_{E\theta_m} + e^2_{Ev_m} + e^2_{Ez_m} + e^2_{\Delta E_m})^{0.5}}{E_m}$$

Pressure term

$$e^2_{Ep} = (a \cdot e_{P1'})^2 + (a \cdot e_{P2'})^2 + \left[(p_{1'} - p_{2'})e_a\right]^2$$

Temperature term
Assuming that all the error found during the check of the calibration made can be transferred to the tests, the maximum possible error is ± 0.00075 °K
The systematic uncertainty in the measurement of the specific heat capacity is assumed as f_{Cp} = ± 0.5%. consequently $e_{fC} = C_p \cdot f_{fC}$
The number of probes used to calculate the mean water temperature on the upstream sections is equal to the number prescribed by the code,

$$e^2_{E\vartheta} = (Cp \cdot e_{\Delta T})^2 + \left[(T_{1'} - T_{2'})e_{Cp}\right]^2 + e^2_{E10} + e^2_{E20}$$

Unless the highest accuracy has been adopted in order to reduce the systematic errors in the low pressure side section,as consequence of the fact that Francis turbines usually have notuniform velocity patterns at the outlet and the relatively low head leads to higher inaccuracies both corrective term have been set to the maximum

$\mathbf{f_{E10} = \pm 0.25\%}$ and $\mathbf{f_{E20} = \pm 0.60\%}$

<u>*Other terms*</u>

The error introduced by the kinetic term and by the potential term extremely low

$$e_{Ev}^2 = (v_{1'} \cdot e_{v1'})^2 + (v_{2'} \cdot e_{v2'})^2$$

$$e_{Ez}^2 = (g \cdot e_{z1'})^2 + (g \cdot e_{z2'})^2$$

The error due to the not estimated heat coming through the measurement sections is to be considered very small considering the poor thermal gradient between water and air. It also can be estimated in ± 0.2%.

Error in hydraulic energy

$$f_{Eh} = \frac{e_{Eh}}{E_h} = \frac{(e_{Ep_h}^2 + e_{Ev\,h}^2 + e_{Ez_h}^2 + e_{\Delta E_h}^2)^{0.5}}{E_h}$$

<u>*Pressure term*</u>

The systematic uncertainty in the measurement of density of water , and defining $\mu = 1/\rho$ the specific volume, is $f_\rho = f_\mu = \pm 0.1\%$ consequently the absolute error is $e_{f\mu} = \mu \cdot f_\mu$

$$e_{Ep}^2 = (\mu \cdot e_{P1})^2 + (\mu \cdot e_{P2})^2 + \left[(p_1 - p_2)e_\mu\right]^2$$

<u>*Kinetic and potential terms*</u>

The error in the kinetic term is connected to the discharge measurement error that, in the case of the thermodynamic method, depends on the efficiency and on the power and on the test head.

In first approximation, we can assume that the efficiency error is ± 1.00% and the power error is ± 0.50%. The discharge measurement error is can be evaluated as ± 1.05%.

Admitting an error in the measurement section of ± 0.25%, the uncertainty connected to the determination of the average speed is ± 1.10%

$$e_{Ev}^2 = (v_1 \cdot e_{v1})^2 + (v_2 \cdot e_{v2})^2$$

The error of the potential term is

$$e_{Ez}^2 = (g \cdot e_{z1'})^2 + (g \cdot e_{z2'})^2$$

Error in electric power

The electric power is measured downstream of the unit TA e TV and the systematic error of these transformers is assumed to be ±0.20%.

The utilized measurement instrument has been calibrated in a certificated laboratory.

The calibration certificates contain also the specifications concerning the reference primary instrumentation. The error of this instrumentation in the range between cos φ = 1 and cos φ = 0.8 is ± 0.04%, while the deviations, with respect to the tested instrument, are of ± 0.10%.

As far as the generator losses are concerned, the values measured during previous official tests have been utilized. The error made during said measurements can be estimated in ± 0.15%.

$$f_P = (f_T^2 + f_{Pm}^2 + f_{Pb}^2)^{0.5}$$

Error in the calculation of efficiency and discharge

Assuming that the error in determining the gravity acceleration is negligible, the global error made in determining the efficiency is:

$$f_\eta = (f_{E_m}^2 + f_{E_h}^2)^{0.5} \quad \text{and}$$

$$f_H = f_{E_h}$$

As far as the discharge is concerned, it is affected by the measurement error of power, head and efficiency; therefore

$$f_Q = (f_\eta^2 + f_P^2 + f_H^2)^{0.5}$$

Total error calculations and values

Once separately calculated by means of the above-mentioned equations both systematic and random errors, the total error of the measurement is then obtained as:

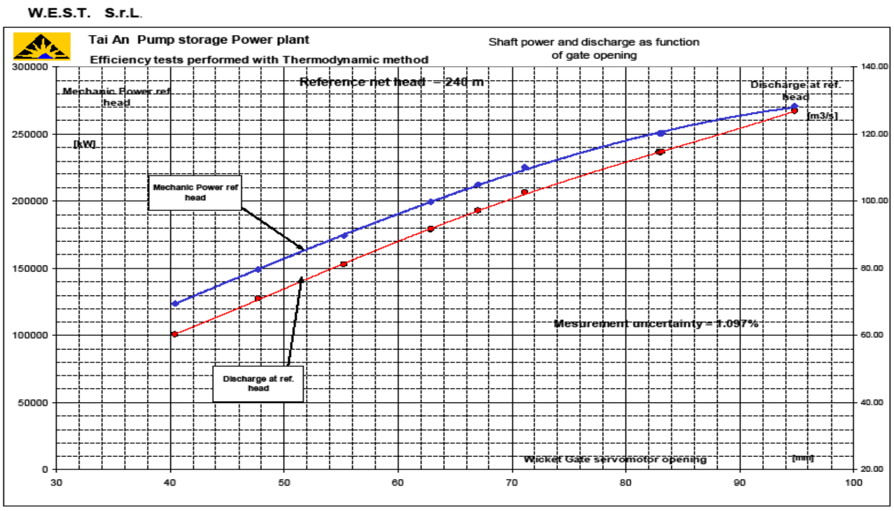
$$f_\eta = (f_{\eta s}^2 + f_{\eta r}^2)^{0.5}$$

During these tests the systematic error in efficiency varies between ±0.825% and ±0.952% while the random error varies between ±0.415% and ±0.545%. The total error is in the range the contractual value with a maximum of ±1.098%

A more accurate analysis of measurement errors, which departs from code prescriptions, but assess the probability of error related to the actual asymmetrical distribution of energy, however, could lead to slightly higher errors.

Results

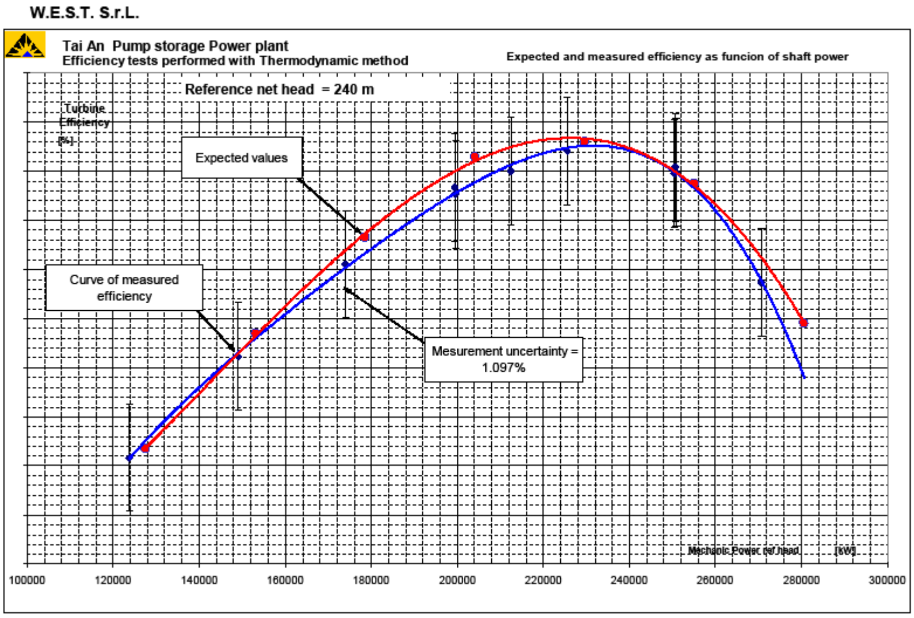
For each test head eleven different tests were performed: changing the power output from 50 to 110% by varying the gate opening. The other unit on the same penstock being standstill the head has been regulated by using the other two units as pumps (in case of need)



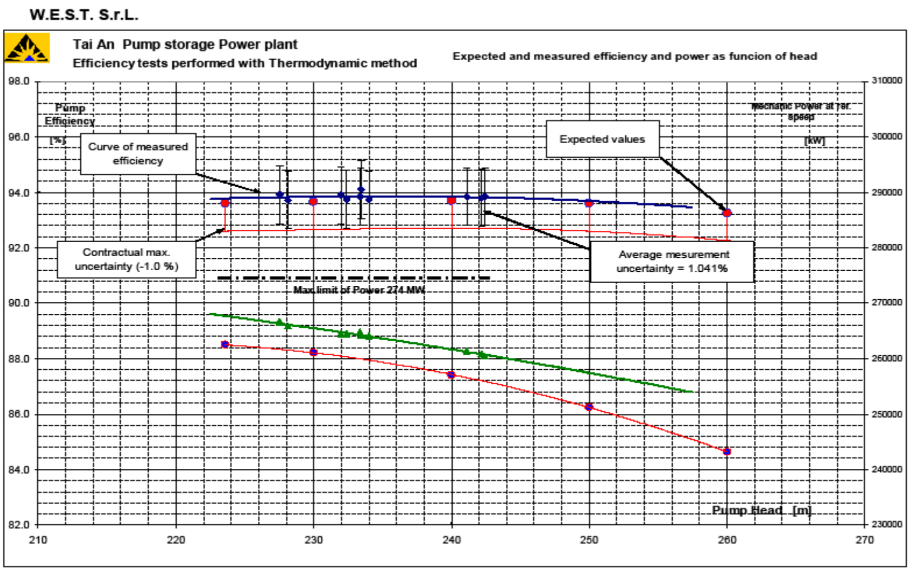
The graph (at one of the tested heads) shows the curve of the discharge related to the reference head in function of the gate opening.

Considering that mechanic clearances may give quite a high uncertainty in the signal, the results show an acceptable shape with small deviations respect to the interpolating curve.

The same diagram shows the trend of the power related to the reference head in function of the servomotor opening. This curve is monotonic and verified in a linear way up to the zero power at the no load running opening. The results show an acceptable shape with small deviations respect to the interpolating curve.



The graph gives the measured efficiency versus the power at the reference head of 240 m. The measured points are well aligned; then the plotting of the interpolating curves shows that the interpolating error is within ± 0.15%. The maximum measured total uncertainty is shown by means of a bar around the measured points. The uncertainty is equal or lower than the expected values.
The curve has been compared with the expected values at the same head. The difference is lower than the uncertainty band



The graph refers to pump results at the contractual rotation speed of 300 rpm. Power and efficiency are shown in function of head
The total error of the measurements is practically equal to tolerance All measurement follow the natural variation of head during the pumping mode (except turbine operation during DAQ to keep stability) and the comparison with guarantees was made by means of the interpolating second order curves. The power is higher than expected but lower than the guaranteed limit

Conclusions

The installation test despite being in accord with the requirements of the international codes was the subject of careful investigation. The main cause of concern was the distribution of energy in sections of the mechanic energy measurements and especially in the outlet sections (low pressure turbine in operation and high pressure pump in the operation). The analysis of differences between the different probes would seem to lead to uncertainty due to lack of exploration of energy higher than that indicated by the same IEC 60041 code even though in this specific case the differences do not appear very big.

The repeatability and matching of results is also evidence that the random error is reasonably content and that the possibly present conditions of uneven mechanical energy distribution are mostly stationary.
All the considerations expressed suggest that despite these simplification reliable and accurate results were obtained

Bibliography

Multipoint Thermodynamic Measurements –A Statistical Approach to Uncertainty Levels M.Sc. Harald Hulaas M.Sc. Terje BryhniPh.D. Ole Gunnar Dahlhaug

International Electrotechnical Commission, International Standard, IEC 60041-1991 “Field Acceptance Tests to Determine the Hydraulic Performance of Hydraulic Turbines, Storage Pumps and Pump-Turbines”, Third Edition, 1991-11.

ASME Power Code for Hydraulic Turbines PTC 18-1992.