Efficiency testing in Belesar power plant

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Abstract
The testing procedures in Belesar had to face high difficulties due to contractual specifications in terms of admissible inaccuracy and plant characteristics due to quite high head variations.
Despite the average head of 100 m the only method that could achieve satisfactory results was the thermodynamic method. It was decided thereafter to test the unit at the highest head by means of thermodynamic and to test all other heads by index testing.
In Francis turbines the biggest portion of the uncertainty comes from the asymmetric distribution of energy at the outlet. Two special frames were designed in order to fit into the downstream stop logs each one equipped with six thermometers, each one collecting water from 16 different dynamic taps. Pressure sensors were also installed.
The relative flow portion related to each thermometer was finally accurately measured by mean of special design flow-meters.
The paper will illustrate the frame design, construction, and installation in detail. It will also describe the actual measurement and the results obtained. Despite some structural failures due to the extremely high asymmetry the big effort was definitely successful giving reliable and quite accurate results.
General conclusions relevant to thermodynamic uncertainty are stressed: the additional term related to lack of temperature investigation at the outlet (as defined in the IEC code 60041) is definitely too optimistic in case of Francis turbines as it has been possible to evaluate the amount of error that could be done if different testing procedures were adopted.

General description
The hydroelectric power Belesar, owned by Union Fenosa, is located in Spain,in the “Autonomia de Galicia”.
To produce energy the plant takes water from the Belesar dam, the largest reservoir of Galicia with 655.10^6 cubic meters capacity and 18,28 km^3 surface.
The Belesar dam is an imposing structure of over 130 m high, built in the river Mino in 1960.
In the central three groups are equipped with Francis turbines, with a head of 128 m a flow rate of 80 m3/s, generating an output of 93 MW.
At present, is under way an update of the groups, by replacing the rotors.
Groups 2 and 3 are already finished, and while shortly be carried out works in the last group.
The aim of the measurements is to determine the performance of the turbines after refurbishment. Therefore the tests have official status and meet the demand for verification of contractual guarantees.
In the area of operation of the turbine has identified four main head values (128, 117, 107, 93 m) and these have been set for the guarantees on performances. All tests will be conducted in accordance with the code of IEC 60041 and contractual requirements.

At the maximum head H = 128 m, it is envisaged the use of the thermodynamic method in order to measure the performances. On this occasion was calibrated the differential pressure between Winter Kennedy taps specifically prepared in the spiral case.
For other heads the measurement of the performances has been done through the index method, using, for measuring the flow,the Winter Kennedy taps previously calibrated.
It is considered that must be achieved a maximum uncertainty of ±1.10% on the measured value of efficiency. Before starting each the test campaign, personnel owner and manufacturer together have inspected the machine that was declared "ready for tests". Before and after each performance tests were carried out both the normal controls zero and the calibration of all instruments used. There were investigations regarding the thermal gradient at the entrance of the turbine and heating tanks poured. All these tests are needed to assess the corrective terms for calculating efficiency and to prove the reliability of results.

Thermodynamic testing – installation and procedures

Tests have required the modification of the circuit cooling of the generator and bearings; because the water cooling significantly influences on the measurement of temperature downstream. The diversion was conducted in another machine

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.

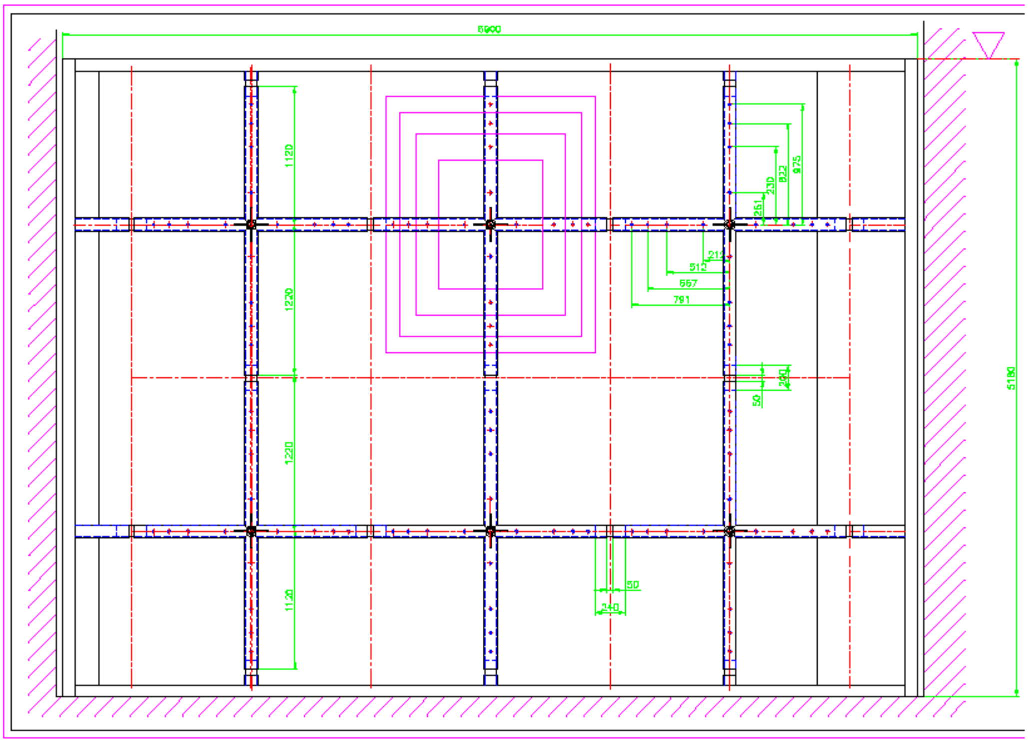
The high pressure side has been also equipped with three sampling vessel for measuring the upstream mechanic energy . Two of them have been placed 60° from the vertical upper axis and the third one at the bottom of the section between the spiral case and the unit main valve. The pressures and the temperatures measured inside the sampling vessels have been identified with the symbol **1'**.
The use of three tanks which means three temperature measurements in the upstream section allows not take into account the error for lack of inspection of entrance energy(f_{E10} = ± 0.25%) as well as indicated in the international code.

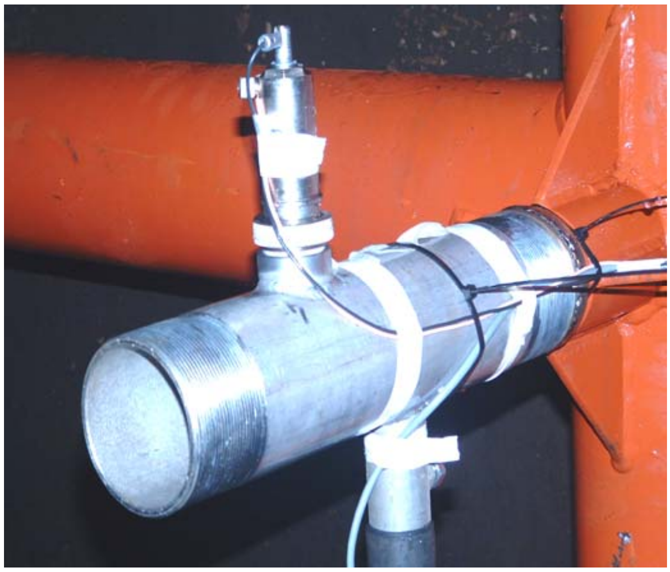
Considering the penstock dimensions and in accordance with the international codes, a sampling probe that allowed a net sinking of 400 mm has been utilized

The measurement of the downstream level is carried out through two level transducers placed in the channel downstream of the machine. The section at the exit of diffuser is identified with the symbol 2

In the two discharge channels 12 probes to measure the temperature in the downstream section were also placed. These probes are placed in the intersection of two tubular structures of three vertical and two horizontal pipes.
Each probe receives the flow of 12 kinetic taps distributed in the structure to represent equal area, so that the measurement from these 12 probes represent an average of 144 points. In addition, in correspondence with each probe, a propeller flowmeter has been installed to provide a weighting factor (depending on the stream) for each temperature measurement .The use of twelve probes and the weighting system allows not take into account the error for lack of

inspection of the downstream energy (f_{E20} = ± 0.60%) as well as indicated in the international code.
Here are the drawings of the structure.





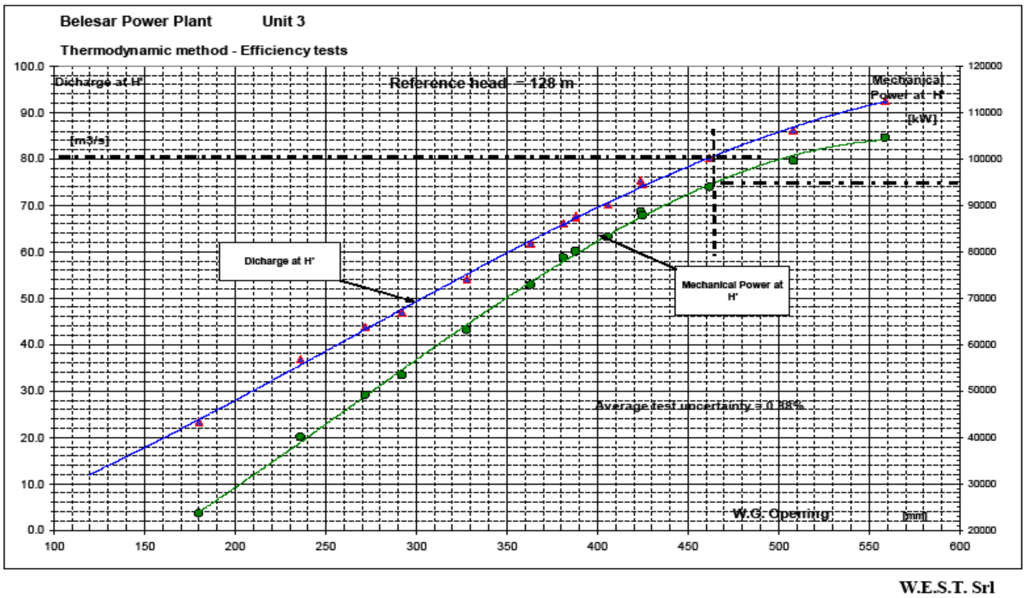
Thermodynamic testing - results

In total fifteen tests have been performed, in different load conditions exploring the area between 25% and 110% of rated power.
For every test point 60 acquisitions have been made, getting the average value of each variable within about thirty minutes.

All tests have been performed with the unit as evidence in manual operation with other groups stand still. Also the level of reactive load remained constant during the tests. Repeat testing has been done with measuring efficiency through "partial expansion” procedure. In these cases where the thermal term of the mechanical energy is negative or near zero no significant variations in efficiency were found with respect to other points made using “without expansion” procedure.
Through these tests also checked the calibrations of thermometers and bridge measurement. It has also verified that there is no effect on the extent of dumping by varying the flow and, consequently, the conditions of heat exchange.
This type of measurement allows the calculation for the correction due to temperature variation within the tank dumping the effect of exchange with the environment. This has been negligible anyway thanks to the insulation system adopted and the low thermal gradient with the environment. Indeed variations in efficiency have been less than + 0.10%, an entity that is orders of magnitude less than the random error.
Through these tests also checked the amount of heat carried by the metal surfaces of the machine have also been calculated albeit with good approximation irrelevant to the measurements, the value of that amount reaches around 0.10% in tests with lowest burden. For the calculation using the formula:

- Em = A Paw (Ta - T1) / M '

The measured temperatures even not perfectly stable during each test indicating variations in order 0,04 ÷ 0,05 °K in the course of each 30-minute acquisition while is normally expected that power plants using water reservoir have water stability at around 0,03 ° K. Variations measures in any case remain below the threshold referred to by code IEC 60041 IN allowing a variation of a 0,005 °K per minute, which means 0,15 °K in 30 minutes.
During the course of the test also measurements of pulses of the flow-meters (installed behind the temperature sensors on the downstream measuring structure) were taken to have the average weighting flow related to each temperature sensor.
The graph shows power and discharge curves versus wicket gate openng



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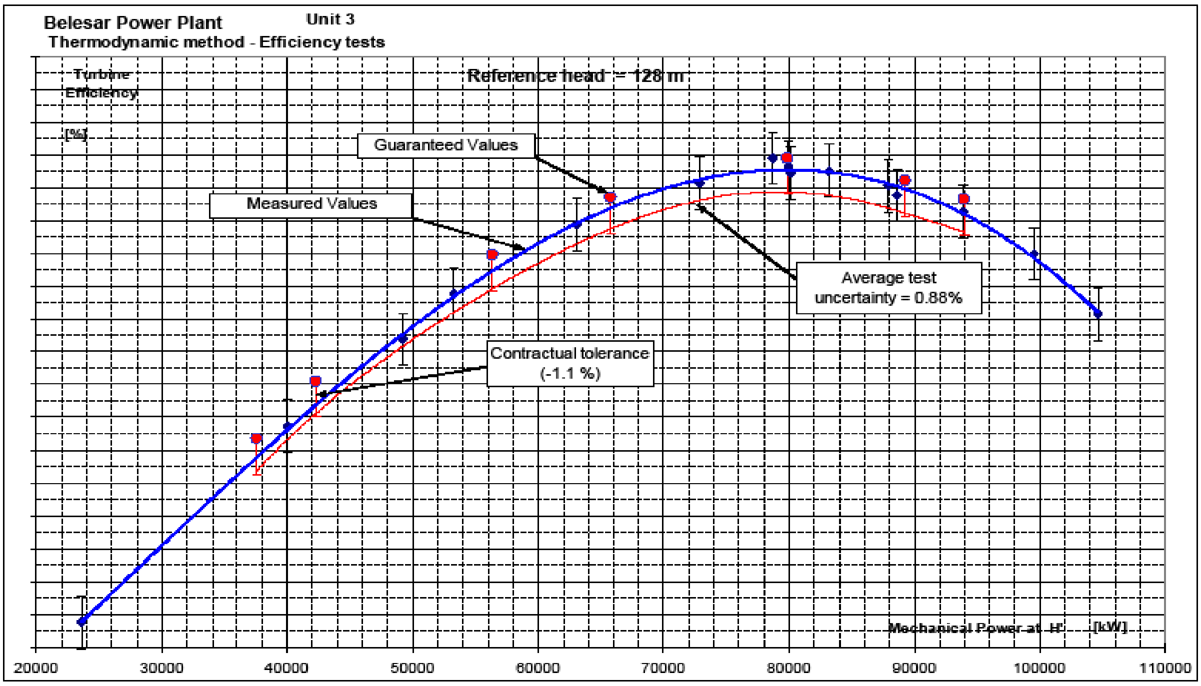
The graph shows efficiency curves versus power



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Thermodynamic testing – error analysis

The measurement errors can be divided in two different categories, systematic (or bias) errors and random errors.

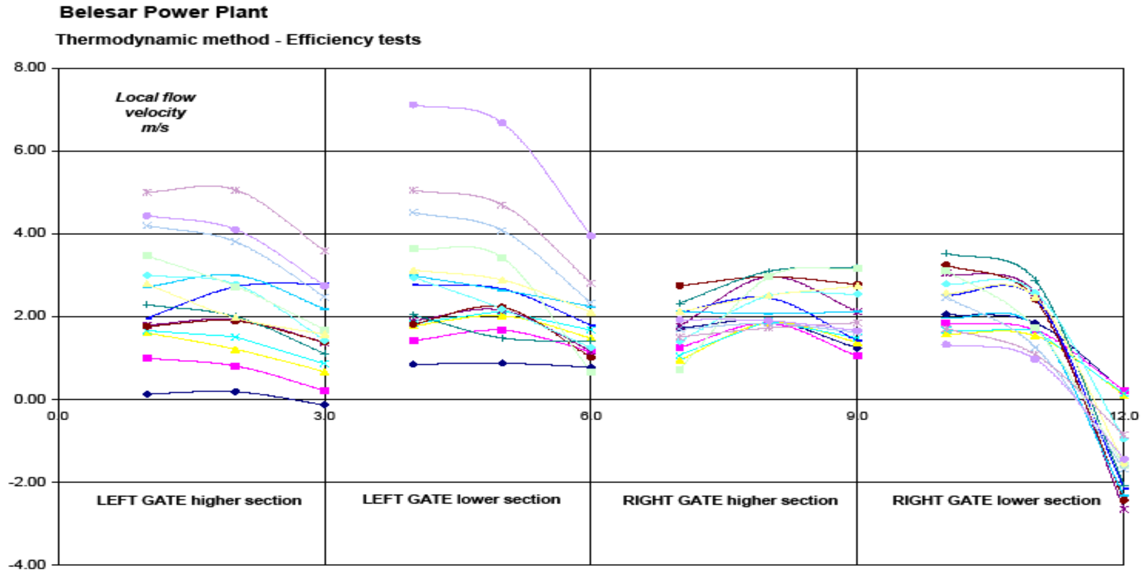
Systematic errors are due to calibration errors (including hysteresis and not linearity of sensors and reference devices), to installation errors (in elevations, sections, and calculation parameters like water mass density) and to specific hydraulic conditions affecting in a constant way the measurements (e.g. the error due to a not-proper location of a temperature sensor measuring values constantly lower or higher than the actual temperature of the fluid).

Random errors can generally be reduced by increasing the number or the frequency in the acquisitions and are normally due to oscillations of the measurements (as consequence of the dynamic part of the signals), to specific hydraulic conditions effecting in variable way the measurements (e.g. presence of vortexes or pulsating phenomena), instabilities in the electric network inducing load variations of the turbine.

The analytical calculations of errors is the same both for systematic and random errors, but the starting point is different being calibrations, installations, etc. in case of systematic and standard deviations of measurements, etc. in case of random errors. When a clear trend in the measurements is observed a proper correction can be made to reduce the errors (e.g. the temperature drift at the turbine entrance is normally corrected in thermodynamic measurements)

Analysis of outlet flow and temperatures

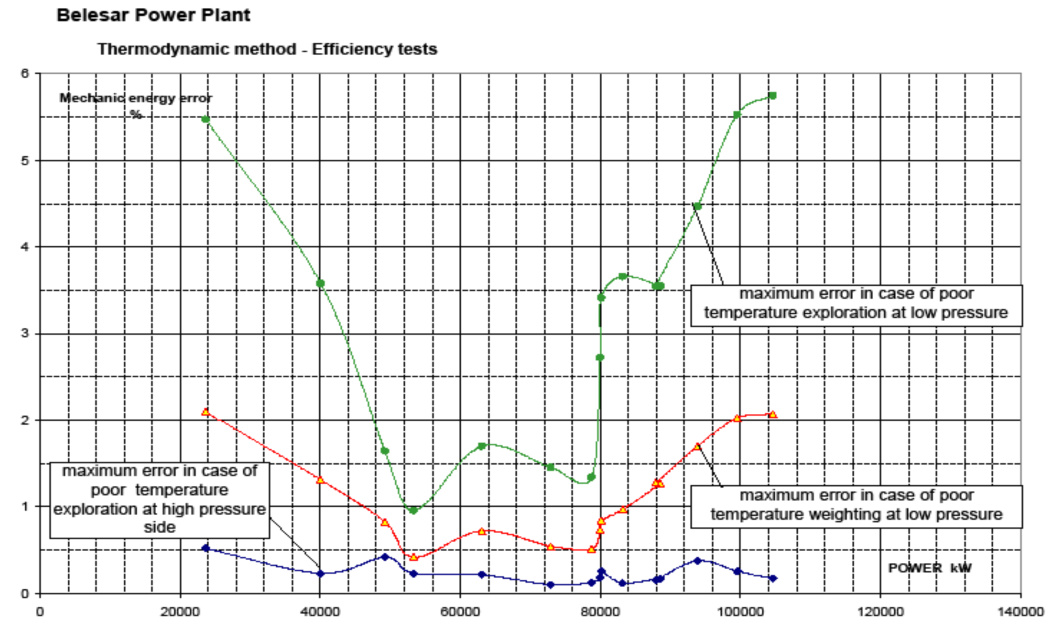
The measure of flow-meter provides extremely interesting data on the trends of speed exhaust. The graph shows the measures speed absolute (positive and negative) in the various points of measurement and for different load conditions.



It is noted that the lower right area is affected by phenomena of recirculation marked with negative speed up to 2 m/s recirculation is present since the lower loads, is less affordable for maximum efficiency and return to show very clearly at high flow rates .
The area upper right has a much more regular and consistent with the evolution of loads. With speed always positive and between 1.5 and 3 m/s

The section right below presents a highly variable pattern with cargo arriving to over 7 m/s in conditions of overload. The upper section instead to partial loads is little affected by the flow reaches trends comparable with the lower section in conditions of maximum efficiency and drastically reduces the scope overloaded. The condition of overload with significant asymmetries led to dynamic load the structure measuring who reported damage.

The measure of the flow allowed a proper weighting of the results, as far as the major sources of error are linked to temperature measurements in the low pressure side. 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.
It is noted that a poor investigation of the outlet temperature could lead up to 6% error in the energy (thus efficiency) evaluation. Only in the range between 50 and 80 MW the maximum errors keep staying below 2%. But even with a complete mapping of temperature, if not properly weighted, the error exceeds 2% both at partial load and in overload operation.
Between 40 and 90 MW the maximum error in this case do not exceed 1.5%
In these circumstances it is evident 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.



The graph also shows the high pressure side error.
In this case all points of maximum error due to poor analysis of the energy distribution lay below 0.40%. Again, there is a trend that minimizes the error in the best efficiency conditions. The measurement uncertainty caused by asymmetries in the side high pressure is then probably close to ±0.25% provided by the codes.

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

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

Assuming, in a precautionary way, that all the error found during the check of the calibration made at site 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 $f_{Cp} = \pm 0.5\%$. consequently $e_{fC} = C_p \cdot f_{fC}$

The number of probes used to calculate the mean water temperature both the upstream and downstream sections allow to consider $\boldsymbol{e_{E10} = 0}$ and $\boldsymbol{e_{E20} = 0}$

Other terms

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

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

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

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

Error on hydraulic energy

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

Pressure term

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 $e_{f\mu} = \mu \cdot f_\mu$

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

Kinetic and potential terms

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 ± 0.70% and the power error is ± 0.50%. The discharge measurement error is can be evaluated as ± 0.85%.

Admitting an error in the measurement section of ± 0.25%, the uncertainty connected to the determination of the average speed is ± 0.90%

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

The error of the potential term is

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

Generally all other error sources in the measurement error of the hydraulic energy are negligible.

Error on 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 ± 0.20%.

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

Error in 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:

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

The error is then limited within the measurement tolerances prescribed by the codes and anyway not very different from the expected values.

$$f_H = f_{E_h}$$

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:

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

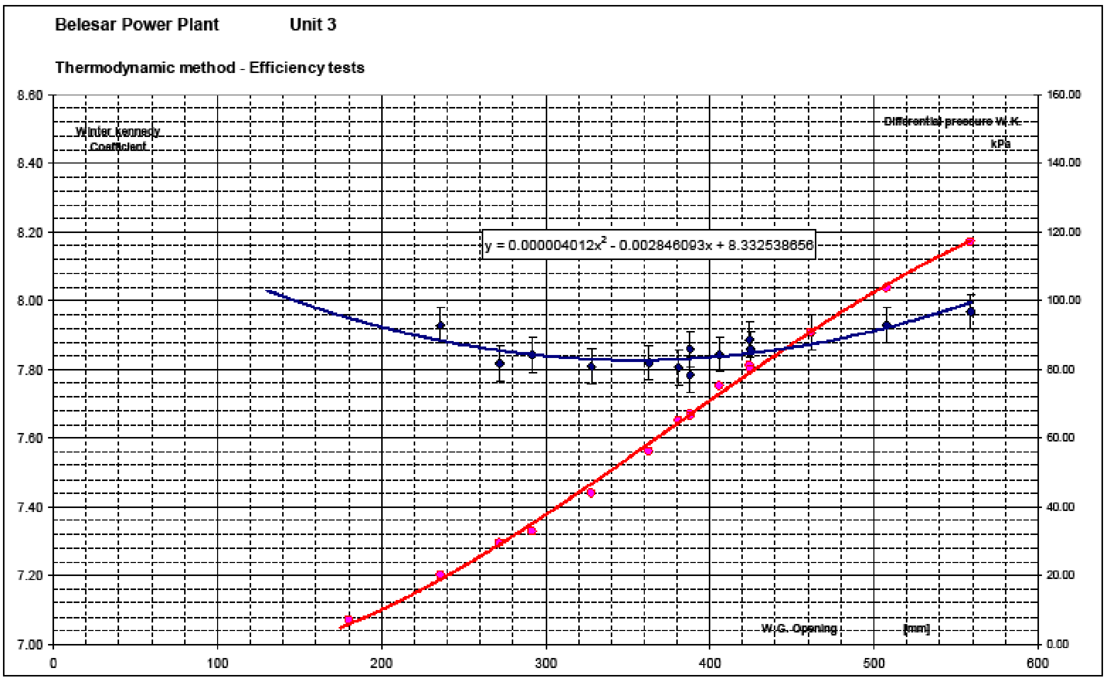
During these tests the systematic error in efficiency varies between ±0,300 % y ±0,398 %, while the random error varies between ±0,479 % y ±0,796 %.. The total error is always lower than the contractual value with a maximum of **±0.891 %**

If the investigation of the upstream and downstream energy was not evaluated properly the so that the values of f_{E10} = **±0.25** and f_{E20} = **±0.60** had to be included the computation the overall uncertainty could have reached an error value of **±1.254%**

As a result of such uncertainty values, there is no need to extend the contractual limit (as well as expected in the reference code once established that the tests were made with the utmost care and quality equipment suited to the needs of the test).

Index testing – installation and procedure

The WK tap calibration made during thermodynamic tests are represented in the graph



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The test procedure with method index is defined in the international standards IEC 60041. The procedure Index will be used in this case to define the absolute value of efficiency because the ratio WK has been calibrated with an absolute measure as the thermodynamic method.
In agreement with the mentioned code for calculating the flow uses the formula

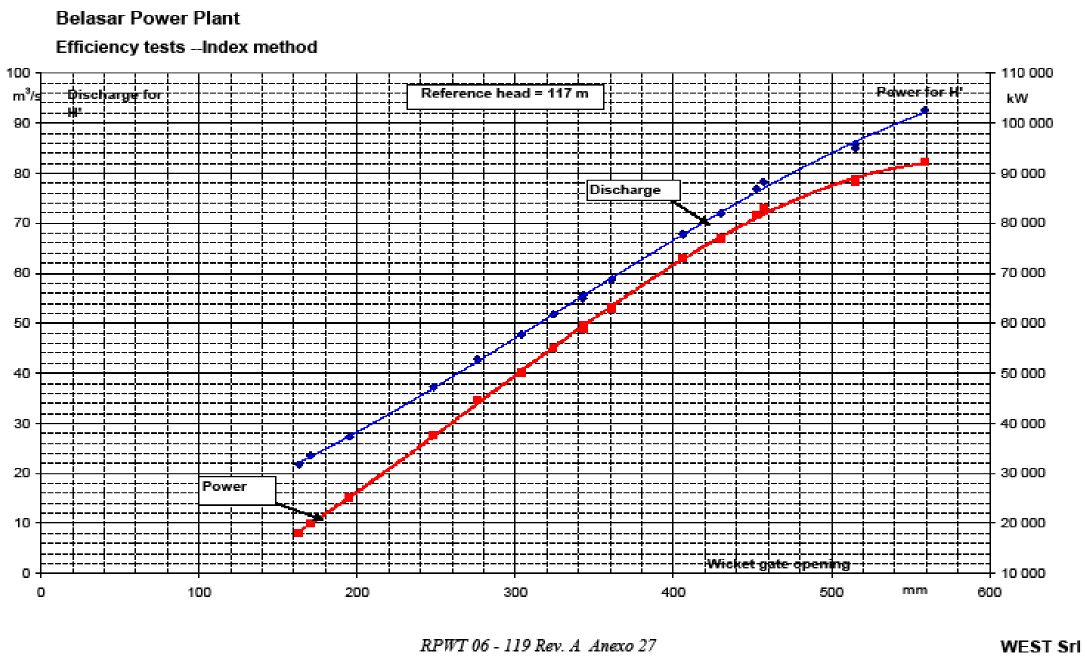
$$Q = K_{WK} \cdot \Delta p_{WK}^{e_{WK}}$$

where Δp_{WK} is the measure of differential pressure transducer WK
The exponent of the pressure differential has been set at 0,513 following the code that allow a change between 0.48 and 0.52 for improving the adjustment of the curve. A fixed value of the constant Kwk = 7.84299 could be used but a scattering of respect of 1% to this value has been detected, a second order equation of the coefficient variations versus opening allows to reduce the discrepancies within 0.5% : the equation being

y = 0.00000401 x2 - 0.00286 x + 8.332

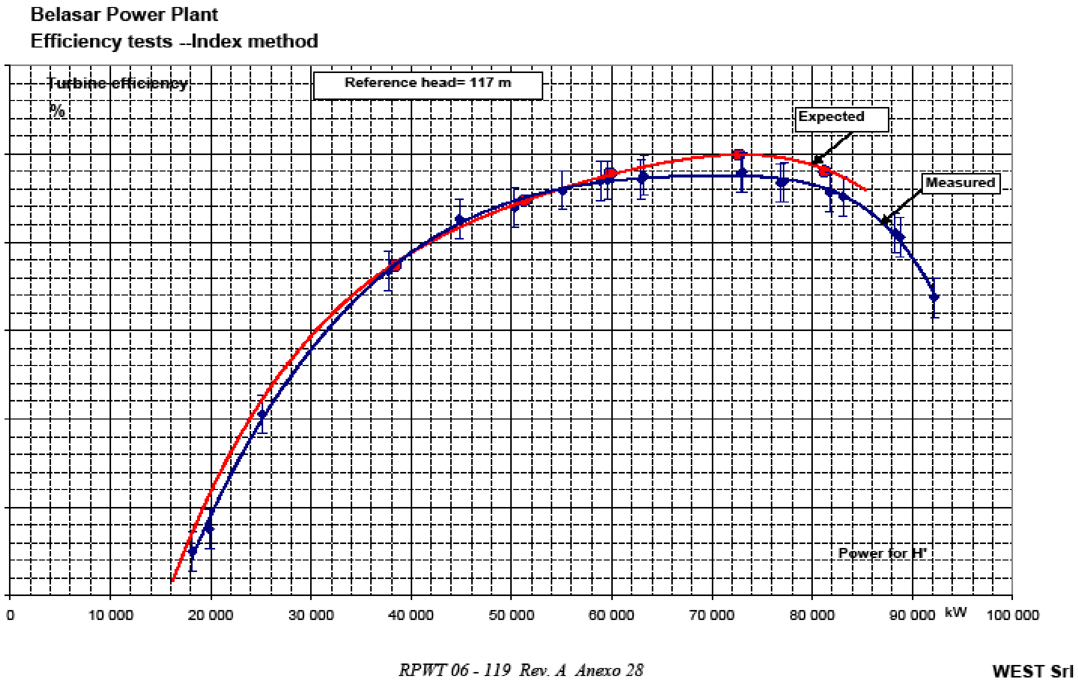
Index testing - results

The graph shows power and discharge curves versus wicket gate openng



In total twenty measures have been conducted in fourteen different load conditions to explore the area between 22% and 108% of rated capacity.
For each load in the area of operation have been guaranteed two consecutive data acquisitions without changing operating conditions. For every test point 250 acquisitions were made achieving an average value of each variable within about five minutes.

The graph shows efficiency curves versus power



Index testing – error analysis

Errors deriving from systematic source due to calibration errors of measuring instruments or misinterpretation of the physical phenomena . Errors deriving from a random source detectable by a statistical analysis of measurements.

Discharge error

The flow measurement method for the index was carried out by contrasting differentia transmitters compared on site with reference instruments. The conversion error of the voltmete used for acquisitions is related to 14 bit AD converter that, used in the range of 0-10 V, and give $f(^A/_D) = \pm 0.20$ %

The error introduced by the dynamic phenomena and asymmetry and consequent neglect i determining the real value of the pressure differential leads to $f(\Delta E) = \pm\ 0.50$ %.,according t statistical data and literature.

There were not detected vibratory phenomena, dynamic resonance effects which could affect th validity of the measures. Therefore it is jointly:

$$F(dp_{wk})=[f(T_{dp})^2+ f(^A/_D)^2+f(\Delta\ E)^2]^{0.5} = \pm 0.552\%$$

The error in measuring flow rate is consequence of an error of differential pressure on the Winter Kennedy taps and of the correct calibration of the constant Kwk of section A and the density The geometrical parameters of the section of pipe used for measurements have been determined from the outside, not clearing the pipe or check the status of the surface and shooting conditions.

You can assess the effect that error in the 0.25%.±determination of Section A is in the range of f (A) = ± 0.25 %.

The error of this constant Kwk linked to measurement error of Benchmark Jan. which this case are the thermodynamic tests, usualy by this type of test is assumed that the eror is

$f(K_{wk})=\pm 0.50\%$

Assuming a linear relationship:

$$f_s(Q_i) = \left[f(A)^2 + f(K_{wk})^2 + f(dp_{wk})^2 + f(\rho)^2 \right]^{0.5} = \pm 0.792\%$$

Error on net head

$$f_s(H) = \pm \left[\frac{E_{p1} f(Ep_1)^2 + E_{p2} f(Ep_2)^2 + E_{c1} f(Ec_1)^2 + E_{c2} f(Ec_2)^2}{E_h} \right]^{0.5}$$

where

$f(E_{p1}) \approx f(p_1)=[f(T_{p1})^2+ f(^A/_D)^2]^{0.5}$ $\quad$ $f(E_{p2}) \approx f(p_2)=[f(T_{p2})^2+ f(^A/_D)^2]^{0.5}$

$f(E_{c1})=(2*[f(Q)^2+ f(A_1)^2])^{0.5}$ $\quad$ $f(E_{c2})=(2*[f(Q)^2+ f(A_2)^2])^{0.5}$

Error on 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%.

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 ± 0.20%.

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

Error in efficiency calculation

Assuming despicable as the error in determining the acceleration due to gravity and considering that the error in determining the specific water mass, linked to the temperature measurement, is approximately 0.1%, the overall error in determining the related Performance is:

$$f_s(\eta) = [f_s(Q)^2 + f_s(H)^2 + f_s(P)^2 + f_s(\rho)^2]^{0.5} = \pm\ 1.07\ \%$$

The error is contained within the measurement tolerance prescribed in the contract and therefore is not worth significantly different from the expected values.

Random error evaluation

To assess the random error, Standard deviations of each magnitude measured in the course of each test regarding the average value of 20 acquisitions were calculated. A comprehensive analysis of the results shows that the overall error in determining the related performance is

$$f_r(\eta) = [f_r(Q)^2 + f_r(H)^2 + f_r(P)^2 + f_r(\rho)^2]^{0.5} = \pm 0.378\%.$$

Overall test uncertainty

The overall incetritud far reaches of the raides the amount of Quadrat systematic and random errors:

$f(\eta) = [f_r(\eta)^2 + f_s(\eta)^2]^{0.5} = \pm 1.134\%.$

As a result of such uncertainty values, there is no need to extend the contractual limit (as well as expected in the reference code once established that the tests were made with the utmost care and quality equipment suited to the needs of the test).

It must be noticed that if the thermodynamic tests had uncertainty of **±1.254%** these index tests could not achieve an overall uncertainty lower than **±1.5%**

The measurement uncertainty caused by asymmetries in the side high pressure is then probably close to ±0.25% provided by the codes.

Conclusions

The overall efficiency uncertainty has been kept in the range of 1% as in the target of the measurement campaign. To achieve this result the application of the code was definitely not enough and complete mapping of the mechanical energy both in high and low pressure side was necessary

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