Efficiency measurements on Pelton turbines with thermodynamic and acoustic methods; troubleshooting and comparison with model test results

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1. Summary

The measurement techniques have remarkably evolved during recent years: for example the introduction of automatic data acquisition has allowed to increase considerably the number of measurement points without slowing down the execution of tests. This process permits also to reduce greatly the measurement errors and, therefore, allows to check with more accuracy the performance of industrial machines. In this way, research and investigation activities concerning the determination of parameters to adopt for model-prototype step up, may be easier developed.

This paper illustrates the results obtained on five Pelton turbines using in parallel the thermodynamic and acoustic methods, they have been compared and analysed taking as reference the values obtained from model tests.

The results of these investigations have pointed out efficiency differences that remain within ± 1.5%, and in some cases even smaller than ± 0.7%.

The comparative analysis of the results has allowed to identify the causes of some discrepancies connected to the measurement techniques relating to installation, number of measurement points and fluctuation in time and space of energetic profiles.

The conclusion is that the measurement methods described in this paper require a great baggage of experiences and of critical ability to obtain certain and usable results.

2. Measuring techniques

2.1. Thermodynamic Method

The thermodynamic method is derived from the application of the principle of energy preservation to the transfer of energy between the machine and the water passing through it and, in case of real operation, there is the possibility to assess the energy that the water transmits to the turbine axis. This energy corresponds to the difference between the energy owned by the fluid in the machine upstream section (1) and that owned by the fluid in the downstream section (2). It can be calculated by measuring, in these two sections, pressure, temperature, velocity and elevation. From the thermodynamic properties of water the following equation can be established:

$$Em = em1 - em2 = a\,(p1 - p2) + cp\,(\theta 1 - \theta 2) + (v1^2 - v2^2)/2 + g\,(z1 - z2)$$

where Em is called specific mechanical energy per unit mass. Generally, in practical cases, Em is determined by measuring the temperature inside two vessels connected to the upstream (11) and downstream (21) sections, where the kinetic heating of the probes can be neglected.
In case of ideal operation, that does not cause any friction loss between flow and machine, it is possible to calculate the specific energy that would have been transferred to the runner. The isoentropic transformation is considered the most representative one of the operation without losses of a hydraulic machine. This energy is called specific hydraulic energy per unit mass:

$$Eh = eh1 - eh2$$

and can be calculated from the measurements of pressure, velocity and elevation in both sections and from the upstream value of temperature that allows the determination of the properties of the fluid.
The machine hydraulic efficiency can be obtained through the thermodynamic method from the ratio between the specific mechanical energy transferred by the fluid to the runner, Em, and the specific hydraulic energy, Eh, available on the basis of an isoentropic transformation:

$$\eta = Em/Eh$$

Therefore, the efficiency and the net head H = Em/g can be directly calculated from the specific energy measurements including the kinetic terms determined through an iterative process. The additional measurement of generated power and relevant losses allows the calculation of mechanical power Pm and of the discharge

$$Q = Pm / \rho g H$$

Describing in detail the use of the measuring vessels in the upstream and downstream sections three possible operating procedures may be identified:
1 The Direct operating procedure: obtained when the valve between penstock and measuring vessel is fully open and no action is made to obtain particular temperature and pressure values.
2 The Partial expansion procedure: obtained when the valve is regulated in order to have the same temperature values in the two measuring sections. Thus the temperature term becomes zero in the Em equation.
3 The Full expansion procedure: obtained when both measuring vessels are positioned at the same pressure value. Thus the pressure term in the Em equation is annulled and the temperature term becomes more significant.

Thanks to its reduced intrusivity and easy application, the use of thermodynamic method has grown in recent years. The possibility of application also increased as an effect of higher quality thermometers, new generation instrumentation and more accurate calibrations, so that the minimum value of 100 m head can no more be considered as an actual bottom limit for the thermodynamic method. Recent experiences with model tests show that good results could be obtained also with heads of about 50 m, provided that all possible causes of error are deeply investigated [1].

Moreover, the computerized data acquisition with on line processing and calculation allows to fulfil the specification of the new Code IEC 41 3rd Ed. 1991-11 in terms of numbers of synchronous measuring points, with possibility of utilizing multiple temperatures probes, all simultaneously acquired.
As a consequence, the average uncertainty of the method, that can be by now considered as the most reliable, due to the direct measurement of the efficiency, has decreased and the systematic error of efficiency measurements on a 400 m head turbine can be assumed in the range of ± 0.65 %.
The thermodynamic method is thus becoming the most effective way to check the reliability of scale effect formulas from model test to prototype and to have reference results, to be compared with new innovative measuring techniques.

2.2 Acoustic Method

The acoustic method of discharge measurement, not yet recognised as a primary method in the Code IEC 41 1991-11, is based on the principle that the velocity propagation of an acoustic wave and the flow velocity can be vectorially combined. The absolute velocity of an acoustic pulse when it travels in the same direction as the flow is higher than the absolute velocity when the pulse travels the opposite direction. By measuring the transit times of acoustic pulses sent along a chordal path in the two directions, the average axial velocity of the fluid crossing the path can be determined.
In a circular cross section, if the velocity distribution is fully axial-symmetric, the average velocity measured along a single path, located in an axial plane can be assumed proportional to the mean flow velocity. In practice, to take into account the actual velocity distribution, it is necessary to install several pairs of transducers at opposite ends of paths located on the measurement planes symmetrically arranged with respect to to the longitudinal axis of the penstock. When two opposite measuring planes are used, the velocities are properly averaged and the error due to the measurement of transit time, caused by the presence of transverse flow components, can be assumed statistically as negligible. In this case, if there are no transverse flow components in the conduit and if all internal times are taken into account, the transit time of an acoustic pulse is given by the formula:

$$t = L / (c \pm \bar{v}_a \cos \beta)$$

Since the transducers are generally used both as transmitters and receivers, the difference in travel time may be determined by the same pair of transducers. Thus, the mean axial velocity crossing the path is:

$$\bar{v}_a = (1/t_d - 1/t_u)\, L / (2 \cos \beta)$$

where L is the distance between the transducer faces, c is the sonic speed in the fluid at the operating conditions, and t_d and t_u are the transit times in downstream and upstream directions.
If certain mathematical conditions, such as continuity and differentiability, are met by the velocity distribution, the discharge Q can be calculated. In case of a truly circular

section, with paths located exactly at the specified distance from the centre, the discharge assumes the simple formula:

$$Q = (D^2/2)\ \Sigma_i W'_i\ \bar{v}_{ai}$$

where the W'i are the weighing or correction coefficients that depend on the assumed integration method. Gauss Legendre and Gauss Jacobi methods are considered in the above mentioned IEC code.

Nowadays, despite the installation of probes for accurate flow measurements needs time and experienced personnel, the possibility of a continuos monitoring of the flow as well as the possibility of using such a method in differential mode for the leak detection in the penstock are giving a big impulse to the application of the acoustic method.

A certain number of experiences, showing comparative results of acoustic method with different primary methods, has been already presented by other authros: this contribution tries to present new successful results, showing in the meantime any possible doubtful applications for which the most frequent causes of error are identified.

2.3 Model tests and efficienty step up to prototype

The results obtained by measurements performed on models using high accuracy test stands in hydraulic laboratories with an estimated systematic uncertainty of ± 0.25 % or better, are extremely reliable. The direct torque measurement on hydrostatic bearing devices, the volumetric calibration of discharge, the possibility of repeating the tests and the controlled environmental conditions allow a result quality that cannot be achieved in prototype measurements.

Nevertheless, unfortunately, the efficiency step-up for Pelton turbines is still considerably complex. As defined by Grein experiences [2], a scale effect formula, based on Reynolds, Froude and Weber number ratios, must be considered like:

$$\eta_{Pr} - \eta_{Mo} = \Delta\eta = \Delta\eta_{Re} + \Delta\eta_{Fr} + \Delta\eta_{We}$$

where

- $\Delta\eta_{Re}$ is the effect on efficiency step-up of the Reynolds number that characterizes the relationship between forces of inertia and viscosity and can be expressed as a function of $C_{Re} = Re_p/Re_m$, ratio between the Reynolds numbers of prototype and model, and ϕ (specific discharge coefficient):

$$\Delta\eta_{Re} = f\,(C_{Re}, \phi)$$

- $\Delta\eta_{Fr}$ is the effect on efficiency of the Froude number that characterizes the relationship between forces of inertia and gravity. If $C_{Fr} = Fr_p/Fr_m$ is the ratio between the Froude numbers of prototype and model, said effect can be expressed as:

$$\Delta\eta_{Fr} = f\,(C_{Fr}, \phi)$$

- $\Delta\eta_{We}$ is the effect on efficiency of the Weber number that characterizes the relationship between forces of inertia and surface tensions. If $C_{Wer} = We_p/We_m$ is the ratio between the Weber numbers of prototype and model, said effect can be expressed as:

$$\Delta\eta_{We} = f\,(C_{We}\,,\phi)$$

where the values of the functions, that depends on the hydraulic profiles of buckets and of other turbine main components, probably need to be properly defined case by case.

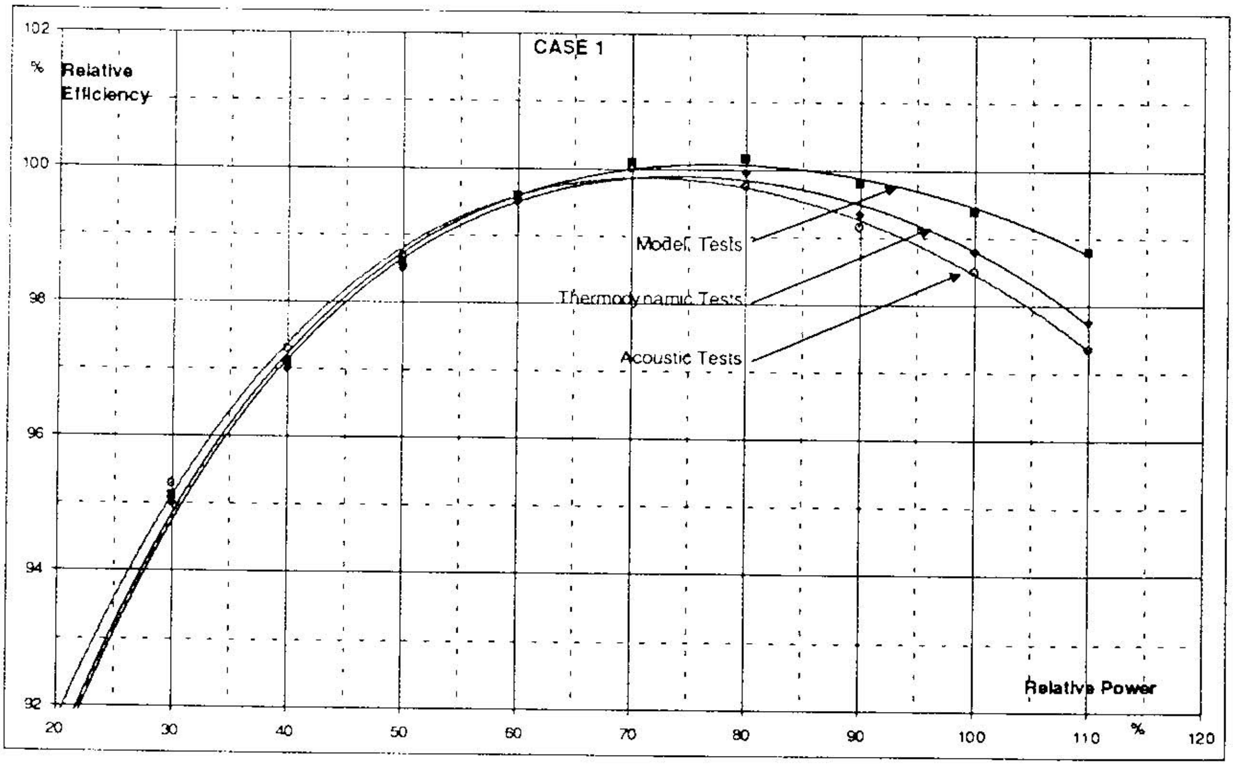
3. Test description and analysis of results

As a sample of different tests and problems related to the application of the above mentioned methods, the results of efficiency measurements performed on five different powerplants are shown here below. The measurements, both with thermodynamic and acoustic methods, are compared each other and with the results of the corresponding fully homologous model tests.

3.1. Case 1 The tested unit is an horizontal shaft Pelton turbine with two runners hanging to each side of the generator shaft, with the following characteristic data:

$H = 680$ m $Q = 6.3\ m^3/s$ $P = 75$ Mw $D = 3400$ mm Bucket type R

The machine has a 1.10 m diameter penstock with spherical valve and one internal servomotor nozzle for each runner.



- The thermodynamic measurements were performed by means of two measuring vessels on the upstream section and eight measuring points at the outlet for each runner. The individual runner efficiencies were detected by splitting the generated power as a function of the hydraulic power available. All instruments were calibrated before the tests (thermometers were checked using the E.d.F. technique). All calibrations were verified on site before and after tests by means of primary instruments and the thermometers' behaviour was controlled using the system with dual expansion vessels. The cooling water system was deviated and a weir was installed downstream the low pressure measuring section in order to prevent back-flow.

- An eight path acoustic measuring system has been installed in the upstream penstock (1.6 m diameter) above the junction of the two runners piping where a straight portion with 18 diameters is available (12 above and 6 below the measuring section). Experienced people performed the installation of the sensors and the chief of tests directly supervised the activity. The location of the sensors followed the Gauss Legendre scheme. The sensor protrusion errors and the penstock deformation under pressure have been taken into account. The flow results show a well-developed velocity profile with a reduced number of rejected outlayers.

The estimated systematic uncertainty of the thermodynamic method is ± 0.64% while the uncertainty of the acoustic method is expected to be lower than ±1.00%.

The result shows a good agreement between thermodynamic and acoustic measurement with discrepancies lower than 0.30 % .

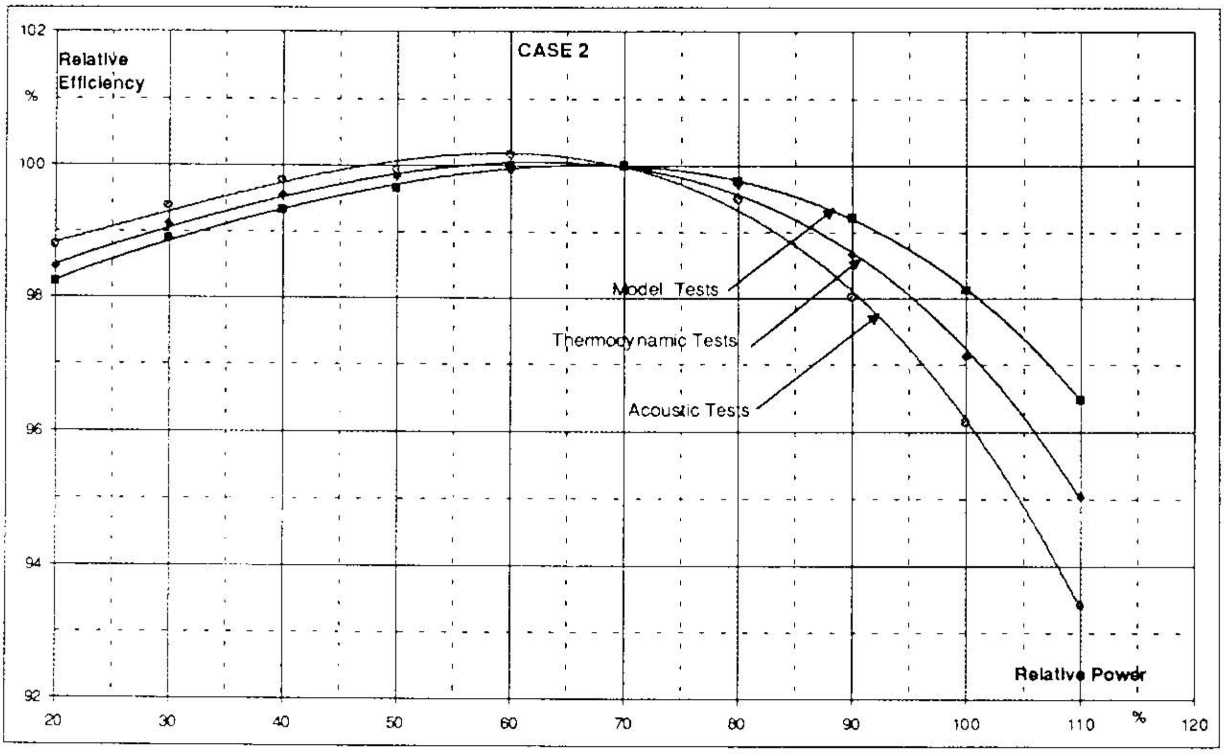
Model test results, obtained on a fully homologous model, except for the bucket width that was a little bit bigger on model, with an efficiency uncertainty of abt. ± 0.20 % were available. As shown by the comparison of efficiency curves, the difference between model and prototype is of about 0.15% except for the full load where the difference is bigger (about 0.89%). Such a difference (lower than the composite uncertainties of the methods in object) could be easily explained by the mentioned difference in the bucket width.

3.2. Case 2 Tests were carried out on a vertical shaft Pelton turbine with six nozzles and with the following main characteristics:

H = 380 m Q = 24 m^3/s P = 80 Mw D = 3600 mm Bucket type P

- The thermodynamic tests were performed using two measuring vessels in the upstream section and eight temperature sensors in the downstream section fixed over vertical frames in the discharge channel, approximately 15 m downstream the unit's axis. Two separate measurements of the upstream pressure and two measurements of the downstream level were made. It was not possible to install a device to prevent a backflow from the afterbay. Tests were carried out during night-time in order to reduce the penstock heating and to reduce the temperature gradient between air and water (air was warmer than water).
- The ultrasonic flowmeter was installed in the penstock, 4 diameters upstream the spherical valve and 8 diameters downstream a bifurcation. The system utilizes eight sensors in a four beams single plane installation. The measuring section was chosen for monitoring purposes without the supervision of the chief of tests. No signed installation form was available to check the proper layout of the system and some evicende made suppose that the Gauss Legendre disposition had been chosen.

The results show a good agreement of the two methods from 40 to 80 % of the operating range, with differences within ±0.50 % of the measured efficiency. From 80 % to the full load an increase of the discrepancy of the two methods is evident: the acoustic method shows a lower efficiency up to 1.50%.



A comparison with model tests, performed on a vertical shaft test rig with an overall systematic error of about ± 0.20 %, scaled up using the Grein formula, shows a good agreement with the prototype tests till 80%, while at full load the model efficiency is higher than the values determined by means of thermodynamic tests. The efficiency of the model shows a 1.50 % decrease passing from 8/10 to full power.

The tests at site were repeated several times and all possible hydraulic differences between model and prototype have been identified and corrected: the outlet angle of buckets was grinded in order to perfectly fit the model design; the effect was a slight increase of the efficiency at full load.

Tail water level was varied to check its influence on efficiency and the actual level below the runner was also measured using a pressure transducer. The influence of lavel variation was within 0.40% on efficiency and power (any interference between water level and runner was carefully avoided).

The thermodynamic measurements have been supported by on site checks of the calibrations of all sensors and with particular care of all temperature probes. The test personnel also verified the measuring bridge and its zero differential set point. The amount of heat exchange with the environment was also analysed and partial expansion tests were performed.

The carefull evaluation of all available data brings to think that the differences found could be caused by the presence of a backflow from the afterbay even if the difference of mechanical energy observed, taking into account every single measuring point in the downstream section compared to the average value, is in the range of ± 0.25%. As a matter of fact, it is well known that the hot fluid pattern can be a subdolous cause of error because its faults cannot probably be detected by the probes.

Foam formation was also detected in some conditions but it was not possible to correlate it to any appreciable variation on efficiency.

In this case, the systematic uncertainty of the thermodynamic method was evaluated in ±0.75%.

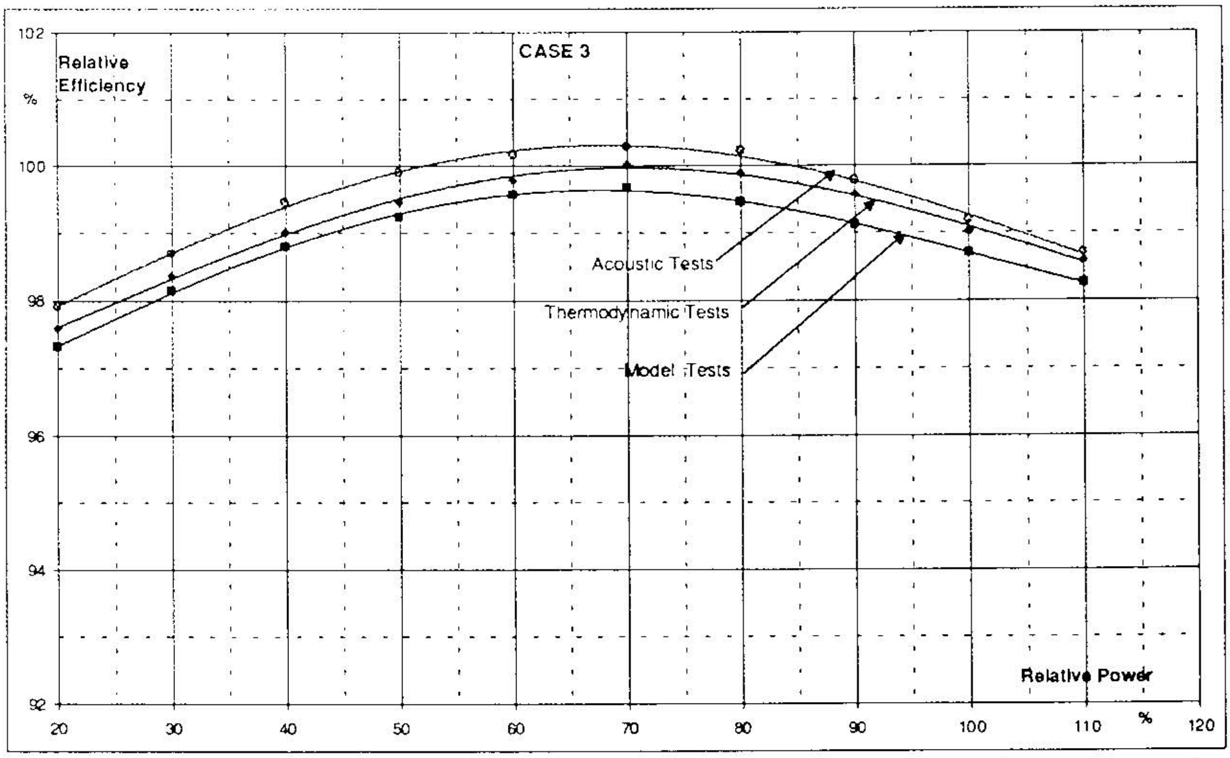
The acoustic method has shown a high number of outlayers increasing with the flow rate. A possible interpretation of this anomaly could be that the perturbation caused by the bifurcation determines unsteady flow conditions that affect the measuring accuracy as the flow rate increases.

While the above described considerations can explain quite well the differences found between thermodynamic and acoustic methods, it is not possible to explain easily the differences found with respect to the model but assuming that, in this case, the efficiency step-up of the model, made with the Grein formula, does not correspond to the reality and that other more realistic coefficients should be used.

3.3 Case 3 The tested unit is a horizontal shaft Pelton turbine with two runners hanging to each side of the generator shaft, with the following characteristic data:

H = 575 m $Q = 12\ m^3/s$ P = 60 Mw   D = 3190 mm   Blade Type R

The machine has a 1.2 m diameter penstock with spherical valve and two internal servomotor nozzle for each runner.



- The thermodynamic measurements were performed by means of two measuring points on the two nozzles bifurcation upstream section and six temperature probes, with four measuring points each, at the discharge channel of each runner. The individual runner efficiencies were detected by splitting conventionally the generated power as a function of the available hydraulic power. All instruments were calibrated before performing the tests (thermometers were checked using the E.d.F. technique). All calibrations were verified on site after the tests by means of primary instruments and thermometers' behaviour was controlled using the dual expansion vessels system. The cooling water was deviated and the discharge channel floor was steep enough to be sure that no back-flow could occur.

- An eight path acoustic measuring system had been installed in the upstream penstock (1.8 m diameter) above the junction of the two runners piping where a straight portion with 21 diameters was available (13 above and 8 below the measuring section). Experienced people performed the installation of the sensors. A check of the geometrical values was also performed before the tests. The location of the sensor followed the Gauss Legendre scheme and the protrusion errors together with the penstock deformation under pressure were duly evaluated. The results showed a well-developed velocity profile with a reduced number of rejected outlayers even if the dispersion of the valid data was quite high.

The estimated systematic uncertainty of the thermodynamic method is ± 0.72% while the uncertainty of the acoustic method is expected to be lower than ± 1.00%.

The result shows a good agreement between thermodynamic and acoustic measurement with discrepancies lower than ± 0.25 % .

The horizontal axis model, tested in laboratory with an accuracy of about ± 0.2%, was completely homologous.The difference with the thermodynamic tests is within 0.50% (lower than the composite uncertainties of the considered methods) and seems approximately constant.

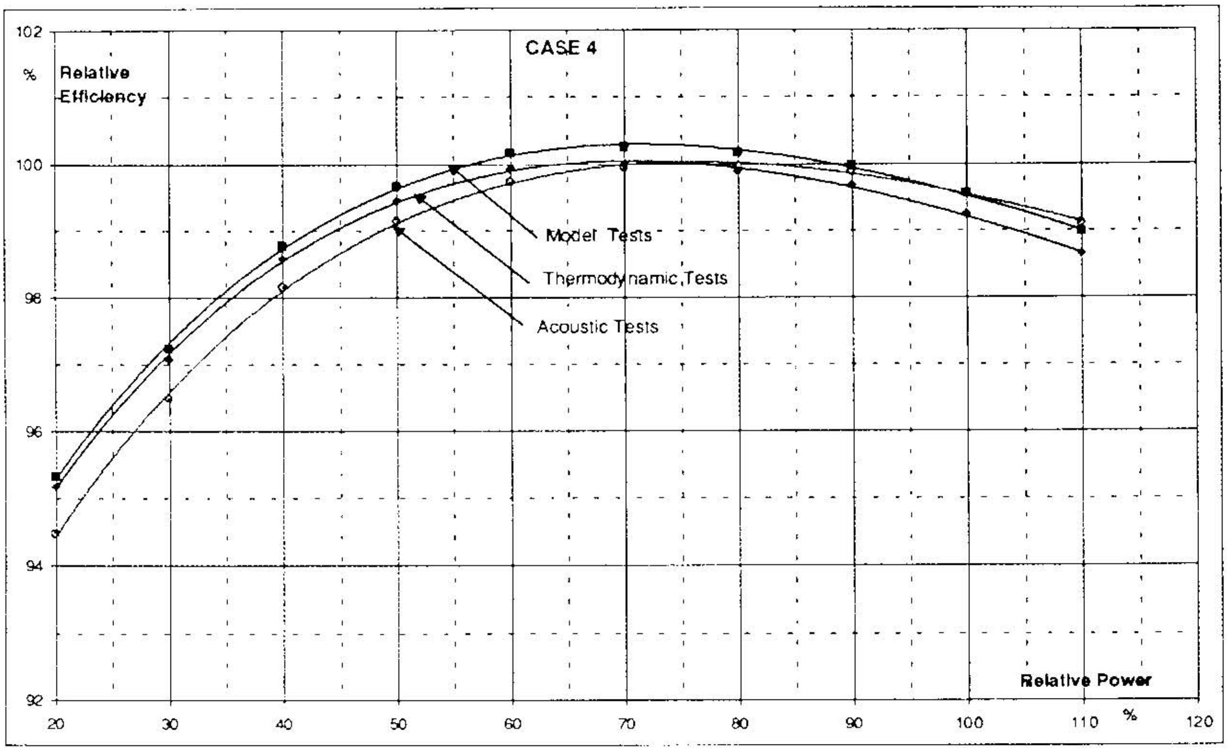
3.4. Case 4 Tests were carried out on a vertical shaft Pelton turbine with four nozzles and with the following main characteristics

H = 752 m Q = 11 m^3/s P = 70 Mw D = 2160 mm Blade Type R

- The thermodynamic tests were performed using two measuring vessels in the upstream section and eight temperature sensors in the downstream section fixed over vertical frames in the discharge channel, approximately 12 m downstream the unit's axis. Two separate measurements of the upstream pressure and two measurements of the downstream level were made. Since it was not possible to install a device to prevent a back-flow, all other units were kept standstill; in this case the downstream channel floor was steep enough to be sure that no back-flow could occur. The cooling water system was deviated. Tests were carried out during night-time in order to reduce the penstock heating and to reduce the temperature gradient between air and water (air was warmer than water).
- The ultrasonic flowmeter was installed in the penstock, four diameters upstream the spherical valve and 12 diameters downstream a bifurcation. The system utilizes sixteen sensors in a four beams, dual plane installation. The measuring section was already chosen for monitoring purposes and, since no signed installation form was available, it was decided to remove the sensors and make an appropriate check of the geometry of the installation. The sensor conditions were good. The results demonstrate that the Gauss Legendre disposition had been chosen.

The results show a good agreement of the two methods, with acceptable differences within ±0.75 % of the measured efficiency. The acoustic method shows a lower efficiency at partial load while it is slightly higher at full load.

A comparison with the model tests, stepped-up using the Grein formula, performed on a vertical shaft test rig with a fully homologous model with an overall systematic error of about ± 0.20 %, shows that in the whole operating range the model efficiency is slightly higher than the values determined by means of thermodynamic tests with discrepancies lower than ± 0.20%.



The tests at site have been also repeated on two different units.
The thermodynamic measurements have been supported by on site checks of the calibrations of all sensors with particular care of all the temperature probes. The test personnel also verified the measuring bridge and its zero differential set point. The amount of heat exchange with the environment was also analysed and partial expansion tests were performed.
The systematic uncertainty of the thermodynamic method was evaluated in ± 0.68%.
The acoustic method has shown a neglecting number of outlayers. The dispersion of readings was not very high (within ± 4%).

3.5 Case 5 The tested unit is a horizontal shaft Pelton turbine with two runners hanging to each side of the generator shaft, with the following characteristic data:

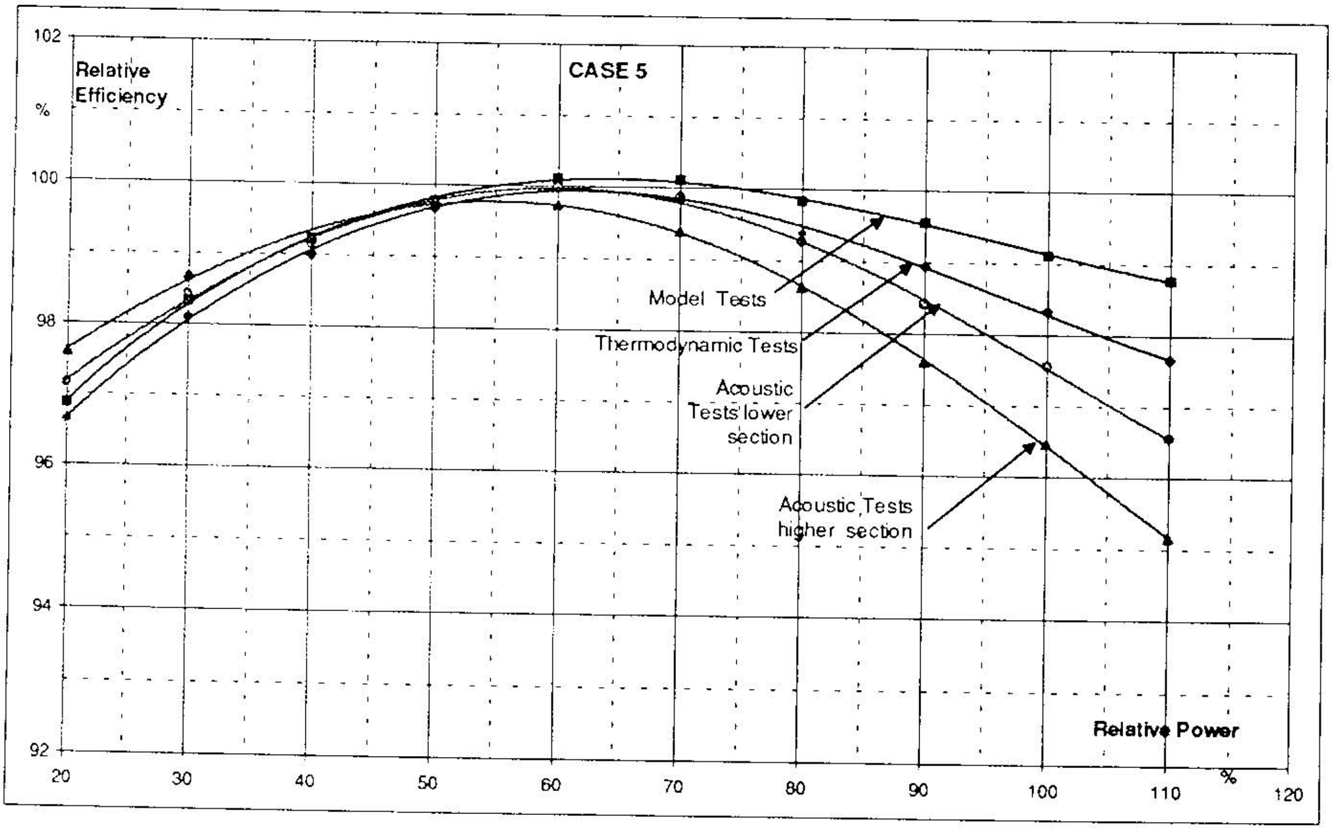
H = 272 m Q = 7 m^3/s P = 17 Mw D = 2140 mm Blade Type P

The machine has a 0.8 m diameter penstock with spherical valve and two external servomotor nozzles for each runner.

- The thermodynamic measurements were performed by means of one measuring point on the upstream section before the bifurcation of the two nozzles and four temperature probes, with four measuring points each, in the discharge channel of each runner. The individual runner efficiencies were detected by splitting conventionally the generated power as a function of the available hydraulic power.

All instruments were calibrated before performing the tests (thermometers were checked using the E.d.F. technique). All calibrations were verified on site after testing by means of primary instruments and the thermometers behaviour was controlled using the dual expansion vessels system. The cooling water was closed during the tests. The downstream channel floor was steep enough to be sure that no back-flow could occur.

- A four path acoustic measuring system had been installed in the upstream penstock (1.2 m diameter) where a straight portion with 15 diameters was available (10 above and 5 below the measuring section). A similar installation, called "higher section", was available directly below the upper reservoir. Experienced people performed the installation of the sensors. The measuring section was chosen for monitoring purposes and with no signed installation form available to check the proper layout of the system. A rough check of the geometrical values was performed before the tests. The location of the sensors followed the Gauss Legendre scheme.



The estimated systematic uncertainty of the thermodynamic method is ± 0.78%, while the uncertainty of the acoustic method is expected to be about ±1.00%. Considering these uncertainties, the comparison of the results between thermodynamic and acoustic measurements shows discrepancies lower than 1.15%. The "higher section" shows a bigger difference, increasing with the load, reaching 2.5% at full load. The acoustic method, beyond some geometrical doubts, has shown presence of outlayers whose number increases with the flow rate. A possible explanation of the differences could be a perturbation, caused by bends or variations of section upstream the measuring section, that determines unsteady flow conditions affecting the results when the flow rate increases.

Completely homologous model tests were performed on a horizontal shaft test rig in laboratory with an uncertainty of about ± 0.20%. The difference with thermodynamic tests is within 0.65% (lower than the composite uncertainties of the methods in object) in the range between 30% and 80% of the rated load; this difference rapidly increases at full load reaching 1.20%.

4. Analysis of errors and uncertainty levels

4.1 Thermodynamic Method

The common use of the direct method (without any controlled expansion device of the water passing from the penstock to the measuring vessel) makes the calibration of thermometers a point of main importance, especially in high efficiency and low head units.

A calibration performed with an accuracy of ± 1 mK is the actual average limit of the best international institutes but the cost of calibration at such an extreme level is very high and, in order to evaluate if it is worth spending this money it is necessary to consider that only secondary environmental changes are able to cause a shift of the characteristics of some mK.

The differential E.d.F. calibration technique, that assures uncertainty of 10 mK on the absolute value of temperature and 1mK on the differential temperature, allows lower cost and can be considered normally enough as the t=0 condition can be normally checked at site (even if it is difficult to ensure and verify a gradient lower than 1mK inside a Dewar pot).

In order to guarantee good results with reasonably low uncertainty level, a way of checking the thermometer calibration on site should be realized using, for example, a portable thermometric bath or an expansion device, as described in the IEC code.

The use of several thermometers on both the upstream and downstream sections, gives the possibility of a statistical reduction of the overall error to reasonable amount and better identification of spurious values. The use of several thermometers could also help to clarify the reliability of the results in case of fluctuations in space and time of the energetic profiles.

An easy way to have an indication of the proper behaviour of the probes could be the repetition of some of the already measured points using a kind of partial expansion technique. In fact the values of pressure and thermal terms of the mechanic energy equation can be modified by changing the expansion rate; if in this change the mechanic energy and the efficiency remain the same, pressure and temperature probes validate each other.

For what concerns the correct evaluation of energy distribution on the measuring sections, it is necessary to consider that it may be difficult and that the magnitude of error introduced by assuming simple mean values could be macroscopic. Each temperature value of a specific geometrical portion of the measuring section should be referred to the relative flow passing through that portion. A measure of the total pressures of the measuring points, referred to the static measurement, can be useful because it can show the lack of uniformity of the kinetic term. Special weighing frames were studied to compensate any possible asymmetry, especially in the downstream section where recirculations and back flows are more common: the downstream measuring section should be always prepared in order to avoid the presence of back-flow or at least its influence on the results.

Moreover, the diversion of all cooling waters falling in the downstream section is always mandatory.

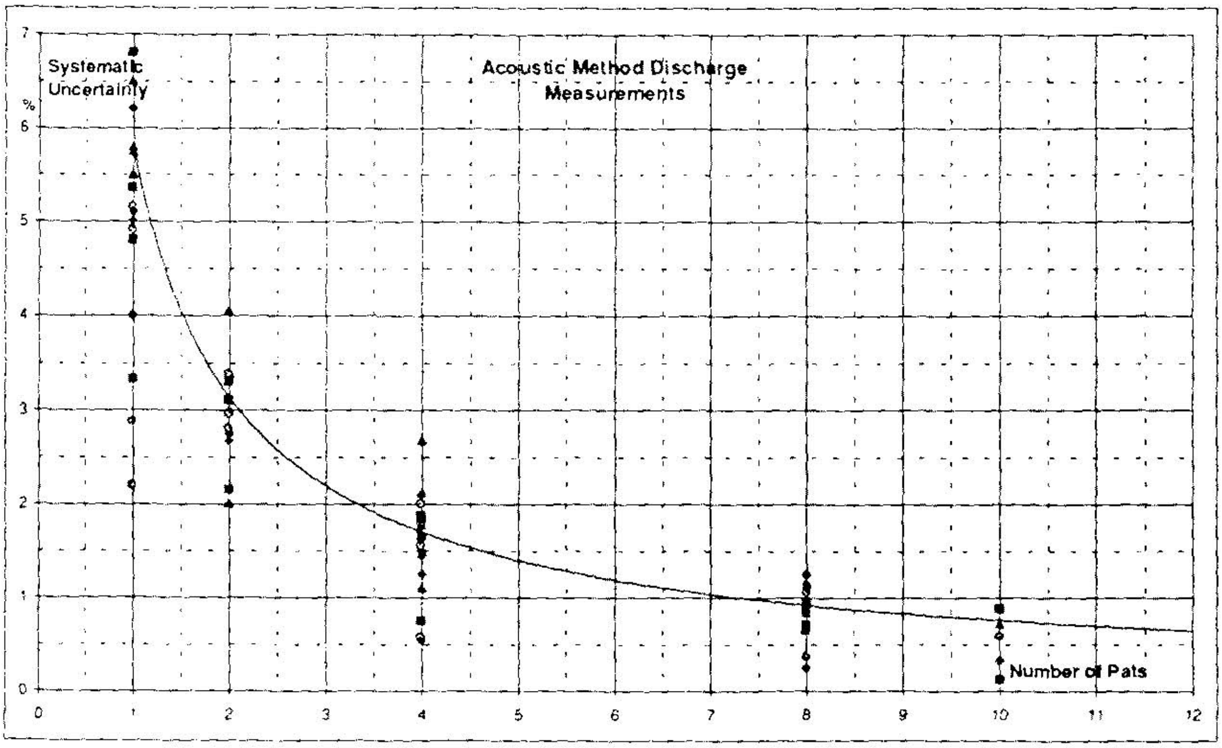
The heat exchange of the measuring system is widely analysed in the codes and can be modified by using accurate thermal insulation. The amount of heat exchange between the measuring sections can be more difficult to quantify. In normal conditions, the possible error is very small but it may be significant in testing low head and high efficiency units. In testing small-hydro the percentage of heat exchange can be higher than the maximum allowed value described in the IEC Code and more accurate formulas should be used. A specific problem of heat exchange occurs when any bi-phase mixture (water-air) exists. For a rigorous evaluation, the amount of energy introduced by the air should be calculated by measuring the air temperature and flow rate. Part of this problem is the bi-phase foamy mixture that can be often found in the discharge channel of Pelton turbines.

Vibrations of the temperature measuring system are another possible cause of error. In fact, temperature probes directly immersed in the flow are affected by the heating coming from the impact of the fluid on the probe. This deeply investigated phenomenon is extremely important in the upstream section.

Finally, it is necessary to remember that indirect temperature measurements could be affected not only by errors due to heat exchange but also by errors connected to the delay in the thermal transmission between fluid and probe.

4.2 Acoustic Method

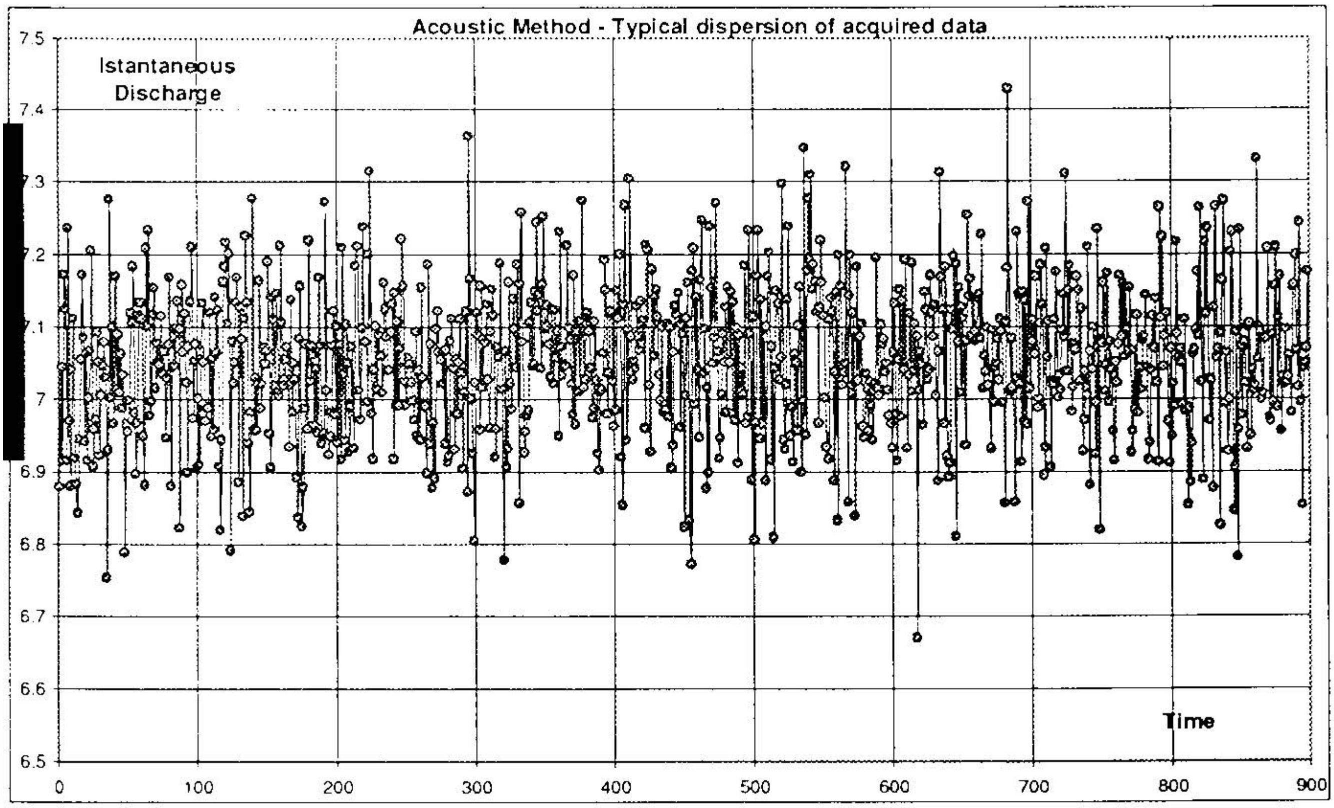
In order to be able to evaluate in the best way this method, it is necessary to state in advance that, ganerally, a proper calibration of the acoustic device cannot be performed. Moreover, self checks, zero checks and determination of theoretical propagation velocity of the wave in the fluid sometimes are not enough to be sure of the proper behaviour of the apparatus.



A statistical evaluation of the uncertainty due to systematic errors for different numbers of sensors can be made. Theoretical and experimental data confirm that the average systematic error in the discharge measurement can be assumed lower than 1% only if the number of measuring paths is higher or equal to eight. The curve of systematic uncertainty versus number of paths, set forth hereabove as an example, is based on comparative tests in all different kinds of units and installations. The experimental results confirm that for efficiency measurements, not less than eight paths should be used (sixteen sensors in dual plane installation).
Other important causes of error, whose influence is theoretically well known, but in practice underestimated, can be reminded such as:

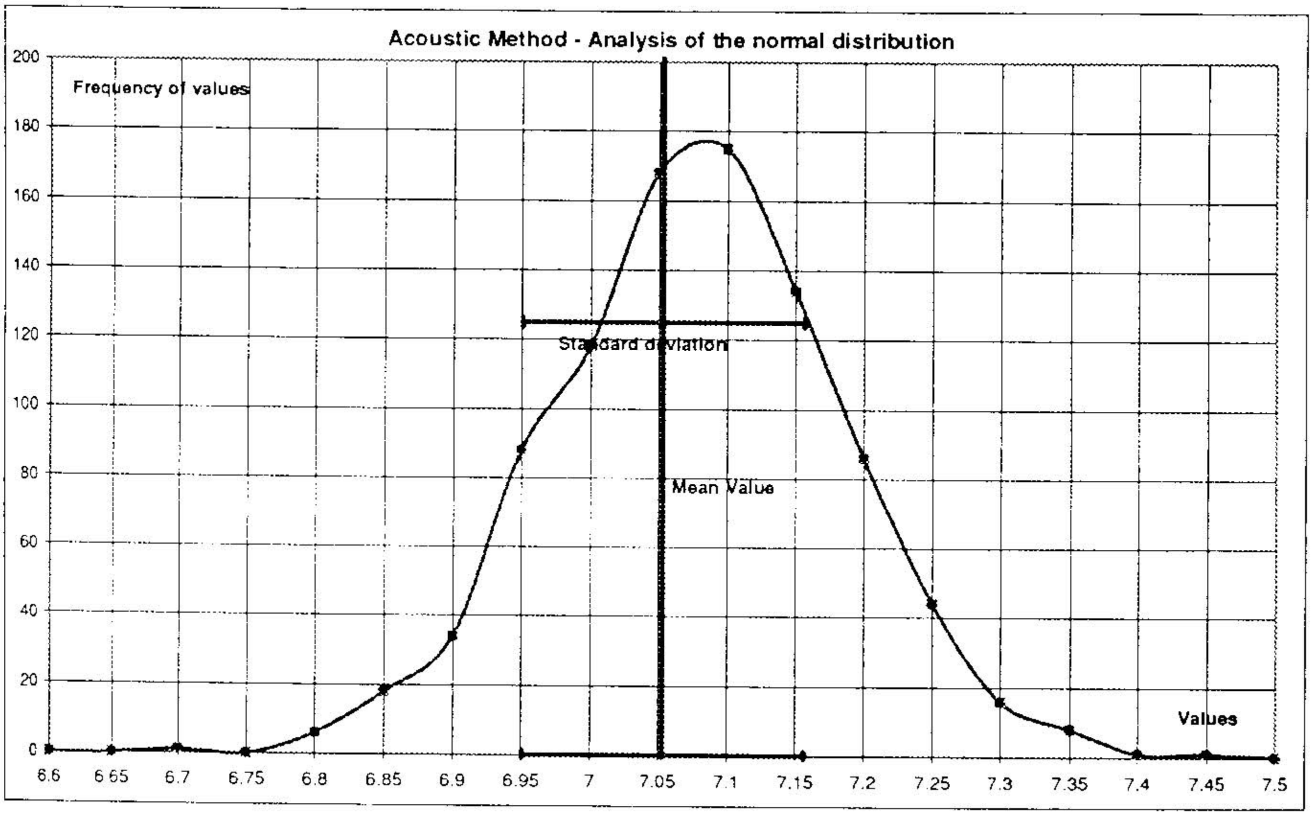
- the errors due to a possible incorrect evaluation of the geometrical layout of the measuring system (a correct installation of the probes, made by experienced technicians, is indispensable to obtain reliable results);
- the errors related to the protrusion of the probes in the measured flow, affecting thus, by their own presence, the velocity patterns;

Furthermore, it is worth remembering that to have proper results, the acoustic method must be operated with great numbers of data; actually, the method itself has a great dispersion of instantaneous discharge values: a fluctuation max.-min. of ± 5% of the measured values should be considered acceptable. In the following example of a measurement sequence, the standard deviation of a 900 samples tests remains at the level of ±1.50%.



In this example, the expected deviation of the mean value is lower than the standard deviation but, in general, in order to reduce the uncertainty, higher numbers of acquisitions should be made.

Moreover, as a firm point, it must be clear that to have the possibility to determine a reliable mean value, the population of the samples have to be considered normal, this means that the dispersion of the acquired data strictly follows a gaussian curve whose peak should correspond to the mean value. The presence of outlayers and the deviation from the typical gaussian shape mean that the acquired data are affected by perturbing phenomena that interfere with the measurements. In this case, the samples cannot be considered a single family data but they become separate families that cannot allow a correct estimation of the mean value. The example shown herebelow refers to a still acceptable dispersion with a presence of some minor phenomena: a small shift of the mean value from the peak of the gaussian curve can be observed.



5. Conclusions

The rapidity of execution of the prototype tests made using the thermodynamic method and the more and more diffused existence of fixed installations of acoustic method, devoted to the continuos monitoring of discharge and efficiency, may give the false idea of an easy use of these measuring techniques.

On the contrary, many problems can affect the measurement accuracy both of thermodynamic and acoustic methods: actually both of them need a deep knowledge of the phenomena and such a wide experience in the real test activity as to allow a proper detection and solution of all inconveniences that may occur.

There is no "Plug and Play" device that can give reliable results: the less we follow meticulous procedure of step by step data analysis, the biggest is the error that may be done.

No dangerous illusions have to be created: sharp and well studied procedures can only help the results critical examination. Eventually, it is the experience that gives the reasonable certainty to obtain good results.

As we have seen, the model tests are able to predict with sufficient accuracy the actual performances of industrial Pelton turbines, but, in this context, only the use of a more reliable scale effect formula, not only theoretical but mainly exsperimental, is able to supply the required results. Thus, the reliability of experimental coefficients must be verified and updated, especially in case of a major change of the hydraulic profile of any of the main components of the machine.

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