Verbundplan
A Member of the Jaakko Pöyry Group

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Thermodynamic Efficiency Measurement-
Method of Partial Expansion and Direct Method

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Content

1 INTRODUCTION

1.1 Verbundplan GmbH – Company Profile

The Verbundplan Group is Austria's leading engineering and consulting firm, and it has been active worldwide for more than 40 years. Its core competencies are in the fields of:

- hydro power
- thermal power
- management consulting
- civil engineering
- transmission & distribution

The Group consists of Verbundplan GmbH with branches in Vienna, Salzburg and Villach, marketing offices in Indonesia and Turkey, and Verbundplan Prüf- und Messtechnik, which maintains a state accredited Testing and Monitoring Centre. The Group's highly qualified staff totals approx. 300 employees at home and abroad.

Verbundplan is a member of the international Jaakko Pöyry Group, a global engineering and consulting firm that has three core areas of expertise: energy, infrastructure & environment, and forest industry. The Jaakko Pöyry Group employs 5,200 experts in 40 countries, and it is one of the 10 largest independent engineering consulting firms in the world.

Within the Jaakko Pöyry Group organisation, Verbundplan belongs to the Energy Business Group. This group also includes other subsidiaries located in Great Britain, Finland, Germany, Sweden, France, Spain, the Middle East, Asia, and Latin America. The Energy Business Group employs a total of more than 1400 people, among which are Civil, Electrical & Mechanical Engineers, Geologists, Experts, Environmental Specialists, Physicists, Chemists, Social Scientists, Agronomists as well as Financial Experts and Economists.

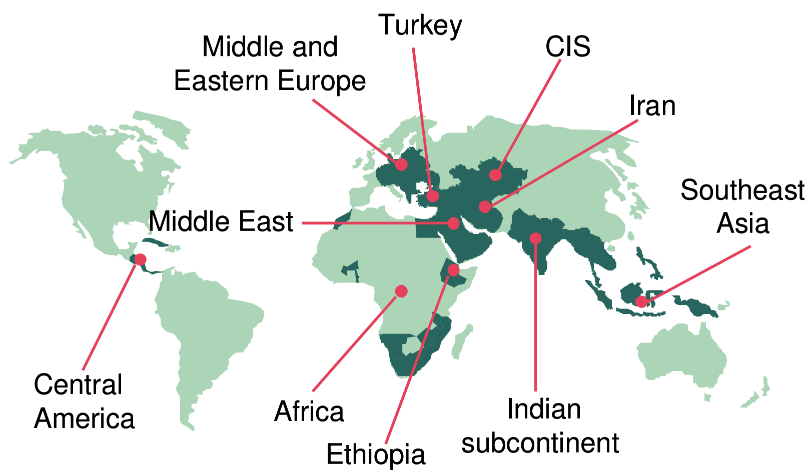
In addition to the traditional range of engineering activities such as: Studies, Expertises, Evaluations, General and Detail Engineering, Planning and Project Design, Consulting, Project Management, Construction Site Supervision, Commissioning, Operation & Maintenance of Power Stations, Training, and Quality Management, Verbundplan is also involved in "General Contractor" activities, which includes EPC (Engineering - Procurement - Construction).

The full integration of a local presence with global competence is a key characteristic of the Jaakko Pöyry business policy. This concept guarantees that projects have access at all times to the group's comprehensive interdisciplinary “know how”. Thus, Clients can be provided with optimal technical and economic solutions through the leadership of experienced Project Managers.

Verbundplan’s broad range of activities includes all design and consulting services for:

- hydro-electric and thermal power plants
- planning and installation of electrical plants and equipment
- high and extra-high voltage grids
- tunnelling and underground structures
- geotechnical and material engineering
- environmental engineering and waste management
- water management and environmental protection
- construction and project management
- management consulting and technical assistance
- energy systems consulting
- digital systems engineering
- environmental consulting
- carbon consulting

Operating in the market as an engineering company that is independent of construction firms and suppliers, Verbundplan assures neutral, customer-oriented consultancy in all fields in which it offers its services. Its customers include public and private investors, governments, banks and international organisations, as well as companies in the energy sector and the construction and plant engineering industries. Verbundplan is continuously involved in the rapidly expanding domestic market, but it is also increasing its presence across Europe, especially in Turkey and in Central and Eastern Europe, and in key markets in Africa, Asia and Central America.



Graph: Key Markets

1.2 Verbundplan GmbH´s experience with thermodynamic measurement

Verbundplan GmbH started in 1976 to perform thermodynamic efficiency measurements by the method of partial expansion. 195 measurements have been done successfully to date. Since 2005 Verbundplan GmbH has also been applying the direct method for efficiency measurements.

1.3 Thermodynamic efficiency measurement

In the presentation both methods, partial expansion and direct method, are described and the characteristics are examined. Advantages and disadvantages as well as corresponding effects are compared. In addition, probable limits in the use of the partial expansion method are shown.

1.3.1 Topics of lecture

- For the method of partial expansion the results of two tests performed with different measuring equipment carried out at the same Francis turbine in a power plant in Austria are presented.
- At a power plant in Austria the results of a thermodynamic efficiency measurement at a Pelton turbine are compared on the one hand with the method of partial expansion and on the other hand with the direct method.
- During an efficiency measurement at a Pelton turbine at a power plant in Switzerland problems occurred with the thermometer on the low pressure measuring section. The effects on the results of the test are shown.
- At a Pelton turbine at another power plant in Switzerland several thermodynamic efficiency measurements were performed before and after the installation of a new runner. The measurements serve to assess the impacts on the efficiency at different modifications of the unit. Index tests have also been performed on occasion of upgrade works and the results were compared with those of the thermodynamic measurements.
- In 2004 thermodynamic acceptance tests were performed at a power plant in Switzerland. Considering these measurements the limits of the partial expansion method are presented, in addition, the practicability as well as the problems of performing measurements by the direct method are described.

2 METHOD OF PARTIAL EXPANSION AND DIRECT METHOD

The inner losses of a hydraulic machine (turbine or pump) warm up the water → „inner efficiency“.

From the first fundamental thermodynamic theorem and the mechanical caloric equivalent we derive

heat = energy

1 K ⇔ 4188 J/kg (427 m)

Based on this fact by means of the thermodynamic efficiency measurement the inner efficiency can be calculated.

The hydraulic losses of a turbine or a pump typically cause a heating of the water passing the unit. The value of heating therefore is a measure of the hydraulic losses which can be calculated from the heating of the water using the specific heat capacity of water. The energy of 4188 J is necessary for heating 1 kg water by 1 K.

For practical use this means that the water flowing through a turbine with a head of 427 m and an efficiency of 90% is heated by 0.1 K due to hydraulic losses. As shown in the example, very small temperature differences have to be measured. With constant efficiency at a lower head these differences are even smaller.

In principle the efficiency is evaluated with the main figures of pressure and temperature at the entrance and exit of the hydraulic machine. On the one hand the static pressure must be measured at the high pressure side (HP), and additionally, a special sampling probe has to be used. This probe enters the pipe and extracts some water. Inside the probe is a throttle followed by a thermometer measuring the upstream temperature of the partial expanded water. In case of a unit with closed downstream measuring section the same equipment is used there – if there is a free surface at the downstream section the thermometer(s) are directly put into the water.

Calculation of the efficiency:

$$\boxed{\eta = \frac{e_m + \partial_{em} - e_x}{e_h} \qquad \textit{for a turbine}}$$

$$\boxed{\eta = \frac{e_h}{e_m + \partial_{em} + e_x} \qquad \textit{for a pump}}$$

e_m	specific mechanical energy	[J/kg]
e_h	specific hydraulic energy	[J/kg]
δ_{em}	corrective terms	
e_x	specific losses which do not affect the water passing the unit, but have to be taken into account for the efficiency examination	[J/kg]

Specific hydraulic energy:

$$e_h = v * (p_1 - p_2) + \frac{v_1^2 - v_2^2}{2} + g * (z_1 - z_2) = (g * H) \qquad [J/kg]$$

$1/\rho$	specific volume of water f (p, Θ) ……………......	[m³/kg]
p_1, p_2	absolute pressure..	[Pa]
v_1, v_2	velocity………..	[m/s]
g	acceleration due to gravity	[m/s²]
z_1, z_2	geodetic head..	[m]
H	head...	[m]

indices 1……. high pressure measuring section

indices 2……. low pressure measuring section

Specific mechanical energy:

$$e_m = a * (p_{1\text{-}1} - p_{2\text{-}1}) + c_p * (\Theta_{1\text{-}1} - \Theta_{21}) + \frac{v_{1\text{-}1}^2 - v_{2\text{-}1}^2}{2} + g * (z_{1\text{-}1} - z_{2\text{-}1}) \quad [\mathrm{J/kg}]$$

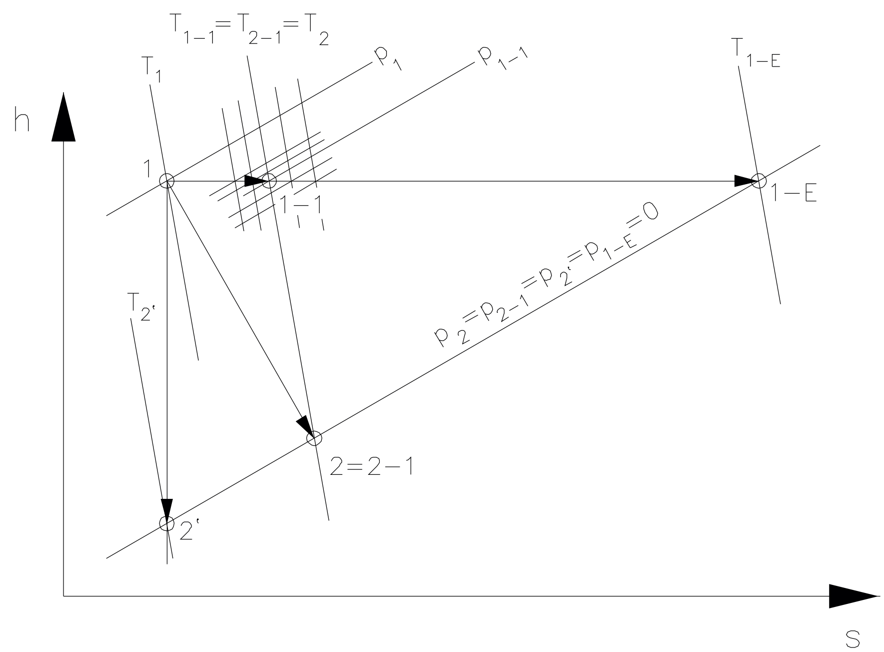
a	isothermal factor of water f (p, Θ)	[m³/kg]
$p_{1\text{-}1}$, $p_{2\text{-}1}$	absolute pressure..	[Pa]
c_p	specific heat of water f (p, Θ)………………….......	[J/kg/K]
$\Theta_{1\text{-}1}$, $\Theta_{2\text{-}1}$	temperature...	[K]
$v_{1\text{-}1}$, $v_{2\text{-}1}$	velocity…………..	[m/s]
g	acceleration due to gravity................................	[m/s^2]
$z_{1\text{-}1}$, $z_{2\text{-}1}$	geodetic head..	[m]

indices 1-1…….. high pressure measuring section

indices 2-1…….. low pressure measuring section

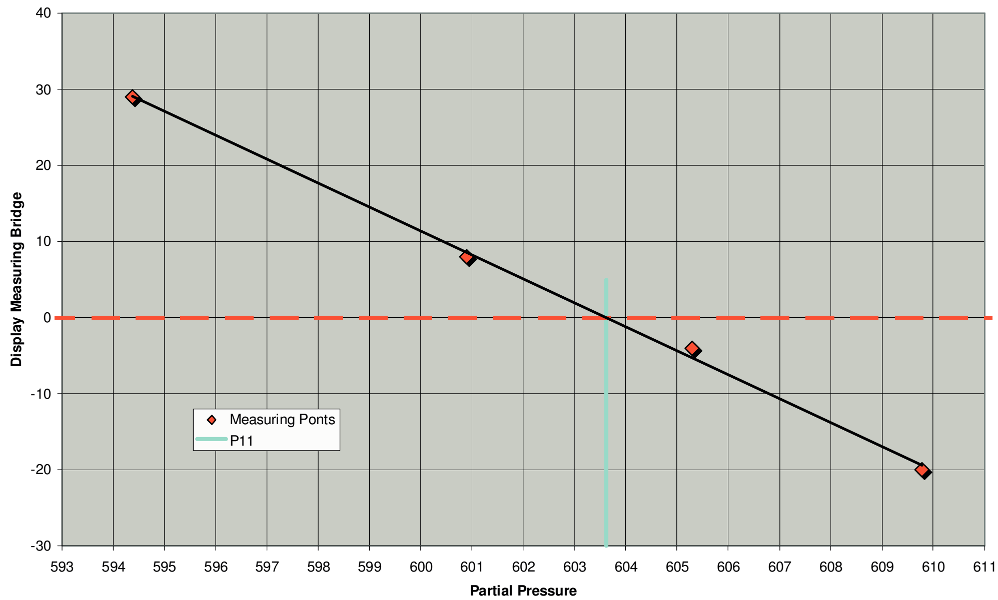
2.1 Partial Expansion

By using the partial expansion method (zero method) to determine the efficiency of a hydraulic machine, high pressure water (indices 1) is extracted and then expanded so that the temperature T_{1-1} (temperature from the upstream probe) is equal to the down stream temperature T_{2-1}. That means that in the equation of the specific mechanical energy the term $c_p * (\Theta_{1-1} - \Theta_{2-1})$ is equal to zero and is not included in the evaluation. Or very simplified, the losses of the hydraulic machine are represented by the expansion in both probes.



Graph: h-s diagram partial expansion with free surface at the low pressure section

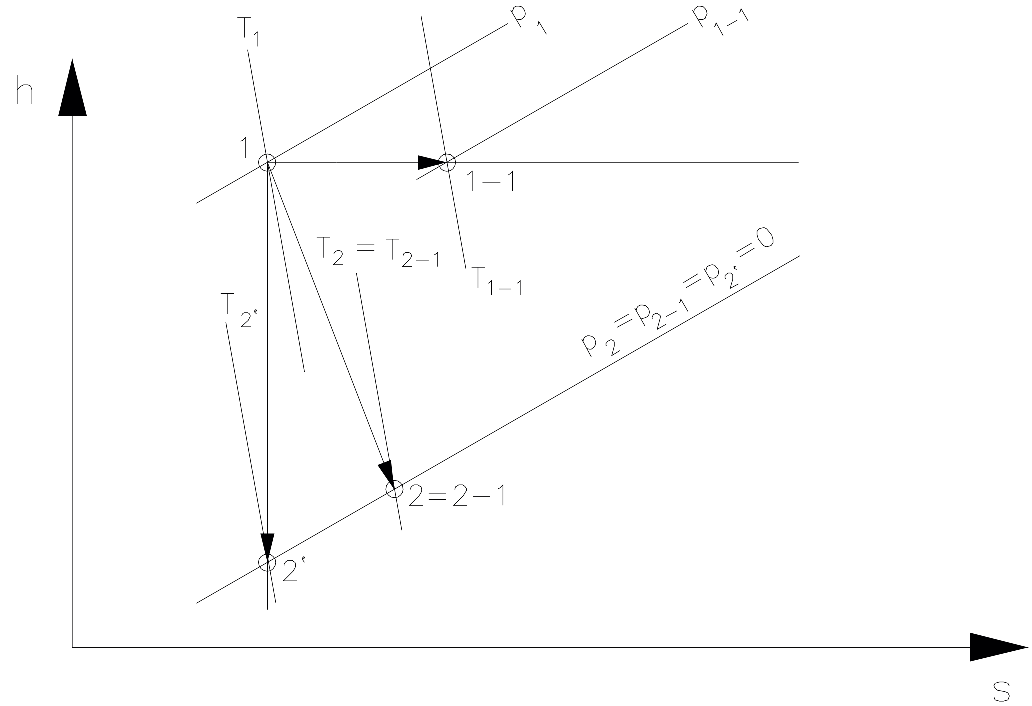
Due to the fact that it is a lengthy procedure to reach temperature equality by trial, some pressures p_{1-1}, usually 4, are recorded in the range of temperature equality. The corresponding temperature differentials are indicated as digital values at the measuring bridge. By means of a linear regression the expansion pressure p_{1-1} for temperature difference is equal to zero, required for evaluation of the efficiency, is calculated.



Graph: Evaluation of p_{1-1}, linear regression

2.2 Direct Method

In principle the measuring equipment is in some cases the same as used for the partial expansion method. The upstream probe is exactly the same. The only really decisive difference is the fact, that instead of temperature equivalence between both measuring sections now absolute temperatures are measured. For the evaluation of the efficiency the difference of the measured temperatures is taken into account. The direct method also makes it possible to install more then one thermometer especially in the low pressure section with free surface. Up to three or even more thermometers are possible to record different temperatures over the measuring section and to get so a more accurate average for the evaluation.



Graph: h-s diagram direct method with free surface at the low pressure section

At the probe in the high pressure section a partial expansion with the direct method is also necessary, but with the difference that the upstream water is expanded to a user-defined value of p_{1-1}.

2.3 Summary

- **Method of partial expansion (zero- method)**

advantages	disadvantages
○ Simple equipment ○ Long time experience existing	○ Extended measuring time for one efficiency point ○ Automatically data acquisition suitable to a limited extent only ○ Only one thermometer per measuring section possible

- **Direct method**

advantages	disadvantages
○ Shorter measuring time for one efficiency point ○ Measuring all necessary values simultaneously in the same time interval ○ In an open downstream measuring section multiple thermometers can be installed ○ Good applicable for automatic data acquisition	○ Very accurate thermometers are necessary ○ More costly equipment

3 FIELD STUDIES

3.1 Comparison of measurements with partial expansion method and different equipment

In 1987 after successful trial run acceptance tests where performed with the thermodynamic efficiency measurement. At this time the temperature difference was detected by means of thermistors. For the temperature measuring bridge a relatively simple Wheatstone bridge was used.

In 1989 the equipment was updated, Pt-1000 thermometers were employed, for the measuring bridge a BUSTER system was used.

In 1997 the Verbundplan GmbH equipment was updated once again. We switched to Pt-6000 thermometers and a more comfortable measuring bridge with an automatic zero point adjustment, supplied by DEWETRON Austria.

In 2005 the operating company decided to undertake an efficiency measurement with respect to a scheduled main overhaul of the unit. This measurement should help to extract components for detailed maintenance investigations.

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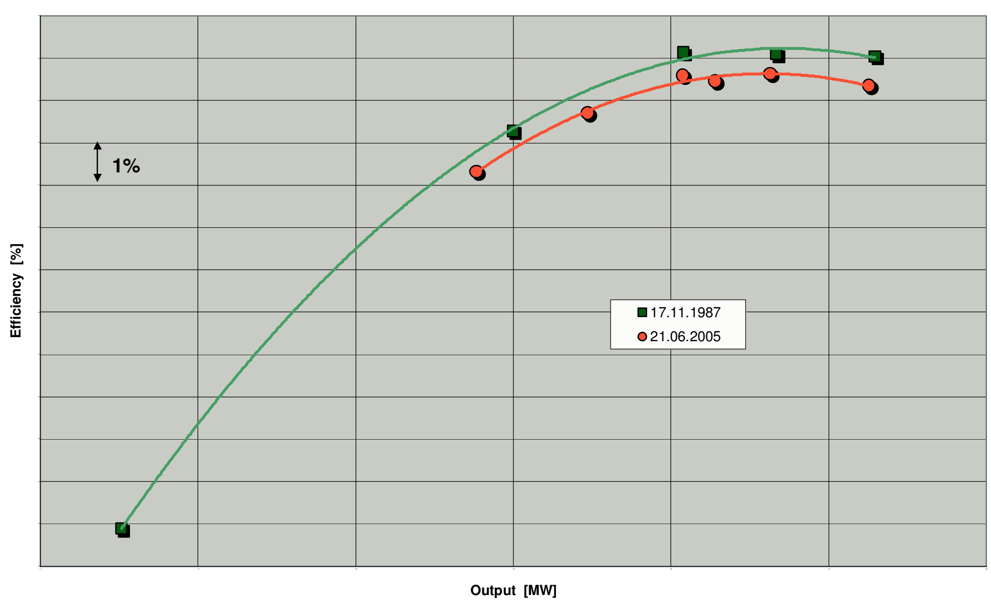
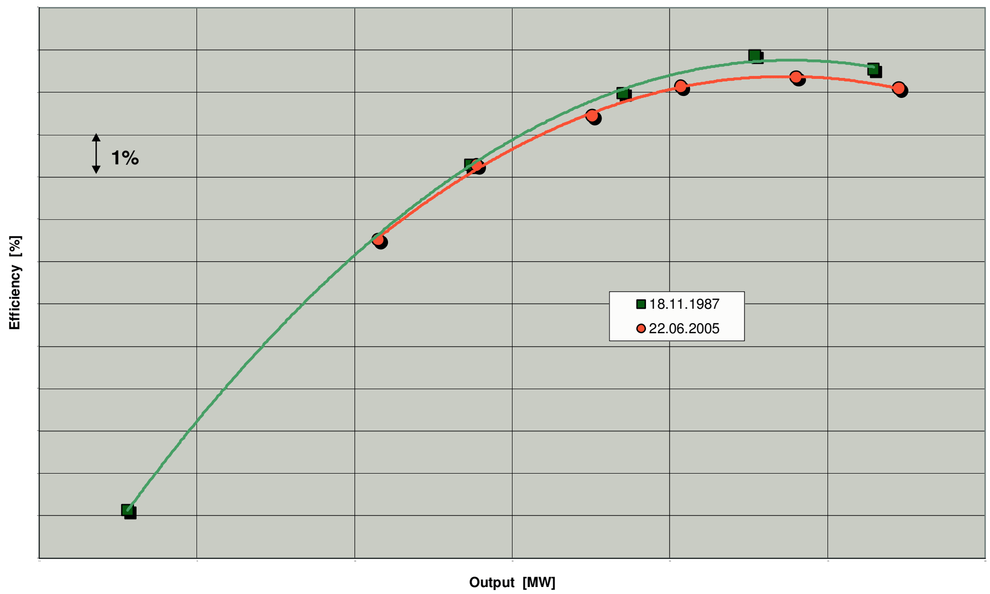


Graph: Measuring results unit one



Graph: Measuring results unit two

As a result it can be said that surprisingly after 20 years of operation, whereat the units have been in service for approx. 20.000 hours each, only a diminutive loss of efficiency appeared due to appropriate maintaining procedures.

3.2 Comparison of measurements with partial expansion method and direct method

The measurements were carried out in a power plant in Austria, in which twin Pelton units are installed. The water released from the turbine flows directly in a balancing basin.

Between 1971 and 1977 in this power plant several thermodynamic efficiency measurements were undertaken using the partial expansion method. At this time the detection of the temperature difference was a lengthy procedure using the advanced available technology at this time.

After Verbundplan´s change to the direct method, another efficiency measurement was carried out in 2005.

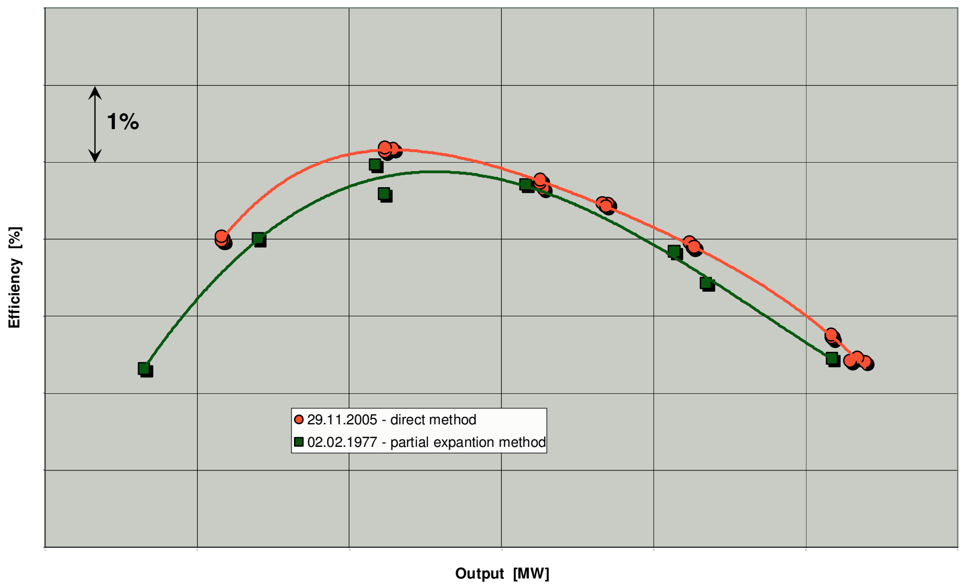
In principle the identical probe used for the partial expansion method was also used for this measurement. Additionally a new data acquisition unit, supplied by AGILENT, was procured. For a selected time and time interval all measuring values are recorded and stored in our Laptop. For the evaluation of the efficiency and the uncertainty as well as for a good presentation of the results Verbundplan GmbH prepared its own new software based on MS VisualBasic.

The high pressure probe was installed in a distance of approximately 3,5 m from the turbine axis. For recording the upstream- and downstream temperature, Pt-2000 were employed. By using three thermometers in the cross section of the downstream canal an accurate average of the downstream temperature was recorded. For attaching the three downstream thermometers, the existing special frame as used in former measurements was mounted in the down stream cross section.

Before starting, and after finishing the measurement, a zero point alignment of the Pt-2000 with different temperatures was carried out.

During the measurements, the variation of the upstream water temperature was marginally due to the big reservoir. Starting with full load, in total seven efficiency points were investigated, whereas every measuring point was recorded three times for repeatability. As indicated in the attached graph an accurate repeatability could be achieved.

Finally at the end of the measurement the zero point alignment at a temperature of 7.5 °C was checked.



Graph: Comparison partial expansion versus direct method

As indicated in the graph it can be said that both measurements show a sound compliance with marginally differences.

3.3 Impact of a defective thermometer to the results

In 2005 Verbundplan GmbH was contracted to carry out a thermodynamic efficiency measurement on a 4-jet Pelton turbine in a Swiss hydro power station. At this turbine, the runner was renewed in 2004. Aim of the measurement was to verify the suppliers guaranteed efficiency. The measurement was carried out by means of the partial expansion method.

For extracting the water in the high pressure side of the penstock, Verbundplan GmbH´s measuring probe was installed.

For measuring the downstream water temperature, a special frame with a steel pipe for collecting the water was manufactured by the client. To achieve a representative average temperature of the downstream flow, 2 times 3 boreholes with differing diameters were drilled into the steel pipe. In the middle of this pipe and the down stream canal respectively one Pt-6000 thermometer was attached for recording the temperature of the collected down stream water. The steel pipe was mounted in the cross section of the downstream canal with a distance of approximately 15 m from the turbine axis and approximately 30 cm above the downstream canal floor.

For measuring the upstream and downstream temperature, Pt-6000 thermometers were employed. For measuring the marginally temperature difference of the two Pt-6000 thermometers a measuring bridge form the company DEWETRON was applied. To get an accurate resolution, both Pt-6000 thermometers were operated as a bridge circuit. Applying this method, a resolution of 0.0005 K/1 digits, compared to the pressure height this equals to 0.21 mWC/1 digit, and a stability of 0.0002 K can be achieved.

Before the measurement started, some adjustments like diverting the turbine cooling water to an area downstream of the measuring section had to be done.

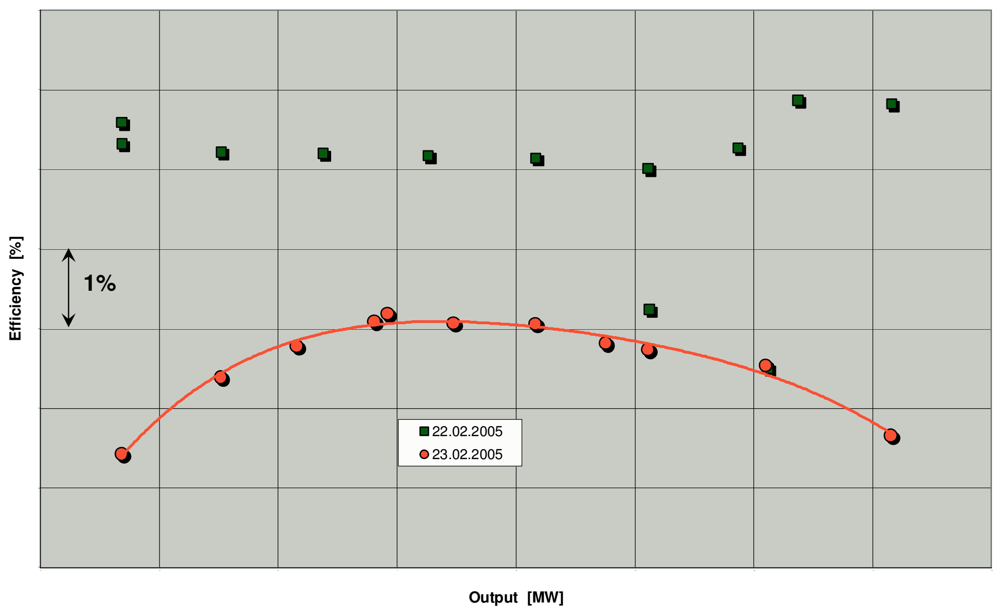
Starting with the first measuring point at full load, the evaluation showed an unexpected high efficiency of approximately 3% above the guaranteed one. Continuing the measurements, the height of the efficiency nearly did not change. A repeatability of the measuring points was not possible.

Finally a check of the zero point alignment was not possible. Due to this fact the measurement was terminated.

On the next day, the downstream Pt-6000 thermometer was identified as defective and changed to a new one.

After trimming of both Pt-6000 thermometers at a temperature of approximately 0.1 °C and 6.3 °C both thermometers were installed.

Eventually the measurement started again and an accurate temperature recording and efficiency determination could be achieved.



Graph: Efficiency curve with defect thermometer and after change of thermometer

3.4 Measurements with modification of the runner and housing

In February 2000 Verbundplan GmbH was contracted to carry out a thermodynamic efficiency measurement at an aged twin Pelton turbine in Switzerland.

The basis for the first measurement was on one hand the information of the existing efficiency and on the other hand the verification that the measuring method is applicable for an acceptance test.

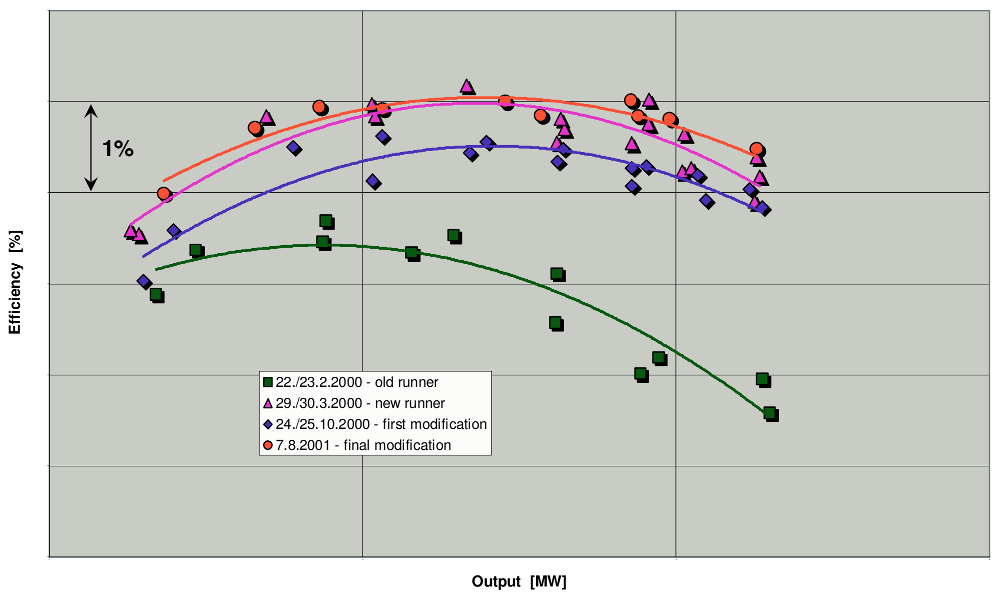
For the measurement the method of partial expansion (zero method) was applied. The upstream measuring sensor was attached between the ball valve and the jet. To achieve a representative temperature recording in the downstream water canal a pipe with six extraction holes with different diameters was produced and installed across the canal.

So the water was collected from different areas of the downstream cross section and led to one thermometer installed in the middle of the pipe. Additionally a small step was constructed to guarantee that the down stream thermometer was submerged for the entire measuring period. For the temperature difference indication Pt-6000 thermometers and a special measuring bridge from DEWETRON was used.

After installation of new Pelton runners in March 2000 acceptance tests were undertaken by Verbundplan GmbH. Regrettably the results did not fully meet the client's complete satisfaction nor the suppliers specification. To compare the results from March 2000 with the February 2000 results, the efficiency of turbine A was marginally higher than turbine B. It was supposed, that this effect is due to an influence of the bifurcation and the incident flow to the jet respectively.

After some modifications at the turbine done by the turbine supplier in October 2000 an additional thermodynamic efficiency measurement was implemented. Surprisingly the results of these measurements were a little lower than the preceding results. As a consequence the turbine supplier performed index tests in January 2001 whereas in principle the essential characteristic of the efficiency tendency was confirmed.

A final check of the implemented modifications was done with an additional thermodynamic measurement in August 2001. This confirmed the improvements of the turbine as indicated in the results of the index tests.



Graph: Results of thermodynamic measurements

3.5 Limits of the partial expansion method

In 2003 Verbundplan GmbH was contracted to perform a thermodynamic efficiency measurement by means of the partial expansion method (zero method). This measurement should be the acceptance test of a 6-jet Pelton turbine.

At this power plant only a small balancing basin is available, generally the plant is operated as a run of river power plant. During spring time when enough water is available, a lot of grass, leaves and needles are in the river.

The new turbine started operation in November 2003. Initially it was agreed that the measurement should be carried out in November or December 2003. Due to technical reasons at the inlet throttle valve, and later on because of too less water, the scheduled measurements were delayed. The aim of the measurement was to verify the supplier's guaranteed efficiency of the new turbine and to calibrate the ultrasonic discharge measurement.

The sampling probe was installed in the high pressure side which joins the probe tube, partial expander and the thermometer. The partial expander is designed with a double layer. To prevent thermal radiation to the probe which might influence the accuracy of the temperature measurement, the outer side probe is flushed with isolating water. The probe itself was installed in the penstock and extracts water by means of an elongated hole which is situated in the direction of the water flow. The partial expander was positioned in this way so that at all measurement points the extracted water flow was approximately 15 liters per second.

With support of the adjustable throttle (control valve or thread throttle) which was fastened on the plane table, the extracted water was expanded totally to atmospheric pressure. By positioning the throttle the discharge was changed and the expansion in the expander can be positioned in a way that the temperature difference between the high pressure side and the down stream side equals to zero.

For the installation of the downstream thermometers a special frame with a steel pipe was manufactured for the efficiency measurement. In the steel pipe, which was mounted in the cross section of the downstream canal, 6 holes were drilled for collecting the water. The mixed water, a representative average, was led to the downstream thermometer, which was implemented in a special attachment in the middle of the steel pipe. This pipe finally was mounted in the downstream canal with approximately 18 m distance from the turbine axis. In the area of the pipe, a threshold was existing. During the measurement the distance of the thermometer to the downstream canal floor was approximately 120 mm.

For the recording of the small temperature differences between the Pt-6000 in the upstream probe and the Pt-6000 in the downstream canal a special measuring bridge made by DEWETRON was used. The measuring bridge transforms the temperature difference of both thermometers to an electrical signal which was displayed on the notebook by means of special software.

To achieve an appropriate resolution, both Pt-6000 thermometers operate as a bridge circuit. So a resolution of 0,0005 K/1 digit and a stability of 0,0002 K can be achieved.

Before the measurement started, the runner buckets, the nozzles, nozzle tip seat ring, as well as the inflow area (by means of a hand hole) was inspected together with the operator and the turbine supplier. Some debris was found, mechanical damages or obviously impacts could not be detected.

For the pressure measurement a rotary piston weight manometer was used which was calibrated in situ with a set of weights. Then the linearity of the entire measuring range was checked. After trimming both Pt-6000 thermometers at approximately 4 °C and 12 °C, both thermometers were installed. During the first test run no steady state condition of the temperature could be achieved.

After the change and trimming of the Pt-6000 thermometers, the displayed temperature difference suddenly jumped by 90 digits. (1 digit equals 0.0005 K, 90 digits equal 0.045 K or with other words, at an average head of 220 m this means a difference of approximately 8,7% in efficiency). The reason for the varying of the displayed values was the start of the frequency controlled motor of a pump installed on a hydraulic aggregate. As a corrective action, the measuring desk was moved away from the hydraulic aggregate. But an improvement of the measuring condition could not be achieved. With a different power supply of the entire measuring equipment and the connection of the instruments with the powerhouse grounding, the interference of the pump motor could be eliminated.

In parallel to the movement of the measuring desk, the upstream probe was removed and a material pollution (seaweed, fern, needles from softwood etc.) was detected. So the probe was dismantled, cleaned and again mounted.

After an additional trimming of the thermometers, the measurement restarted on the next day. Again it was not possible to achieve a steady state condition of the temperature difference.

Following an internal discussion, it was decided to terminate the thermodynamic efficiency measurement and to carry out an index test using the available measuring equipment.

Additionally it was declared, that the turbine supplier has to carry out a thermodynamic efficiency measurement by means of the direct method under the condition that an external expert (Mr. Werner Mayr from Verbundplan GmbH) shall supervise the measurement.

In the high pressure side an identical probe was installed whereas in the downstream section three thermometers were attached.

After assembling and controlling of the measuring equipment, some trial measurements were carried out. Unfortunately no reproducibility of the measurements could be achieved even with the direct method. In case of low output the scattering of the measuring value was incredible high.

Practically the temperature of the upstream water never was stable. According to the IEC 41, in such cases special corrective measures can be done. In case of decreasing temperature at the turbine entrance (upstream measuring temperature) the water temperature of the downstream measurement is too warm. That means that on one hand ΔT is too high or on the other hand the measured efficiency is too bad. Vice versa the same statement is applicable with increasing temperature. Eventually taking into account the correction of the thermal gradient at the turbine entrance, a sensuous repeatability could be realized.

The identification of the thermal gradient influence to the result of the thermodynamic efficiency measurement is done by the formula according to IEC 41. The correction factor for the specific mechanical energy is calculated with

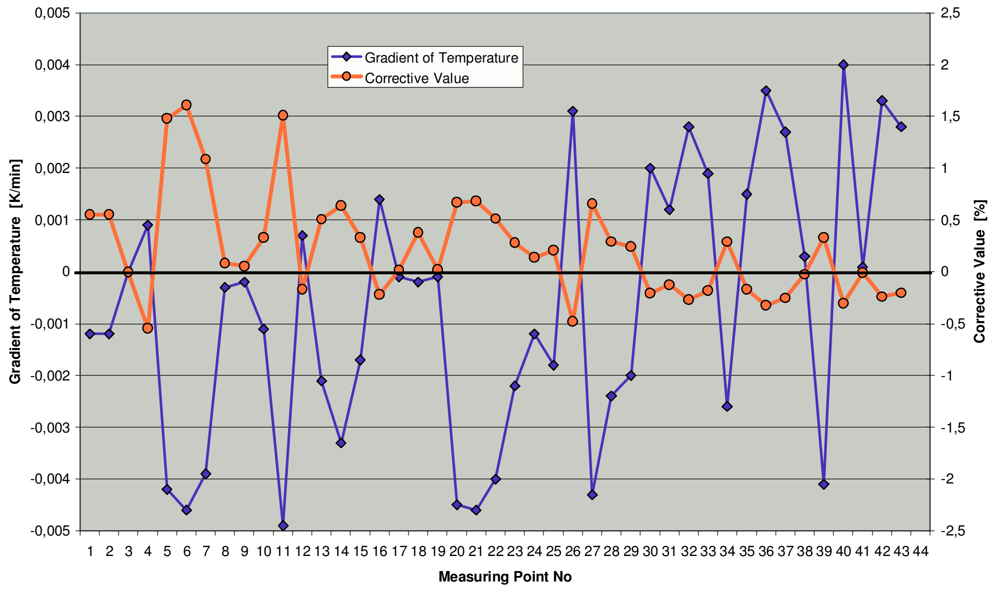
$$\delta_{em} = c_p * \frac{d\Theta}{dt} * (t_a - t - t_b)$$

t is the time, in seconds, taken by the water to pass through the machine between the two measuring sections

t_a is the time, in seconds, taken by the water to pass from the high pressure tapping point to the corresponding measuring vessel

t_b is the time, in seconds, taken by the water to pass from the low pressure tapping point to the corresponding measuring vessel

During the main measurement a lot of measuring points had to be eliminated due to the fact that the thermal gradient exceeded 0.005 K/min. According to IEC 41 this is the limit for corrective measures performing the thermodynamic efficiency measurement. The quantity of the corrective measures is indicated in the following graph:



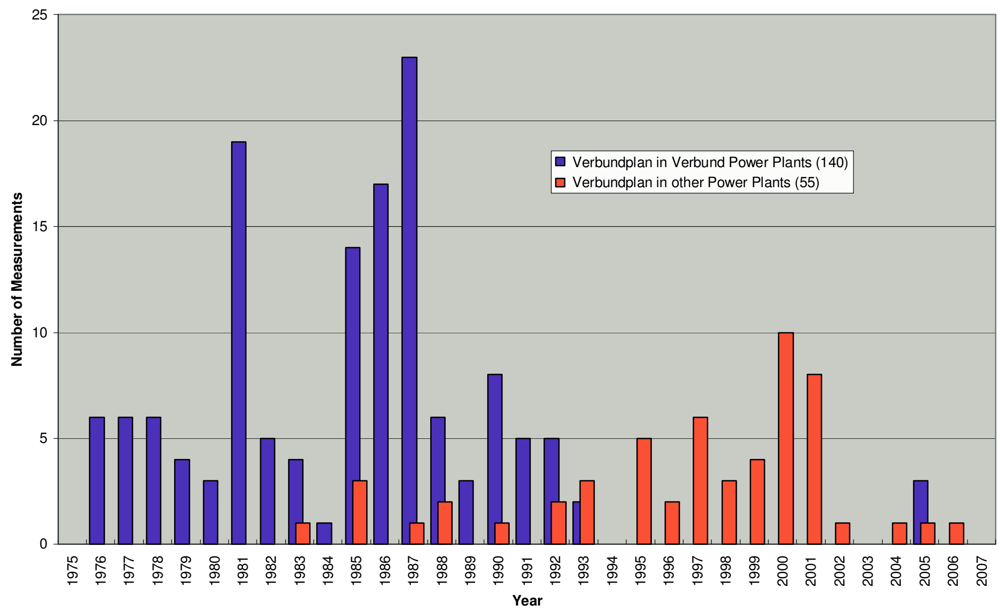
Graph: Corrective measures

The necessary corrective measures are enormously especially in the range of low output, due to the fact that the flow takes a long time between the two measuring sections.

In principle it can be said that in case of unsteady temperature of the water flow the method of partial expansion is not applicable because a correction as indicated in the IEC 41 practically is not possible. In these cases the direct method has to apply.

4 CONCLUSION

Since Verbundplan GmbH´s involvement with thermodynamic efficiency measurements, up to now totally 195 measurements have been carried out successfully. In 2005 Verbundplan GmbH procured a new measuring equipment and started to apply the direct method.



Graph: Verbundplan GmbH´s activity in thermodynamic efficiency measurements

Both methods, partial expansion and direct method were presented by some executed measurements.

One most important result derived from our experience is that the partial expansion method is not applicable in case of unsteady upstream water temperature.

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