A new Measurement and Data Acquisition System for Field Acceptance Tests using the Thermodynamic Method

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Introduction

Efficiency is among the most significant factors that describe the quality of a hydraulic contour and plays an important part when a new power plant project undergoes a feasibility study or the possible gains of an upcoming refurbishment are debated. The guaranteed efficiency is almost always part of the contract between turbine supplier and costumer and is often penalized with a liquidated damages clause. While predicting efficiency by model testing and CFD analysis already provides reliable results, a final field acceptance test is often required to verify the efficiency of the installed system.

While most efficiency testing methods state the efficiency as hydraulic-to-electric power ratio, the thermodynamic method uses the adiabatic state change of water as basis for the determination of efficiency. This allows eliminating the need of a precise discharge measurement, an issue that limits the accuracy of conventional efficiency measurements.

Since the first efficiency tests following the thermodynamic method were carried out in the 1920s, digital systems have revolutionized science and did not stop at measurement technology. At the laboratories of the Institute of Hydraulic Machinery at Graz University of Technology, Austria, a new measuring system was developed and benchmarked to define the actual range of application for the thermodynamic method.

Scientific Background and Impact Factors

During a conventional efficiency test the relevant measured variables are discharge “Q”, generated power “P”, inlet pressure “p_1” and outlet pressure “p_2”. Additional, density “ρ” is the only specific value of water which is needed.

For the thermodynamic method it is required to identify the change of the specific internal energy “dU” and external energy “dE_a” of the water passing through the hydraulic machine set. The specific internal energy of a one-phase fluid is always defined by two intensive properties. Hence it is possible to describe the internal energy in correlation with pressure and temperature.

$$dU = dU(p,T) = a \cdot dp + c_p \cdot dT$$

To determine the external energy, mainly specific kinetic and potential energy, given by flow velocities “v_1”,”v_2” and geodetic levels “z_1”,”z_2” at both considered measurement sections, are required. Although the determination of the flow velocity equivalents a discharge measurement, the low requirements concerning accuracy to achieve a good overall result will be shown later in this paper.

Beside density, two further water specific values are required in the thermodynamic method. While the specific heat capacity “c_p” is best known from a wide range of appliances, the so called isothermal factor “a” describes the gradient of the specific enthalpy over the pressure at constant temperature.

To describe the adiabatic state change, the internal energy can be formulated as a function of pressure and entropy “s”. As entropy does not change during an adiabatic state change, the change of the internal energy equals the specific hydraulic energy.

$$dU_{is} = dU(p, s = const) = \frac{1}{\rho} \cdot dp$$

According to international standards, the change of internal and external energy of the tested turbine will be summarized as mechanical energy “E$_m$” while the available energy given by the reference process will be named hydraulic energy “E$_h$”.

$$E_m = a \cdot \Delta p + c_p \cdot \Delta T + \frac{{v_1}^2 - {v_2}^2}{2} + g \cdot \Delta z$$

$$E_h = \frac{1}{\rho} \cdot \Delta p + \frac{{v_1}^2 - {v_2}^2}{2} + g \cdot \Delta z$$

The efficiency can be calculated by the ratio between mechanical and hydraulic energy.

$$\eta = \frac{E_m}{E_h}$$

To investigate the impact of the uncertainty inherent in each measurand and material property, a full error analysis was carried out.

$$\Delta\eta = \sqrt{\sum_{i=\Delta T, \Delta p, v_1, v_2, \Delta z, g, \rho, c_p, a} \left(\frac{\partial \eta}{\partial i} \cdot \Delta i\right)^2}$$

To illustrate the results, they are represented for a fictive hydro power plant (head “H”=100m, power output “P”=10 MW, efficiency “η”=94%) assuming a water temperature at the intake of 10°C. This would lead to a temperature increase of approximately 9mK. The impact on the resulting accuracy assuming a deviation of 1% at all impact factors are shown in Figure 1. While 1% uncertainty in measuring differences in pressure “Δp”, temperature “ΔT” and level “Δz” show approximately the same influence on the result, flow velocity is of minor importance. Therefore a precise determination of the flow velocity, respectively discharge, is not necessarily needed. The significant impact of the fluid properties density and isothermal factor has to be highlighted.

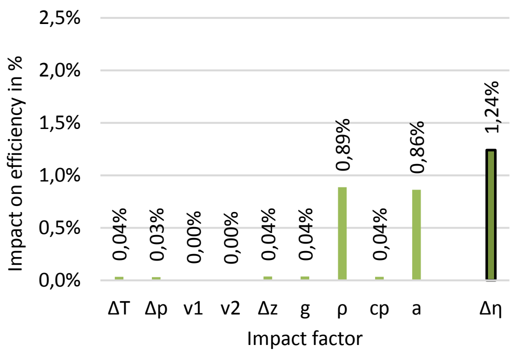

Figure 1: Error propagation on efficiency of a 100m head power plant anticipating 1% uncertainty per measurand

The data derived from Figure 1 indicates that a 1%-precision on all required data (measurement plus material data) will allow to determine efficiency with an overall precision of less than 1,24%, which is mainly determined by density and isothermal factor. Using the values for systematic uncertainties that can be expected under normal conditions according to IEC 60041, it can be observed that the achievable precision is mainly limited by determination of the temperature difference (Figure 2).

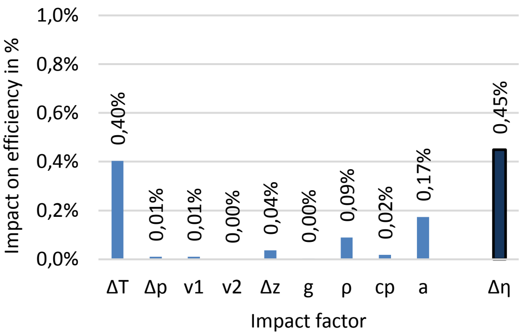

Figure 2: Error propagation on efficiency of a 100m head power plant – systematic uncertainties acc. IEC 60041

Furthermore, the impact of fluid properties cannot be neglected and have to be considered.

In the light of these results, the Institute of Hydraulic Fluid Machinery at Graz University of Technology started to develop a measurement and data acquisition system for field acceptance tests focusing on temperature measurement.

Measurement and Data Acquisition System

The guiding principle during the development of the new system was to achieve a maximum of flexibility concerning change and extension of application fields without making concessions related to accuracy and reliability. In accordance to this principle, a CompactRIO (cRIO) platform from National Instruments is forming the heart of the system (Figure 3).

The cRIO fulfils the requirement of reliability by providing an on-board real-time processor for communication and signal processing. The embedded system allows the execution of predefined measurement programs without using any additional hardware, while it is still possible to access the system during operation by any network device (e.g. laptop or tablet) to read or set data from/to the system.

Figure 3: cRIO Measurement and Data Acquisition System

In order to take full advantage of the connected sensors and transducers, a user-programmable FPGA connects the A/D-modules to the processor. While the A/D modules provide raw signals (e.g. bit, byte or integer), the FPGA allows custom timing and triggering directly in hardware to simultaneous convert the information from all A/D-models into processable information. The simultaneousness happens on a one-tick scale, allowing all input signals to be forwarded within a single 25ns clock-tick. This feature is of decisive importance when it comes to parallel frequency measurements on multiple channels in order to compensate the variation of the time base.

Temperature Sensors and Signal Processing

The system was designed to connect up to 16 temperature probes type SeaBird SBE 3S. These sensors were initially developed for oceanographic monitoring purposes, hence they are designed to withstand high pressures and harsh environmental conditions without taking damage. The sensing element is a glass-coated thermistor bead, functioning as controlling element in an oscillator circuit. The oscillator frequency is proportional to the temperature and can be defined with an accuracy of 1mK by the supplier. This accuracy is primarily limited by the fact that the International Temperature Scale (ITS-90) is based on a set of fix points, which only allow an accuracy between 0,2mK and 3mK (e.g. Triple point of water).

To enhance the accuracy for the purpose of measuring temperature differences rather than absolute temperatures, the developed system allows measuring a difference in frequency with an accuracy of 35ppm. This allows reducing the systematic error in temperature difference caused by the master clock error of the acquisition system to 5µK. With a typical calibration residual of less than 100µK, the overall accuracy for measuring temperature difference could be defined by 0,1mK.

Physical Properties of Water

As the initial analysis of impact factors shows, the properties of water, mainly density and isothermic factor, have a significant effect on the overall accuracy of the measurement.

It is proposed in the IEC 60041 to use material properties derived from the empirical equation of state for the free enthalpy of water, formulated by Herbst and Rögener.

The International Association for the Properties of Water and Steam (IAPWS) issued a formulation for the thermodynamic properties of water in 1997. This “Industrial Formulation” (IAPWS-IF97) provides a closed equation for a wide pressure and temperature range and surpasses the accuracy of Herbst and Rögener’s formulation significantly.

Using a powerful tool as the embedded processor in the NI cRIO, the handling of IAPWS’s 34th grade polynomial equation using more than 100 coefficients can be done easily.

Expected Accuracy

Alongside with the above mentioned improvements on measuring temperature differences and physical properties in use, the pressure transducers were calibrated using a dead weight manometer. The calibration included the whole measurement chain to cover systematic errors of pressure transducers and A/D converters alike.

Taking all these efforts into account, it was possible to decrease the uncertainty in the efficiency measurement significantly. Applied on the fictional 10 MW power plant introduced before, this results in an excepted uncertainty of only 0,10%. An analysis of the distribution on the impact factors is shown in Figure 4.

Comparing the influence of the impact factors with those derived from IEC (Figure 2), the uncertainty originating from temperature differences measurement and physical properties is significantly decreased.

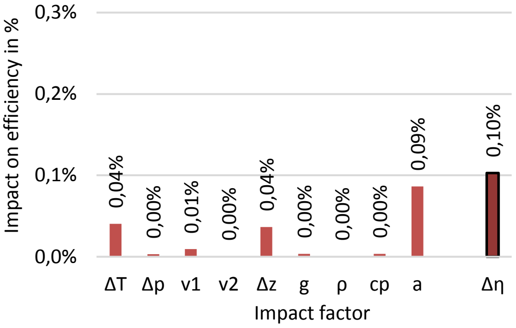

Figure 4: Error propagation on efficiency of a 100m head power plant – systematic uncertainties of the developed system

Validation Measurements

The first step in the validation process was to ensure the accuracy in measuring the temperature difference. Therefore the full equipment was tested in an external laboratory specialized on measuring physical properties of fluids. By measuring the temperature in a low gradient water bath at different temperatures, a maximum deviation of less than 0,1mK could be verified (Figure 5).

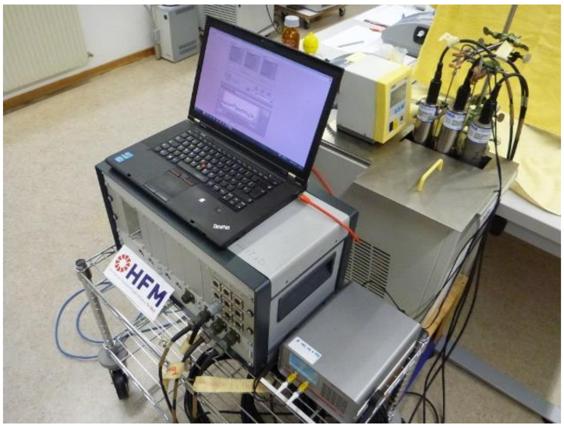

Figure 5: Verifying the maximum error in temperature difference measurement

To validate the theoretical approach on the complete system’s accuracy, a test rig for a speed adjustable multi-stage pump was established. The setup of the rig is shown in Figure 6. Besides the necessary instrumentation for the thermodynamic method, the test rig was also equipped with a system for conventional efficiency measurement. Therefore a torque measuring shaft was fitted between the pump and the motor. An optical probe for measuring the rotational speed was installed at the non-drive end to verify the speed set by the variable frequency drive.

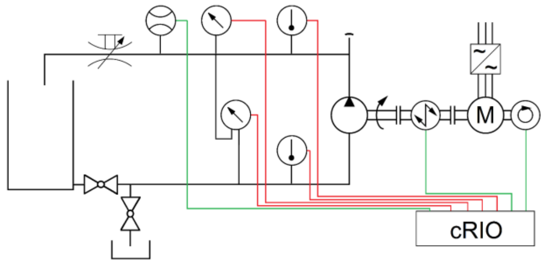

Figure 6: Test rig setup showing instrumentation for the thermodynamic method (red) plus additional instrumentation for reference measurements (green)

The discharge was measured by a magnetic flow meter installed on the high pressure side of the pump keeping sufficient distance to all fittings and installations to provide precise results.

In order to reduce the impact factors, both measuring sections were aligned horizontally ($\Delta z=0$) and realized with same cross section areas ($v_1=v_2$). Secondary impact factors like extraneous heat exchange and variations of temperature where taken into account as well.

By adjusting the speed of the pump it was possible to perform measurements in a wide range of heads from 169m down to 15m.

The results of the executed measurement campaign support the analytical investigation on the systems accuracy (Figure 7). The deviation between hydraulic efficiency, calculated by the thermodynamic method, and overall efficiency obtained by the conventional measuring system, originates in losses from the bearing, placed between pump and torque measuring shaft. The losses of this bearing were calculated by the supplier and fit to the actual difference between hydraulic and overall efficiency.

The measurements were done over a period of several weeks and repeatedly rerun with different sensor arrangements to ensure the reproducibility of results.

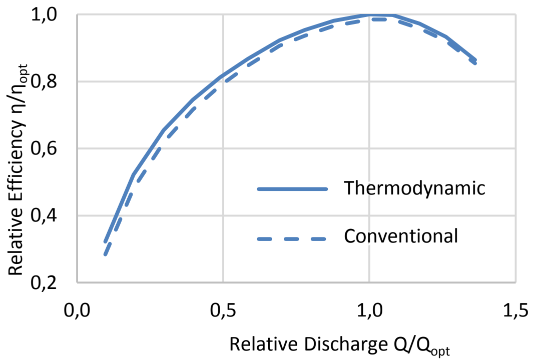

Figure 7: Comparison between measuring results gained by the thermodynamic method (full line) and a conventional method (dashed line)

At low heads, in particular below 25m, results obtained by the thermodynamic method start to deviate from the overall efficiency. When showing the hydraulic efficiency on a characteristic map (Figure 8), it is obvious that low heads show a not feasible behavior regarding efficiency which results from the increased uncertainty. The lowest head limit where it was possible to achieve repeatable results deviating less than 1% was 25m.

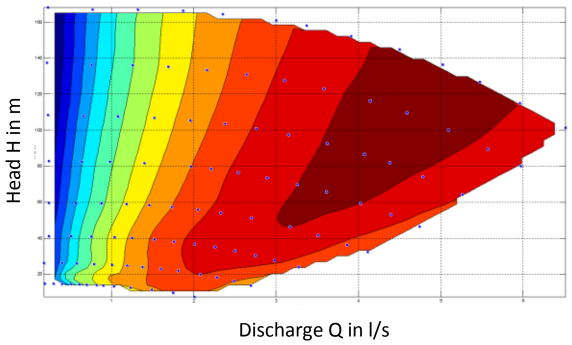

Figure 8: Characteristic map of the tested pump including isarithms for hydraulic efficiency

Application for Field Acceptance Tests

After the completion of the laboratory testing, the approved system was taken into the field. In cooperation with two Austrian power supply companies, efficiency tests were performed at three different hydro power stations (Figure 9).

Figure 9: Instrumentation for thermodynamic method on the inlet side

To cover the full variety of application three different types of turbines where tested:

- Vertical Francis (306m, 28MW)
- Vertical Pelton (224m, 12MW)
- Horizontal Pelton (810m, 68MW)

The measurements were performed according to IEC 60041.

Each measurement campaign could be completed within one day including repeating measuring points to prove the reproducibility of results. Due to the immediate feedback provided by the system, any irregularities or deviations during recording a measuring point could be quickly identified. As all necessary parameters are logged in one single device, the cRIO, post processing can be directly implemented and happen on site to provide a full table of results immediately.

Summary and Further Research

Reducing the uncertainty of temperature difference measurement by using a fully tuned system allows to increase the achievable precision of efficiency measurement significantly. Together with critical questioning the origin of physical properties used for calculation it was possible to decrease the average uncertainty in determining the efficiency from 0,45% to 0,10% on a 100m head hydro power plant.

Using one single system for data acquisition, data logging and data processing allows to significantly reduce time in the post processing and report generation as well as allows to identify faulty measuring points or invalid measuring conditions already during the measuring period. Furthermore data synchronization is automatically achieved and traceability as well as transparency give no point of vantage in case of disagreements on the result.

While the development of the measurement equipment itself is well advanced, more research has to be done according measurement procedures. This will include an approach on the number of necessary mapping points in the tailrace as well as on the correction factors. Mapping the distribution in the tailrace should not only consider temperature but also flow velocity to determine the average transported energy rather than the average temperature.

References

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Nomenclature

a	[m³/kg]	Isothermal Factor	
c_p	[J/(kg·K)]	Specific Heat Capacity	1 J = 1 kg·m²/s²
E	[J/kg]	Specific Energy	
g	[m/s²]	Gravitation	g_{norm} = 9,81 m/s²
H	[m]	Head	
P	[W]	Power	1 W = 1 J/s
p	[N/m²]	Pressure	1 N/m² = 10^{-5} bar
Q	[m³/s]	Discharge	1 m³/s = 1000 l/s
s	[J/(kg·K)]	Specific Entropy	
T	[K]	Temperature	
U	[J]	internal Energy	
v	[m/s]	Flow Velocity	
z	[m]	Geodetic Level	
η	[-]	Efficiency	
ρ	[kg/m³]	Density	

Indices

1	High Pressure Side
2	Low Pressure Side
h	Hydraulic
m	Mechanical
is	Isentropic

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