IEC 60041 – 1991, "FIELD ACCEPTANCE TESTS TO DETERMINE THE HYDRAULIC PERFORMANCE OF HYDRAULIC TURBINES, STORAGE PUMPS AND PUMP-TURBINES". CLAUSE 14 "THERMODYNAMIC METHOD FOR MEASURING EFFICIENCY" COMMENTS

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INTRODUCTION

Since the last revision of the test code IEC 60041 - 1991 there has been a large development in instrumentation and computers, and a lot of test experience has been gained. Some of the recommendations in the code were important because of insufficient accuracy and repeatability of the earlier instrumentation, as the code states in 14.1.3 "Instrumentation" that "the apparatus presently available varies widely and may possibly become obsolete in the future". The introduction of new instruments and equipment may also introduce new problems not addressed in the present code.

Anyway, our goal is to start a discussion that can be useful input to the committee that shall revise the code – some time.

In this paper we have discussed some topics regarding the thermodynamic method that should be changed in the next revision of the code.

The numbering of chapters in this paper refers to IEC 60041.

14.1   General

14.1.2   Excluded topics and limitations

Due to the lack of uniformity in values measured at the reference sections of the machines, the limitations of measuring equipment and the relatively high magnitude of the corrective terms originating from the imperfect measuring conditions, the range of application of this method is limited and can only be used for specific hydraulic energies in excess of 1000 Jkg-1 (heads in excess of 100 m). However, under highly favorable conditions, the range could be extended to cover lower specific hydraulic energies (heads) subject to an analysis of the accuracy of the measurements.

The lower head limit for application of the thermodynamic method for precision efficiency measurements is important. The method is by far the most cost effective one when applicable, so it is important to have the possibility to use it when the conditions are really favorable. The limiting factors are:

- the temperature measurement (thermometer sensitivity and stability)
- the temperature stability of the inflowing water
- the temperature distribution across the measuring sections
- the experience and judgment of the test engineer

During the last decade thermometers with high accuracy and superb stability have become available, and the analog to digital converting instruments are very reliable and accurate, see f. instance ref [11].

The temperature stability of the incoming water can be a serious problem at shallow intakes with stratified water, and when the water passages in addition are large and relatively short, the measuring conditions can be too difficult — even if the head is well above 100 m. On the other hand, "highly favorable measuring conditions" often occurs with deep intakes and moderate cross section of the water passage, - ref. [5] [6] [7]. In cold climates with ice on the reservoir the conditions may be very stable and yield reliable results at heads far below 100 m.

To judge if the measuring conditions are *"highly favorable" (according to the code)* can be a challenge to the Chief of test. From our experience there are many pitfalls when doing thermodynamic measurements at low heads. It is easy to underestimate the systematic uncertainties, and for guarantee measurements there may be disputes if the guarantees are not met.

The use of computers and data acquisition systems has made the handling of many simultaneous temperature measurements easy, so detailed investigation of the energy distribution at the turbine outlet is relatively easy.   Thus, a major source of systematic errors has been reduced.

Taking these facts into account, we may ask if the limit still should be 1000 Jkg^{-1} (100 m), or could it be lowered to 800 Jkg^{-1}? Performing a thermodynamic measurement at 80 m head with an uncertainty of ± 1.5% is clearly a good option to other more expensive and time-consuming measurement methods, - even if some additional thermometers and a more comprehensive uncertainty analysis are required.

Our recommendation, though, is to leave the text in the code unchanged, alternatively add a few words to the last sentence so it will be less subject to interpretations:

However, under highly favorable conditions and if both parties agree, the range could be extended to cover lower specific hydraulic energies (heads) subject to an analysis of the accuracy of the measurements.

14.3   Procedure for measurement of specific mechanical energy

14.3.1   General

> *Due to the difficulties inherent in measuring directly in the main flow, the quantities defining E_m may be measured in specially designed vessels [...]*

Temperature measurements in an insulated measuring vessel with water tapped off the main flow is undoubtedly the best, but immerging the temperature sensor directly into the flow has been done in some cases. The consequences of such an installation could be useful to mention in the code.

At the turbine inlet the velocity is high – about 10 m/s. In ref. [3] it is shown that the impact of viscous heating may be very high and cause considerable deviations from the real temperature. We therefore suggest adding a warning in the code in order to limit the use of temperature probes directly immersed into the main flow. Ref. [3] also gives a correction formula to be used in this case. This correction formula is empiric, and we suggest to set restrains to the use of thermometers directly in the main flow rather than to allow the use of a somewhat uncertain correction formula. The correction formula may be given in an appendix.

The velocities at the turbine outlet are usually low – about 2 m/s. The error in temperature reading due to viscous heating at 2 m/s may be in the magnitude of 2 mK (or 0.8% efficiency at 100 m head). It is therefore advisable also to use some kind of "measuring vessel" with thermometer(s) collecting water samples from a series of sampling orifices, - see 14.4.1.1 below.

We propose the following warning to be put in 14.3.1.:

Direct measurements of the temperature using temperature probes directly immersed into the main flow should be done with great care, as the thermometers may get additional heating by fluid friction and deformation of the temperature profile. At velocities up to 1.5 m/s the additional heating of the probe is less or close to 1 mK. The additional heating of the temperature probe may be over 20 mK at velocities of 10 m/s.

This method (direct measurements of the temperature using temperature probes directly immersed into the flow) should not be used for velocities above 1.5 m/s, and never for heads below 200 m.

14.3.2 Direct operating procedure

[…]

The thermometers shall be calibrated beforehand (see 14.3.4). Whenever this procedure is adopted, the partial expansion operating procedure (see 14.3.3) for one test point or in situ calibration of the thermometer will be undertaken for checking purposes.

This "beforehand" calibration obviously means calibration at site, but the thermometers for thermodynamic efficiency measurements have to be lab-calibrated beforehand, and a certificate and a record for each thermometer should be required. The mentioned "one point partial expansion" or "site calibration by full expansion" will just be for checking purpose as stated in the code text.

The benefit from doing one test point with the partial expansion operating procedure is far from obvious, because the partial expansion operating procedure has some serious shortcomings, - see below.

Our recommendation is to change the text in 13.3.2. by taking out the whole sentence.

14.3.3 Partial expansion operating procedure

This procedure had its advantage when small, robust thermometers (accurate and stable) not were available. Temperature equality, however, could be determined by having two platinum resistance thermometers in a Weatstone's bridge with galvanometer. By throttling the sampling flow from the pressure side to the measuring vessel the pressure drops and the temperature increases in the insulated vessel. With accurate adjustment of the throttling valve (expansion valve) points with nearly temperature equality between vessel and tail water can be found. By taking several readings of Δp and $\Delta\theta$ (galvanometer reading) and interpolating, the point of temperature equality is found. When the temperature difference is zero, the temperature term becomes zero and the mechanical energy E_m essentially entails the pressure term.

Disadvantages of this procedure are (from Ref. [8]):

- It takes time to adjust the expansion valve, to do the Δp and $\Delta\theta$ readings, readjust valve and take new readings, and so on until there are enough for interpolation – usually 4 points.
- If there is temperature variation (usually with variable gradient) in the inlet water over time, a good correction is difficult. Stable temperatures are preferred for this procedure. Automatic data acquisition can only be applied to a limited extent.
- Survey of energy distribution across a measuring section by using more thermometers is impossible – only one thermometer per measuring section can be used.
- The insulated piping, expansion valve and measuring vessel are very sensitive to heat exchange and require special attention.

Our recommendation is to describe the "Direct operating procedure" as the primary procedure, and to place the "Partial expansion operating procedure" in an Appendix or remove from the code.

14.3.4 Thermometer calibration

For the application of the direct operating procedure described in 14.3.2, the temperature- difference thermometer must be calibrated. […]

The reading of the differential thermometer for a zero temperature difference must be checked over a total range, which includes the water temperature in the penstock, of 5 K. For this the two thermometer probes are placed together in water baths of at least three different temperatures within this range.

In the code text the use of full expansion between two insulated vessels is considered as an "in situ calibration" of the thermometers. But even if the full expansion method is used, it cannot be a substitution

for a lab-calibration of the thermometers, and the lack of calibration may give erroneous measurements. If the "full expansion thermometer check" is applied, it should preferably be done without the turbine in operation to avoid disturbing variation of the inflowing water. Such a two-chamber apparatus is very sensitive to heat leakage and requires special attention. Therefore the part of the text describing this calibration method should be taken out of the code.

A good way of checking the thermometers is to exchange the high and low pressure thermometers for one or more measurement point. By doing this some of the systematic uncertainties may be accounted for.

The text in 14.3.4. should have the "throtteling metod" for calibration removed and two sentences added,:

The thermometers used to measure the temperature difference should be calibrated in an accredited laboratory before the measurements.

For low heads it is useful to check the thermometers by exchanging the high and low pressure thermometers for one or more measurement point(s).

14.4   Apparatus

14.4.1   Main measurements

14.4.1.1 Sampling water circuits

All active elements of the hydraulic circuits (pipes, expanders, vessels) shall be carefully insulated so that the sampling flow is of constant total energy .Any imperfections in the thermal insulations shall be taken into account by the following procedure [...]

The above check shall be made for all points of the efficiency curve. [...]

The thermal insulation of a measuring vessel and its connecting piping is a physical property of the vessel with connections. It does not change from test point to test point.

It has to be noted that this insulation check procedure requires that the measuring conditions are good. If there are difficult measuring conditions (fluctuating inlet temperatures and/or pressures or other instabilities), performing this check procedure may introduce errors in the efficiency measurement. A better approach would be to carry out the insulation checks for the measuring vessel under stable conditions (at a stable test point) to prove the heat exchange characteristics.

Some vessel designs, see **Figure 1**, have very little, if any, heat exchange with the surroundings, as the thermometer is well inserted into the sampling probe which is surrounded by the main flow.

The pressure at the temperature sensor in the measuring vessels should be measured simultaneously with the temperature, in order to have a correct mechanical energy. This is only possible when the direct operating procedure is applied.

We propose the following addition to 14.4.1.1:

The measuring vessel should be shown to have small values of heat exchange with the surroundings. If the check of heat exchange is required the measuring conditions should be good, else addition errors may be introduced. If the conditions are unfavorable the insulation quality of the vessel can be documented by a record of checks being conducted on that particular vessel.

The following text should be taken out:

The above check shall be made for all points of the efficiency curve. However, if the correction is in the order of 0,2 % on efficiency, the number of measuring points for which these auxiliary measurements shall be made may be reduced by mutual agreement.
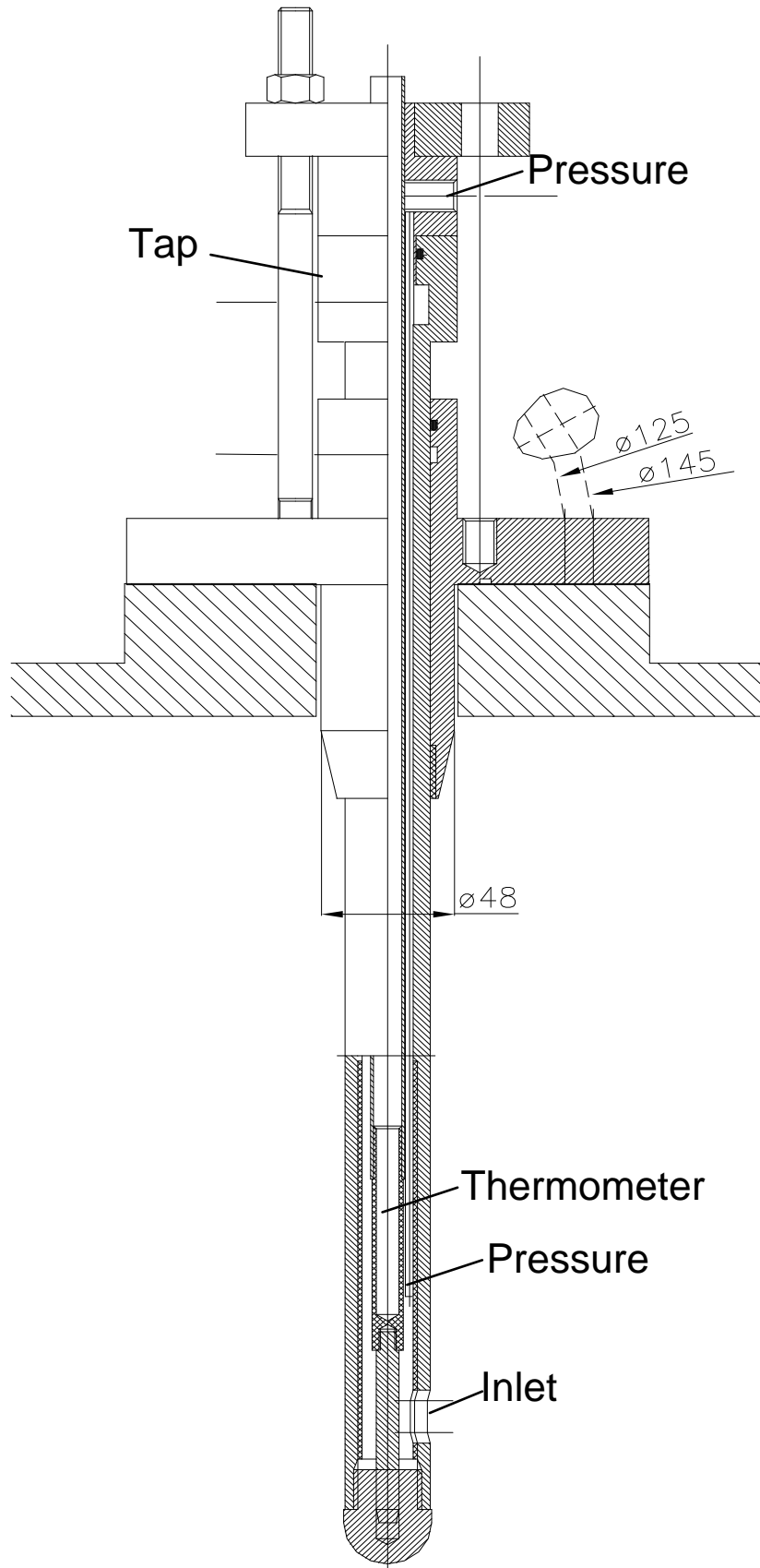
Pressure

Tap

ø125
ø145

ø48

Thermometer

Pressure

Inlet

Figure 1 Measuring vessel

14.1.1.2 Pressure measurement

Under sub-clause 11.4 "Pressure measurements", 11.4.6 "Measuring apparatus" says: *Liquid column manometers and dead weight manometers are considered as primary instruments.* 11.4.7 "Checking of pressure gauges" says in 11.4.7.2 "Comparison with primary measuring instruments":

> *Spring gauges and pressure transducers must be checked at least over the measuring range during the test against primary instruments (see 11.4.6) or by comparison with water levels.*

This implies that a dead weight manometer should be brought to the site, or a static water level should be established by stopping the hydraulic machines and measure the water level elevation. For practical reasons the dead weight manometer (which normally is a lab-instrument) is normally avoided, - and it is not always possible to shut down all units in a plant due to operational obligations, and there is usually only one head-water level available. However, today's high-precision pressure transducers are very long-term stable. The primary lab-calibration is checked at site when static water levels can be established, and the deviation from calibration is very small. A record of lab-calibrations and site checks is therefore made to document the stability of each instrument.

In the text of 14.4.1.2 the following should be added:

High-precision pressure transducers with record of primary calibrations and calibration checks may be used. A lab-calibration after test may be recommended on special occasions.

14.5   Test conditions to be fulfilled

14.5.1   Measuring sections and sampling conditions

14.5.1.2 Low pressure measuring section

14.5.1.2.1 Open measuring section

> *Exploration of temperature variation across the measuring section shall be made in at least 6 points. […]*

The variation of temperature across the measuring section is considerably larger on the low-pressure side than on the high-pressure side of a turbine. The effort is therefore put into the determination of temperature distribution on the low-pressure side.

There are different ways of taking water samples for temperature measurement from different locations in the measuring section. Here are three principles described:

- Fixed sampling pipes (often 3) with sampling orifices are connected to a common mixing and measuring chamber with temperature sensor and discharge pipe. The location and size of the sampling orifices are designed to account for the head loss in the sampling pipes. The discharge pipe is located in a point of the measuring section where the flow is positive independent of turbine discharge. This arrangement has been used particularly for Francis turbines where the fixed frame cam be installed behind a closed draft tube gate.

- Another way is to use a central mixing/measuring chamber with temperature sensor and horizontal sampling pipes from 4 or more points distributed over the canal width, and this horizontal "sampling beam" is held in different depths to get the vertical temperature variation. The sampling beam is supported by to vertical steel wires pre-tensioned from the sill to the lintel or bridge above, - see **Figure 2**.

A third method is to have 3 or more vertical perforated pipes from the canal bottom up to a bridge over the tailrace, and one or more temperature sensors can be placed in various elevations in each of the pipes to get the temperature variation over the measuring section, - see **Figure 3**.
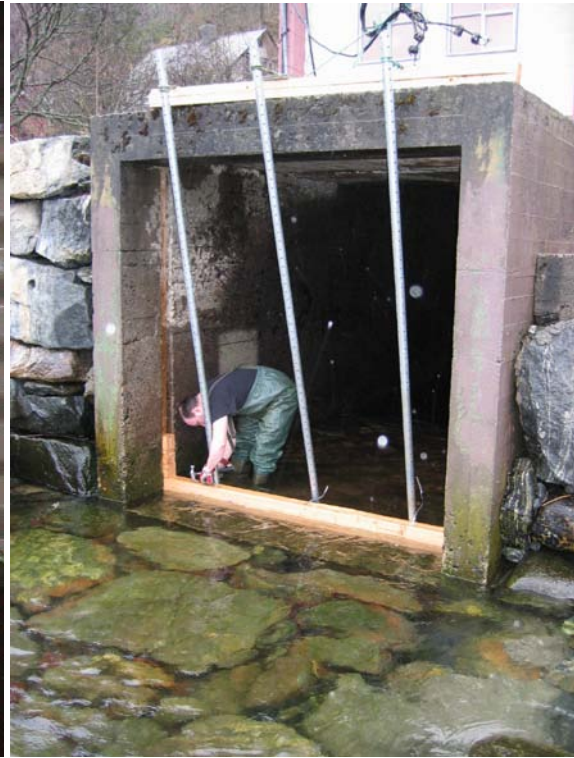
Figure 2 Horizontal "sampling beam"   **Figure 3 Vertical perforated pipes**

It is useful to have the temperature from each measuring / sampling point in the section to be able to carry out a statistical analysis of the deviations, but that is only possible for the third method. With the first method a mixing of all the samples is done in the pipes and the mixing chamber, so no knowledge about deviations between points is available. The second method provides information about the temperature deviation between the vertical positions of the sampling beam, but it is impossible to document how good the "hydraulic averaging" in the beam is at each vertical position.

However, the principle of "pitot sampling" given in the two first cases is very useful, as the amount of water sampled into the pipes are proportional to the water velocity. The measured energy is therefore very close to the average. In ref. [4] it is shown that there is a good agreement between multipoint measurements and sampling frames.

Thus there is little doubt about the "hydraulic averaging" in the pitot sampling arrangement compared to a numeric averaging of multipoint measurements. The code's requirement of at least six points is considered to be met with the pitot sampling arrangement.

14.6   Corrective terms

14.6.1   Variations of temperature

The variation of temperature over time is a problem that is compensated for by logging the temperature gradient over a period and calculating the travelling time between the two measuring sections. By continuously monitoring the temperature gradient it is possible to measure the temperature difference between the two sections when the gradient is close to zero over a sufficiently long period of time.

The maximum gradient of 5 mK/min has been discussed several times, but long experience tells that when the gradient is so steep there might be other problems from inhomogeneous water masses causing larger temperature variation across the measuring sections. Therefore the maximum gradient defined in the code should be kept.

14.7   Uncertainty of measurement

The systematic uncertainty due to the absence of exploration of energy distribution.

In 14.7 "Uncertainty of measurement" it is stated that systematic uncertainty due to *absence of exploration* of energy distribution can amount to ± 0.6 % of E_m on the low pressure side of a turbine. It is not clearly said that "absence of exploration" means water sampled from only one orifice in the measuring section, but it is likely to believe that. However, a clarification is required, because the figure ±0.6 % of E is often used in the uncertainty calculation even if samples are taken from 6 points or more.

By applying the uncertainty of ± 0.6% of E_m for the low pressure side, inappropriate levels of uncertainty may be the result. This is illustrated in Figure 4. Ref [2] shows that this value (i.e. ± 0.6%) underestimate the efficiency uncertainty at low heads and overestimate the efficiency uncertainty at high heads.

As systematic uncertainty by its nature is unknown, it is impossible to estimate the true value of this. We really do not want to underestimate this uncertainty, as it will be expensive for turbine manufacturers to pay unfair penalties. On the other hand, an overestimation may be expensive due to postponing of profitable rehabilitations for the plant owner.

For the high pressure side the code suggests an uncertainty of ± 0.2% of E_m due to absence of exploration of energy distribution. That seems more realistic according to ref. [9], even if an uncertainty expressed in mK would be preferred.

The energy distribution will be better mapped using more thermometers, but there are of cause practical limits. In ref [4] it is shown that using 6 thermometers at a head of 130 m the uncertainty level is within ±0.6% (2σ).

In cases where temperatures in 6 or often 9 points are measured, we have sometimes for Pelton and high head Francis turbines made an agreement with the parties that the maximum deviation between temperature measured at different points can been used to characterize the uncertainty. The measured maximum deviation is multiplied with a factor of for instance 1.5 to have the temperature uncertainty to be used in the calculation of uncertainty of efficiency, and a minimum figure of temperature uncertainty for the calculation is set at ± 2 mK.

This approach is possible for the third method mentioned under our discussion in 14.5.1.2.1, but more complicated for the two others. Some correlation between method 2 and 3 was however presented in ref. [10]. Statistical models based on further research could bring interesting and useful results.

The systematic uncertainty due to the absence of exploration of energy distribution should be determined using a <u>constant temperature difference uncertainty</u> rather than adding a constant percentage of E_m as stated suggested in the code today. The level of this temperature uncertainty has to be discussed more closely in general before new figures are put in the code.
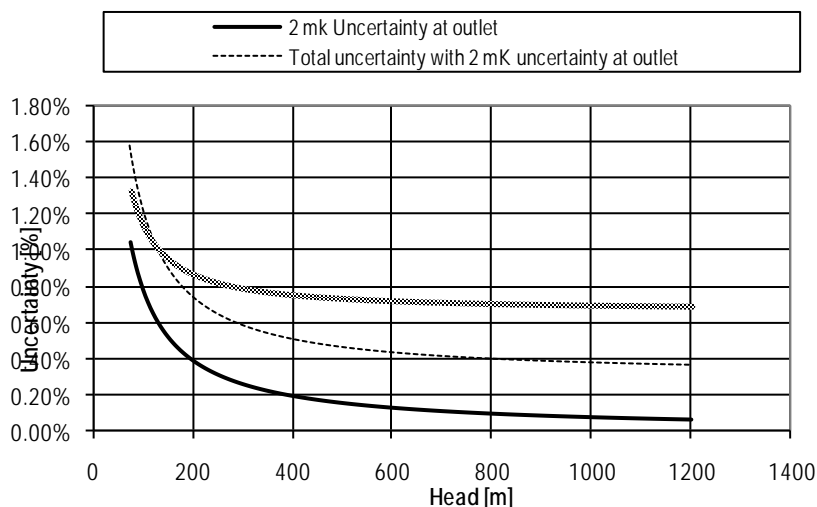

Figure 4   Example of uncertainty levels (% efficiency) versus hydraulic head (m)

Summary

The table below gives a short overview of the issues commented in this paper.

Chapter	Issue	Suggestion
14.1.2 Excluded topics and limitations	Minimum head limit for thermodynamic method	100 m is lower limit in general, but lower when agreed by both parties
14.3.1 General (E_m measurement)	Temperature sensor directly in main flow	Warning about viscous heating of temperature sensor
14.3.2 Direct operating procedure	One point with partial expansion operating procedure	Take away "one point partial expansion" – no benefit
14.3.3 Partial expansion operating procedure	Method with several short-comings.	Move description of method to Appendix
14.3.4 Thermometer calibration	In situ calibration with full expansion between two insulated vessels	Not practical today when using stable and accurate thermometers with lab calibration and site checks.
14.4.1.1 Sampling water circuits	Check heat leakage from sampling circuit for each test point	Not required, - check only for one point under stable conditions, or document thermal properties of vessel
14.4.1.2 Pressure measurement	Dead weight manometers or water column for calibration of pressure transducer	Not practical today with stable and accurate pressure transducers with lab calibration and site checks vs. static head.
14.5.1.2.1 Open measuring section (low pressure side)	Exploration of temperature variation across measuring section	"Hydraulic averaging" equivalent with numeric, but problem to determine deviation between points
14.6.1 Variation of temperature	Steepest acceptable gradient 5 mK/min	OK
14.7 Uncertainty of measurement	The systematic uncertainty due to absence of exploration of energy distribution can amount to $\pm 0{,}6$ % of E_m on turbine outlet	This has to be clarified: does "absence of exploration" mean measurement in only one point? A method for calculation of systematic uncertainty due to variation of temperature is required. The uncertainty should be given as uncertainty in temperature rather than percentage of Em

References:

[1]   International Standard IEC 60041, "Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines", third edition, 1991-11.

[2]   "Thermodynamic Efficiency Measurements, The Uncertainty of Efficiency versus the Hydraulic Head", IGHEM Conference, Kempten 2000, by E. Bøkko, and L. Vinnogg, Norconsult AS.

[3]   "Applied thermodynamic method without drawing off fluid", IGHEM Conference, Kempten 2000, by H. Mesplou, E.D.F., Division Technique Générale.

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[8]   "Thermodynamic Efficiency Measurement – Method of Partial Expansion and Direct Method", IGHEM Conference, Portland 2006, Rudolf Fast, Michael Kundt, Werner Mayr, Verbundplan GmbH, Austria

[9]   "Thermodynamic Efficiency Measurement – The Energy Distribution in the Boundary Layer at the Turbine Inlet", IGHEM Conference, Montreal 1996, Leif Vinnogg, Norconsult AS.

[10]   "Thermodynamic Efficiency Measurements of Pelton Turbines – Experience from Investigation of Energy / Temperature Distribution in the Discharge Canal Measuring Section", IGHEM Conference, Milano 2008, Harald Hulaas, Erik Nilsen Leif Vinnogg, Norconsult AS and Eirik Bøkko, ECO Vannkraft.

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