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Thermodynamic Efficiency Measurements
The uncertainty of efficiency versus the hydraulic head

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SUMMARY

The distribution of specific mechanical energy in the flow entering and leaving a turbine is the most important point of uncertainty in thermodynamic efficiency measurements. The test code [1] suggests an uncertainty proportional to the hydraulic head of the machine. However, experience from field measurements of energy distribution in the inlet and the outlet section has shown that this uncertainty seems independent of the hydraulic head of the machine. It rather appears as if the maximum difference of mechanical energy within a measuring section is limited to a certain absolute amount. Other factors as uneven intake temperature distribution, hydraulic design of water passages, heat exchange with boundaries and velocity of flow are determining the distribution of specific mechanical energy in the measuring sections. By using the head-depending uncertainties suggested in the test code, the resulting uncertainty will be underestimated at low head and overestimated at high heads.

Introduction

The turbine efficiency η is the power output/input ratio of the machine. The input can be expressed as the hydraulic energy available to the turbine; specific hydraulic energy E (energy per unit mass of water passing through the turbine). The turbine output is the mechanical power delivered to the turbine shaft. According to the law of conservation of energy, the energy delivered to the shaft can be found as the difference in specific mechanical energy E_m between the inlet e_{m1} and the outlet e_{m2} of the turbine.

Measurement of specific hydraulic energy $E=g \cdot H_n$ is simply a determination of the turbine net head H_n. However, the thermodynamic measurement of the specific mechanical energy

$$E_m = e_{m1} - e_{m2} = a \cdot \Delta p + c_p \cdot \Delta T + 0.5 \cdot \Delta V^2 + g \cdot \Delta z$$

is more challenging. Orifices directed towards the flow are used to take water samples into heat insulated measuring vessels at defined elevations (z) where the internal pressures (p), temperatures (T) and velocities (V) in the vessels are measured. The gravity constant (g) and the physical properties of water, i.e. specific heat (c_p) and isothermal factor (a), are taken from tables in the test code [1]. The mechanical energy E_m is sometimes also called "total entalpy", which is entalpy i (= $a \cdot \Delta p + c_p \cdot \Delta T$) plus velocity and elevation terms.

The ideal procedure would be to explore the whole conduit cross section to find the average specific mechanical energy in a flow, but practical experience has shown that a limited number of sampling points are required. This is specified in the test code. The major uncertainty comes from the temperature measurements. The turbine inlet cross section normally has a quite even distribution of e_{m1}. The outlet, however, requires a more comprehensive survey over the cross section to find the average e_{m2}. This is described in the following two chapters.

Objective

The test code [1] chapter 14.7, says: *"The systematic uncertainty due to absence of exploration of energy distribution can amount to ± 0.2 % of the specific mechanical energy E_m on the turbine high pressure side, and ± 0.6 % on the low pressure side."* For practical reasons and to avoid discussions these figures are often used in the analysis of uncertainty, but there are reasons to believe that the uncertainties of mechanical energy distribution in the two measuring sections are independent of E_m ($E_m = \eta E$).

High pressure measuring section

Test results presented by Vinnogg [2] at the 1996 Montreal conference, indicate that an uncertainty of ± 0.2 % is relevant for heads above 200 m and smaller conduit diameters (less than about 2 m). It is, however, interesting to observe that the order of magnitude of the absolute uncertainties in the two tests presented (at 240 m and 470 m head) were nearly the same, less than 0.4 m wc (which is equivalent to about 1 mK in water temperature difference).

To investigate the energy distribution further, data from 12 different field tests using two tapping points at the high pressure measuring section, has been analysed.

The test head varied from 50 m to 380 m. The conduit diameter covered the range from 1.80 m to 3.40 m. The sampling probes have been located between the turbine shut off valve and the spiral case/distribution pipe inlet. One sampling probe has been installed at the top of the conduit, the other one more or less diametrically opposite at the bottom of the conduit. The intrusion of the probes varied from about 0.07 D to 0.10 D.

The test results are presented in **Figure 1**, showing half the energy difference between the two tapping points. The specific energy E_m is converted to head of water H ($H = E_m / g$ where g is the gravity constant).

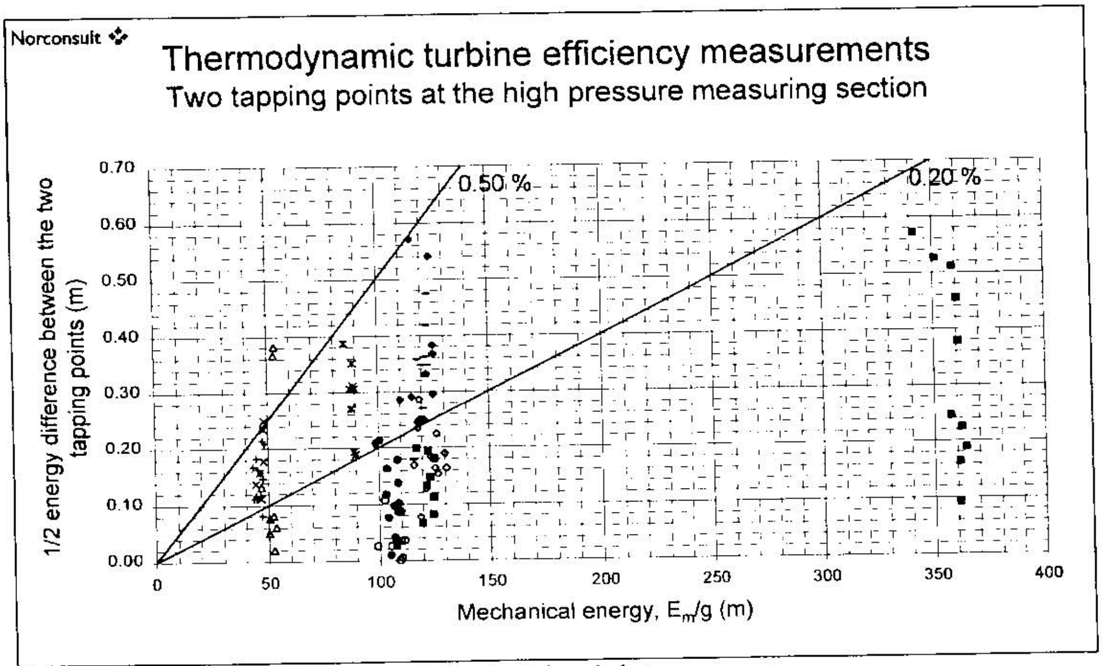


Figure 1 Energy differences at the turbine inlet

The energy difference between the two tapping points is largely determined by the two factors:

- hydraulic design
- inlet velocity

Bifurcation, bends etc. in the immediate upstream neighbourhood of the measuring section, will most certainly increase the energy variation, Δe_{m1}. An example is shown in **Figure 2.** At the power station described in **Figure 3**, thermodynamic turbine efficiency tests were performed for three identical units, unit no. 3, 5 and 6. The average energy variation , Δe_{m1} for units 3 and 6 was three times the average value recorded for unit 5 due to the more complex water passages.

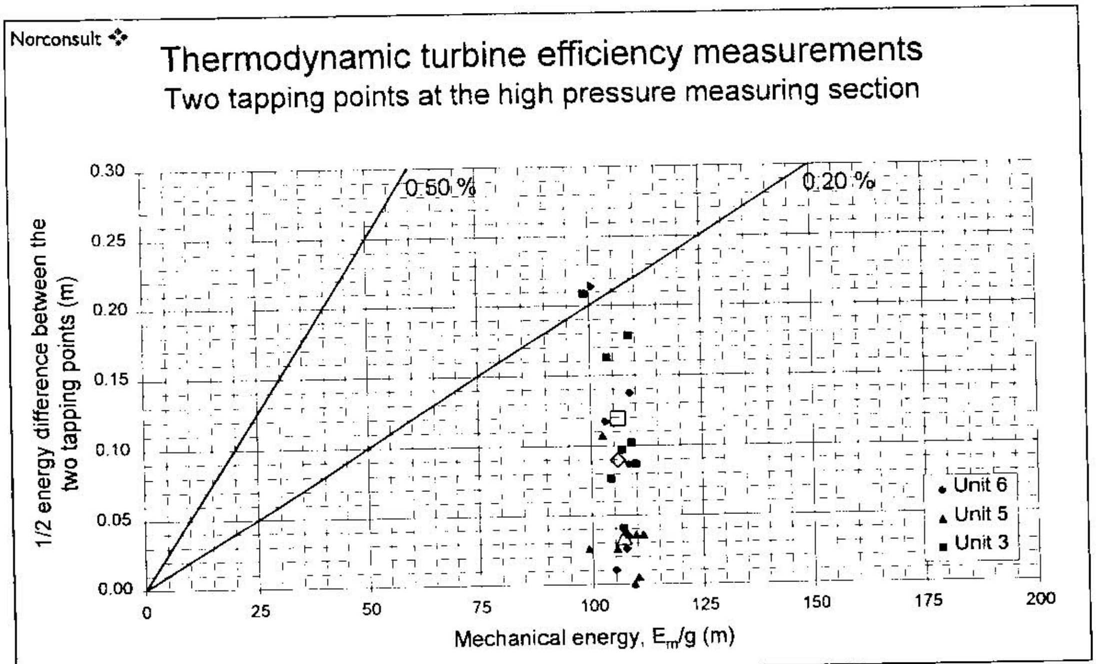


Figure 2 Energy differences at the turbine inlet

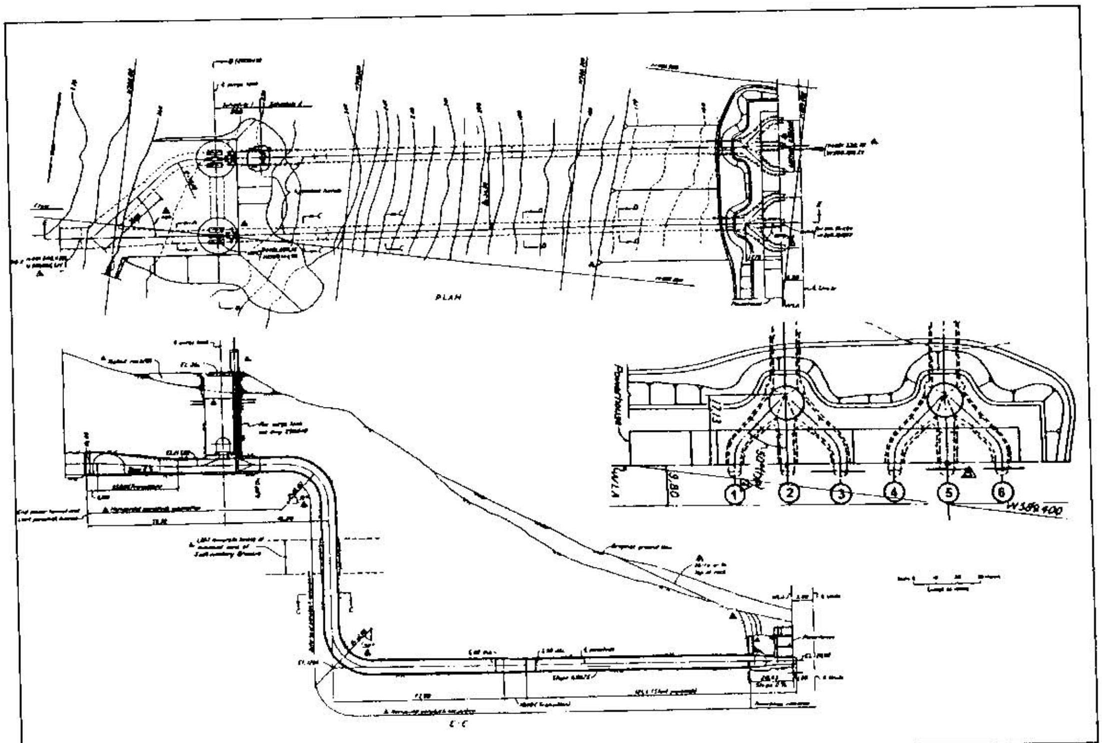


Figure 3 Test plant, water passages

At higher velocities the wall friction will increase creating higher temperature gradients throughout the flow. An increase in the energy variation, Δe_{m1} is therefore expected. This can be seen from the test data presented in **Figure 4**. The increase in the energy variation is, however, plant specific depending on the hydraulic design.

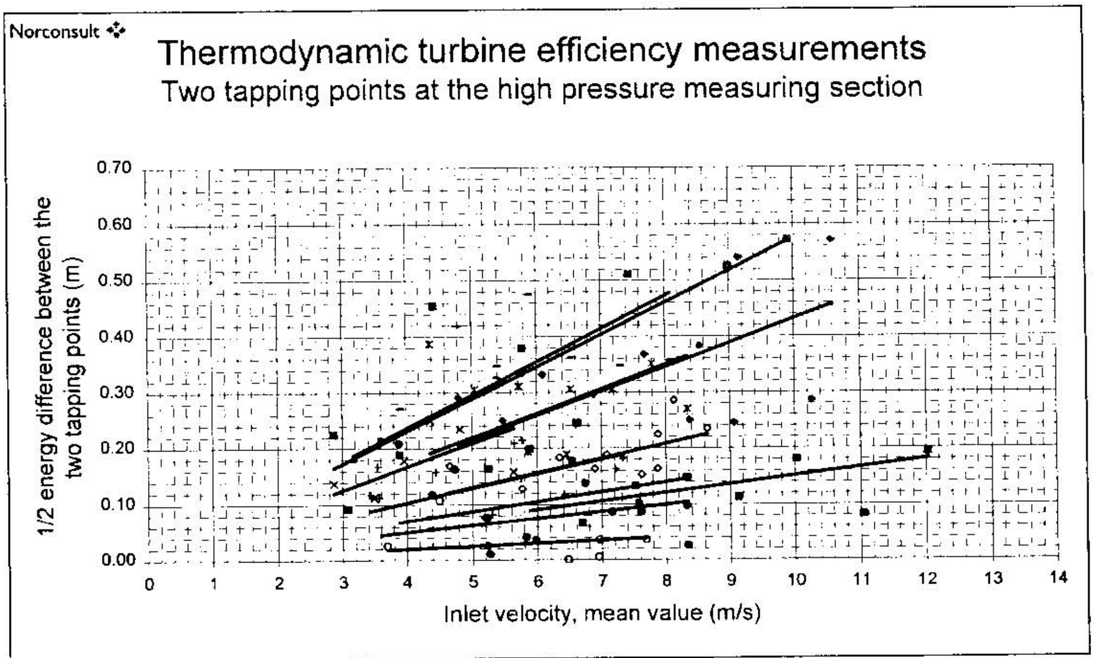


Figure 4 Energy differences at the turbine inlet versus inlet velocity

As the test results indicate, a variation in the energy at the high pressure measuring section is present. If two or more tapping points are used, the uncertainty due to the energy distribution should be estimated based on the recorded values.

If only a single tapping point is used, the uncertainty due to the energy distribution should rather be estimated based on a fixed value instead of being expressed as a percentage of the specific energy, E_m. Using the percentage value, the uncertainty due to the energy distribution will most certainly be overestimated for high head measurements. On the other hand for low head measurements the uncertainty due to the energy distribution could easily be underestimated. Based on the test results, an average variation in the energy distribution of ± 0.2 m (which is equivalent to about ± 0.5 mK in water temperature difference) is recommended.

Low pressure measuring section

There are many types of measuring arrangement being used at the low pressure measuring section to get the actual average temperature of the flow. Some examples are given in Appendix 1. The choice of measuring arrangement is often restricted by the accessibility at the turbine outlet and by the costs.

To investigate the energy distribution at the low pressure measuring section, data from different field tests have been analysed.

The test code [1] says: *"Exploration of temperature variation across the measuring section shall be made in at least six points."* A typical measuring arrangement that directly meets this requirement, consists of three vertical perforated pipes (Appendix 1, Type C) in the measuring section where the temperature sensor(s) can be positioned in different elevations, often 3 elevations. That means nine points. **Figure 5** shows half the maximum measured energy difference, Δe_{m2} between points in the outlet section for 15 different turbine tests with this type of measuring arrangement. The hydraulic head is in the range of 175 m to 970 m. The energy differences are of the same order of magnitude over the whole head range. The 5 tests (one Francis and four vertical shaft Pelton) showing energy difference more than ± 2 m did not fully meet the test code requirements because the low pressure measuring section was too close to the turbine. Statistical analysis of the 3 by 3 array of temperature readings can tell the uncertainty of the average energy value.

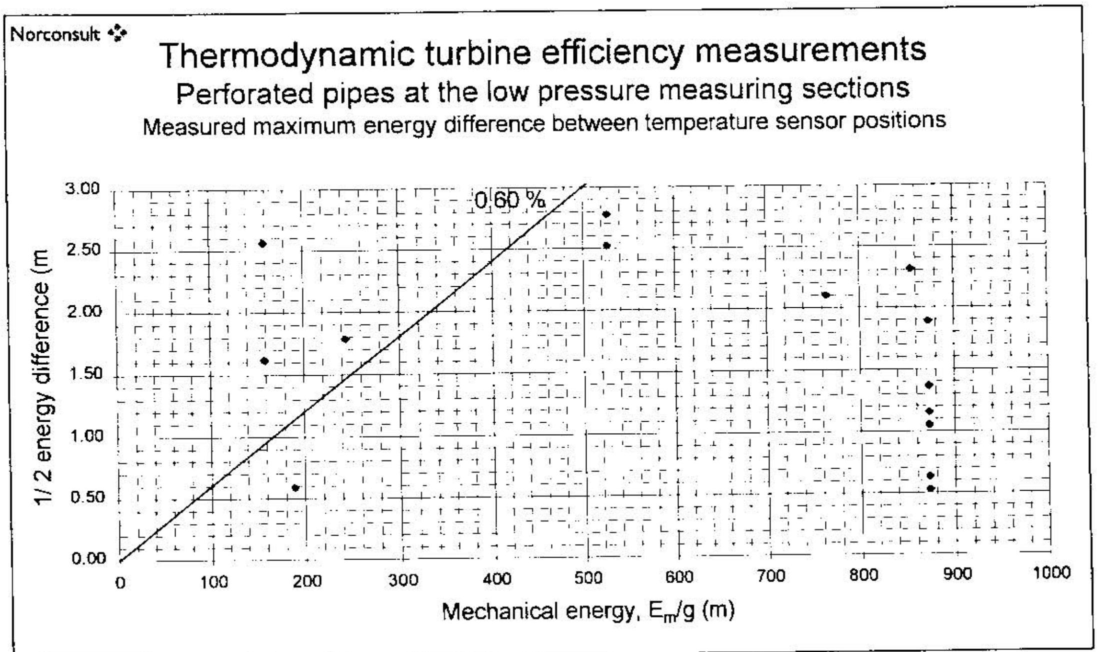


Figure 5 Energy differences at the turbine outlet; perforated measuring pipes

The energy difference for each test shown in Figure 5 is the measuring point with maximum difference of energy in the outlet section. This is usually at full power output. It is, however, interesting to see how the measured energy difference depends on the relative flow (or velocity). **Figure 6** shows a clear trend; the energy difference increases with the flow velocity, which is not unexpected for vertical Pelton turbines.

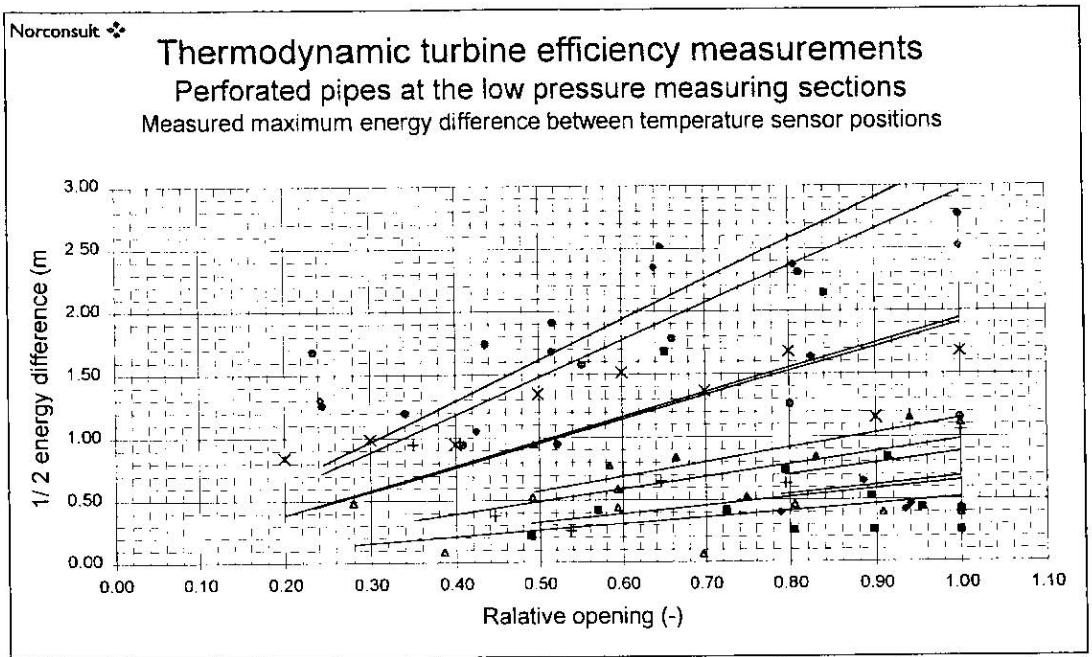


Figure 6 Energy differences at the turbine outlet versus relative turbine opening (outlet velocity)

Another type of arrangement uses a horizontal sampling manifold with four or six orifices (Appendix 1, Type H and I) with individual pipes to a mixing and measuring vessel with temperature sensor and discharge pipe. The manifold is supported on a steel beam. It can be moved vertically. Measurements are usually made in 3 or 5 vertical positions. Orifices in areas with high flow velocity collects more water than orifices in low velocity areas. Thus, this orifice manifold automatically makes a velocity compensation that improves the averaging of the flow temperature. Because of the averaging that takes place in the sampling flow system, the differences in temperature (energy) between the vertical positions (3 or 5) will be much smaller than for the system described above. **Figure 7** shows half the maximum measured energy difference, Δe_{m2} between manifold positions in the outlet section for 48 different turbine tests using the horizontal sampling manifold. The hydraulic head is in the range from 50 m to 950 m. The energy differences are of the same order of magnitude over the whole head range, even if there is an indication of decreasing difference with increasing head. The 2 tests showing energy difference close to ± 2 m are performed on Francis turbines with uncommon draft tube design.

When using the horizontal sampling manifold, the same trend between the measured energy difference and the turbine opening as shown in Figure 6, can be seen. The local energy difference increases with increasing flow velocity as shown in **Figure 8**. The average increase is however quite small, less than ± 0.3 m.

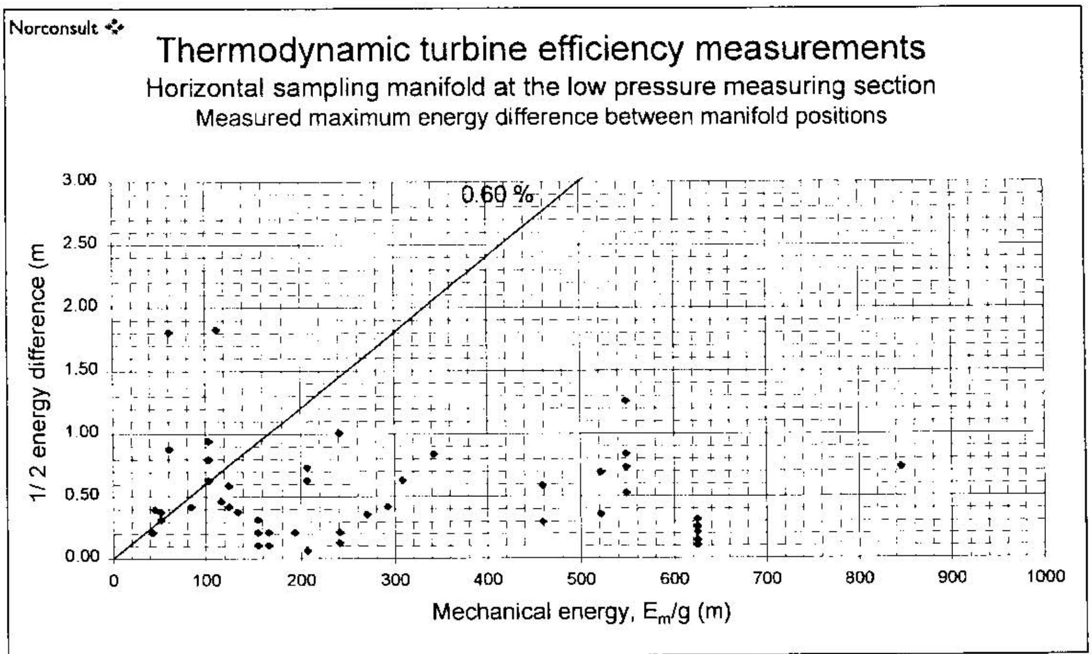


Figure 7 Energy differences at the turbine outlet; horizontal sampling manifold

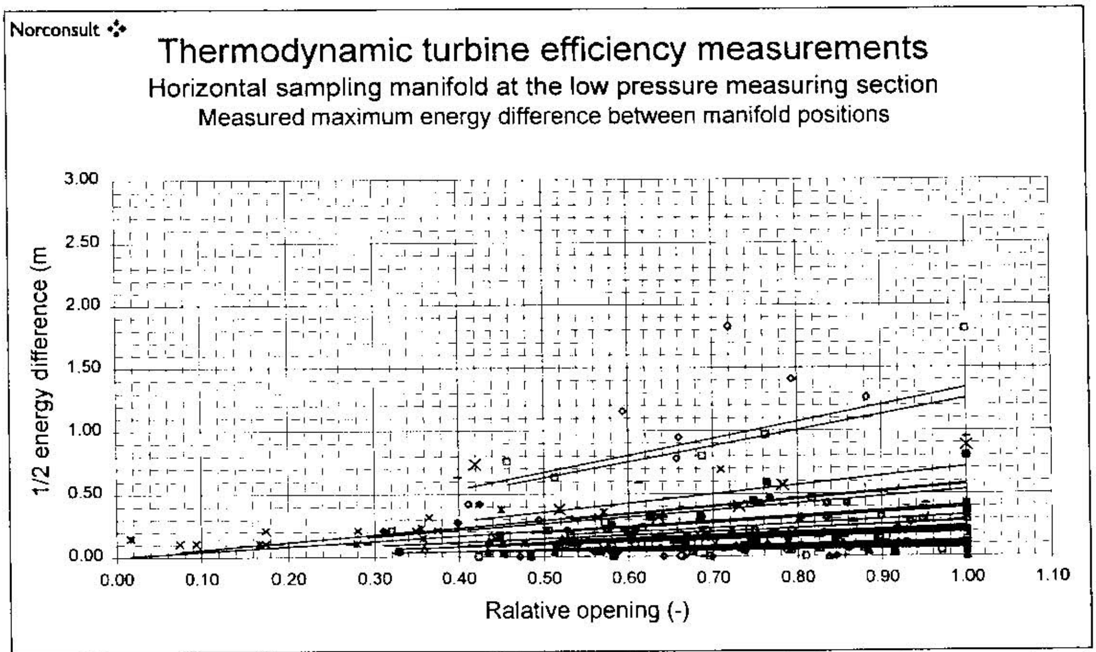


Figure 8 Energy differences at the turbine outlet versus relative turbine opening (outlet velocity)

Conclusion

The presented test data shows that the uncertainty of mechanical energy in the two measuring sections seems to be independent of E_m or the hydraulic head of the machine. Therefore the uncertainties being a percentage of E_m as suggested in the test code, probably should be changed. The uncertainties rather seem to be depending on:

- uneven temperature distribution in the intake
- hydraulic design of the water passages (bends, bifurcations etc.)
- heat exchange with the surroundings
- velocity and velocity distribution in the measuring sections

The question is then how to determine the uncertainty, in particular in the low pressure measuring section.

1. By using the measured energy distribution as input to a statistical analysis, it should be possible to calculate the uncertainty in each measuring section. Two or more sampling probes in the inlet would then be required. The type of sampling arrangement in the outlet would influence the statistical evaluation.
2. It should also be possible to use fixed absolute amounts of energy, for instance expressed as uncertainty of temperature distribution in each measuring section because the temperature term is dominating the total uncertainty calculation.

We have made uncertainty calculations for turbines with heads from 50 to 1200 m head; first according to the test code guide lines and then with 1 and 2 mK uncertainty in the inlet and 2 and 3 mK uncertainty in the outlet. **Figure 9** shows the diagram with the three curves. The two new curves crosses the "IEC 41" curve at 140 m and 210 m head respectively. This shows that the calculation according to the test code underestimates the uncertainty at low heads and overestimates it at high heads. All the uncertainties used in the calculations are within the range of usual values listed in Table AI Appendix A in the test code [1].

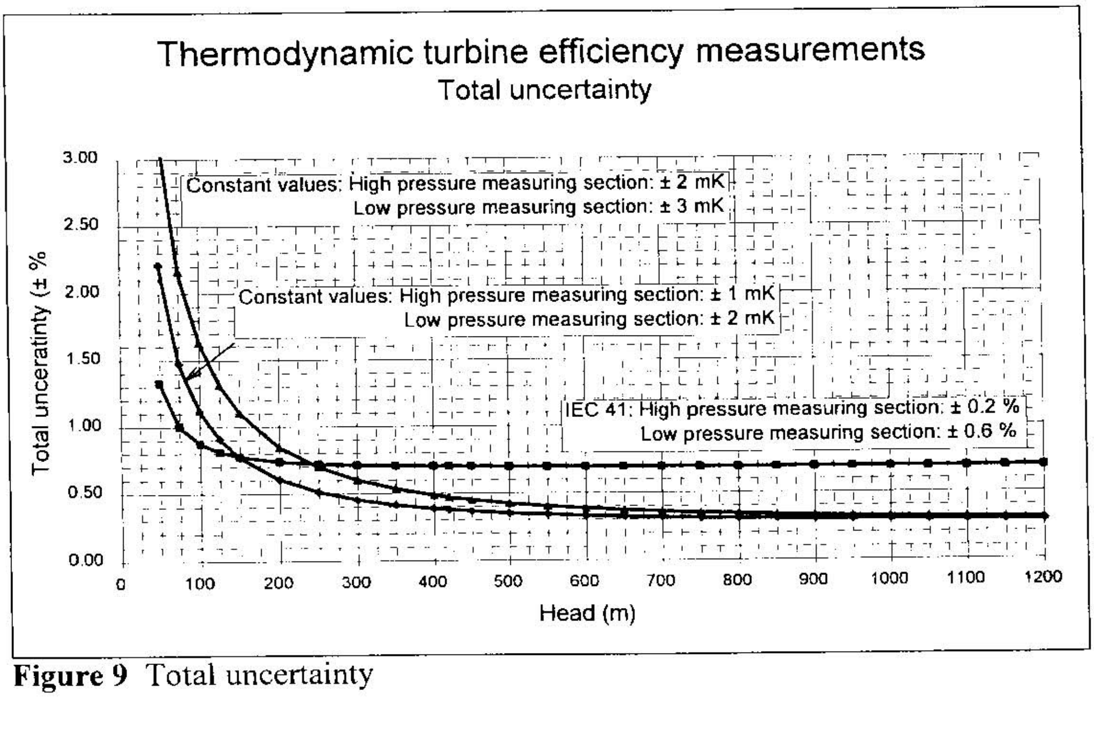


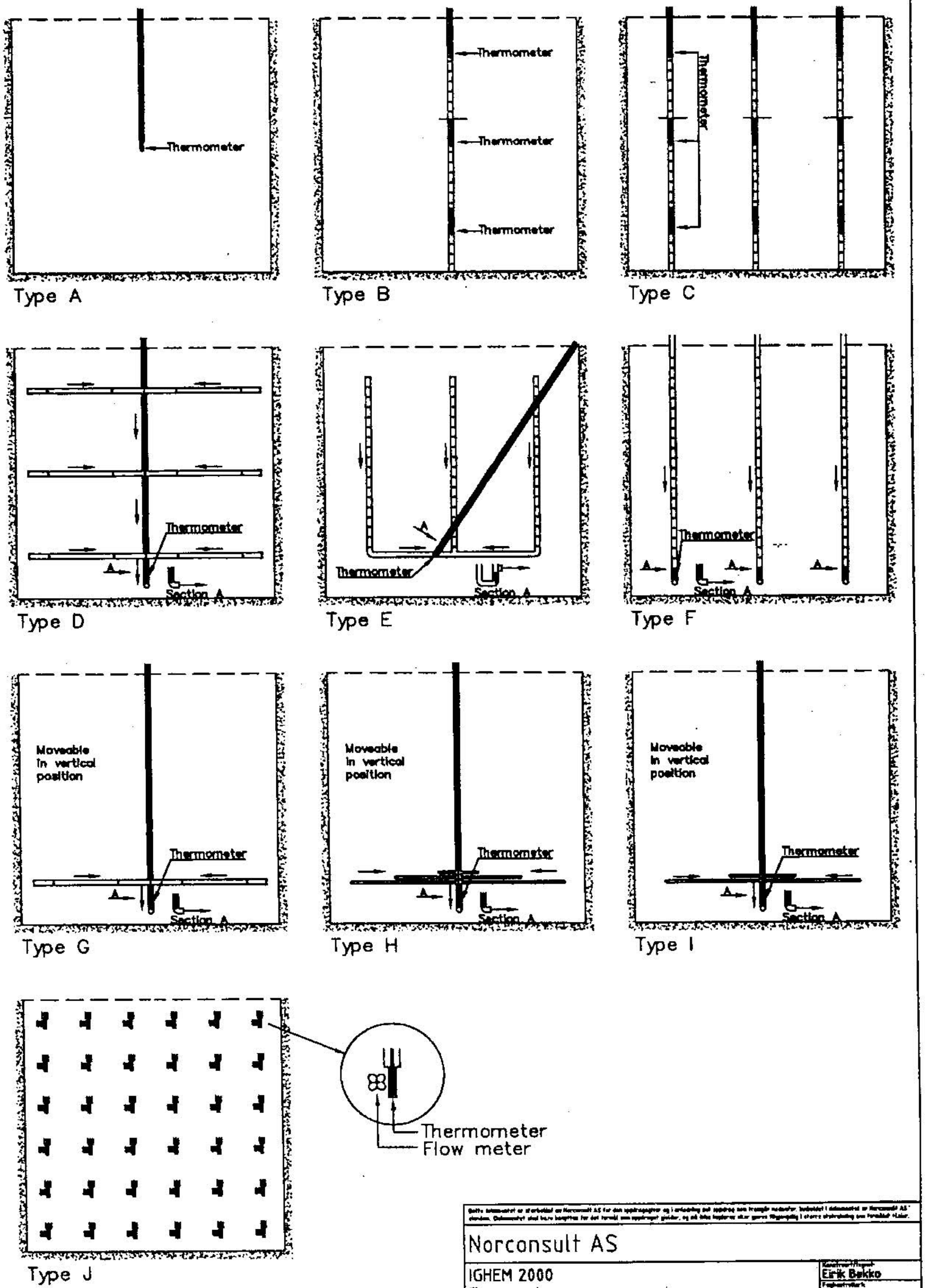
Figure 9 Total uncertainty

References

[1] IEC Publication 41 "Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines", Genève 1991-11

[2] Vinnogg, L. "Thermodynamic Efficiency Measurements. The Energy Distribution in the Boundary Layer at the Turbine Inlet", IGHEM Conference, Montreal, June 1996

Appendix 1



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in turbine outlet

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