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Comparison between pressure-time and thermodynamic efficiency measurements on a low head turbine

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Introduction

In Norway, prototype efficiency measurements are mostly carried out by the thermodynamic method. For low head turbines, the pressure-time method can be most accurate and the cheapest way to perform efficiency measurements. The pressure-time method is not very well known by the Norwegian consultants and hydropower plant owners and therefore not often used. The experience data from Norwegian power plants measured by the pressure-time method is scarce, and the uncertainty of the measurements is often a question mark. The uncertainty of thermodynamic measurements at heads lower than 100 meter and the uncertainty is also questioned since IEC 41 does not recommend this.

Comparison tests has been carried out at Laforge-1 Power Plant in Canada, (ref. Lévesque, 1996). This comparison tests show good correlation between the two methods.

The paper will present efficiency measurements carried out at Svean Power Plant which is located near Trondheim, Norway. Here, both pressure-time and thermodynamic efficiency measurements has been carried out during the autumn 2005 by students and staff from the Waterpower Laboratory at The Norwegian University of Science and Technology (NTNU). Svean Power Plant has installed 3 Francis manufactured by Kværner Bruk and made in the period from 1940 to 1948. Efficiency measurements where carried out on all three units. However, the pressure-time measurements were successful on one unit and only partly successful on the other two units.

Svean Power Plant

Svean Power Plant has installed 3 Francis units where the head is 50 meter and the nominal power output from each turbine is 11 MW. The pressure shaft has a 27 degree slope, it is about 110 meter long, it has a steel riveted lining in its whole length and the diameter is 3,18 meter. The speed number, Ω of the turbines are 0,9 and the speed is 300 rpm. The turbines are of the twin-Francis type as shown in Figure 1. This means they have two runners back to back, two draft tube bend and one spiral casing. The outlet of the draft tube is one cross section with the flow rate from both draft tube bends.

$$\Omega = \omega \cdot \frac{\sqrt{Q}}{H^{3/4}} \qquad [1]$$

Where :

ω	=	Angular speed	[rad/s]
Q	=	Flow rate	[m³/s]
H	=	Head	[m]

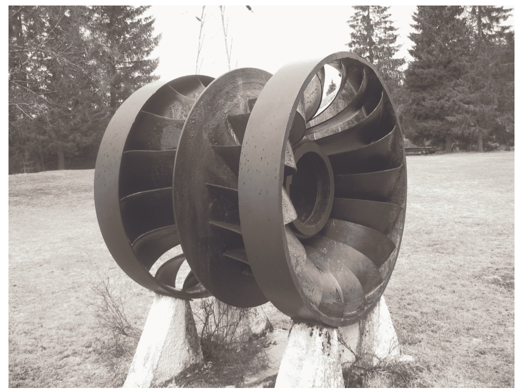

Figure 1. Twin Francis runner

The pressure time measurements

The measurements were carried out through three steps. The first step was to calibrate the pressure transducers, the second was to measure a leakage flow rate through the guide vanes and the last was to carry out the efficiency measurements itself. In the following, measurement procedures for the leakage flow and efficiency are described.

The leakage measurements were carried out with the following procedure:

- The cross section of the pressure shaft is measured
- The turbine was stopped and the guide vanes are closed
- The gate at the inlet of the pressure shaft is set to a closed position
- Measurement of the time and pressure, p_3 in the pressure shaft while the water is leaking out of the guide vanes.
- The initial leakage flow rate is calculated based on the change of the level, ΔZ in the pressure shaft by using Equation 2.
- The leakage flow rate is recalculated by using Equation 3.

$$Q_i = \frac{dV}{dt} = \frac{A \cdot \Delta Z}{\Delta t \cdot \sin \alpha} \qquad [2]$$

$$Q_{Leakage} = Q_i \cdot \sqrt{\frac{H_1}{H_2}} \qquad [3]$$

Where :

α	=	Slope of the pressure shaft	[degrees]
A	=	Cross section of the pressure shaft	[m^2]
Δt	=	Change of time	[s]
ΔZ	=	Change of level	[m]
H_1	=	Static head of the power plant	[m]
H_2	=	Actual head while doing the leakage flow rate measurements	[m]
Q_i	=	Initial leakage flow rate	[m^3/s]
$Q_{Leakage}$	=	Leakage flow rate	[m^3/s]
t	=	Time	[s]
V	=	Volume	[m^3]

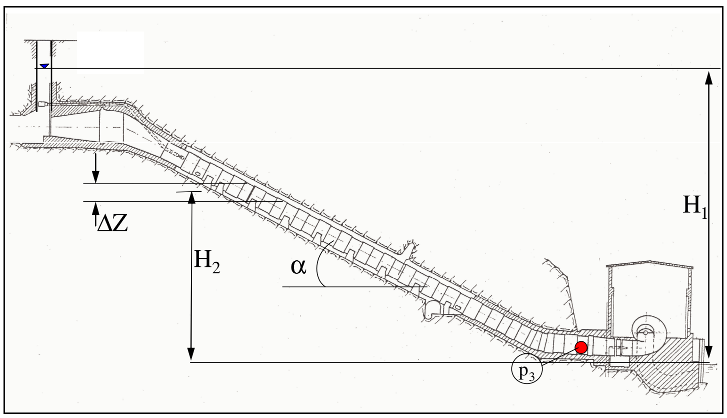

Figure 2. Leakage Flow measurements

The efficiency measurements were carried out with the following procedure:

- Two cross sections are set up with 4 pressure transducers as shown in Figure 4 and Figure 5.
- The diameters and length between the two cross sections are thoroughly measured
- Set the turbine at a constant load and carry bout measurement on the following:
  - Atmospheric pressure
  - Inlet pressure, p_3 to the turbine
  - Water level at the outlet of the draft tube
  - Generator power output and load factor
- Close the guide vanes as fast as possible and measure the pressures at the two cross sections in the pressure shaft.
  - These measurements are recommended to start two minute before the closing starts and end four minutes after closing has finished.
  - The pressure measurements are carried out at 150 Hz

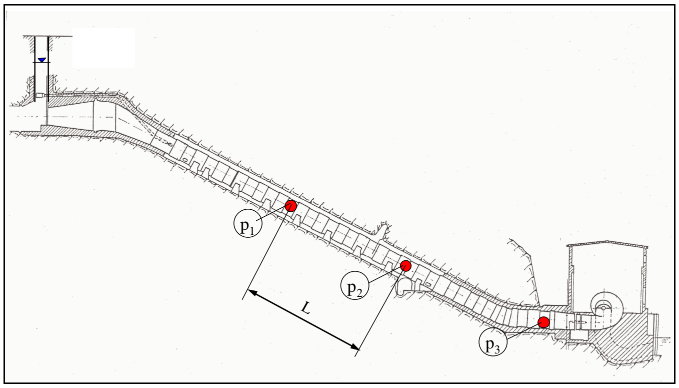

Figure 3. Pressure measurements

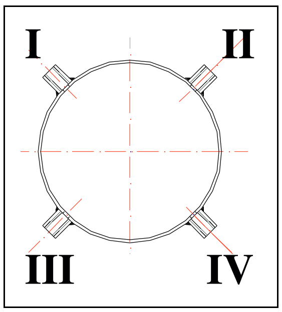

Figure 4. Upstream cross section

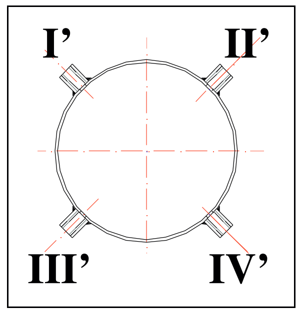

Figure 5. Downstream cross section

The calculations were carried out with the following procedure:

- The differential pressures, Δp_i are found for all time steps
- Control each differential pressure to check that the transducers are working properly.
  - $$\Delta p_I = p_{I'} - p_I \qquad \Delta p_{II} = p_{II'} - p_{II}$$ $$\Delta p_{III} = p_{III'} - p_{III} \qquad \Delta p_{IV} = p_{IV'} - p_{IV} \qquad [4]$$
- Double check the transducers by the differential pressures between the diagonals
  - $$\Delta p_V = p_{IV'} - p_I \qquad \Delta p_{VI} = p_{III'} - p_{II}$$ $$\Delta p_{VII} = p_{II'} - p_{III} \qquad \Delta p_{VIII} = p_{I'} - p_{IV} \qquad [5]$$
- Find the mean pressure for each time step at each cross section
  - $$p_1 = \frac{1}{4} \cdot \sum_{j=I}^{IV} p_j \qquad p_2 = \frac{1}{4} \cdot \sum_{j=I'}^{IV'} p_j \qquad [6]$$
- Find the mean pressure during the period before the guide vanes starts to close, p_{start} and after the guide vanes has closed, p_{end}.
- The head loss in the pipe between the two cross sections is given by the difference between the pressures p_{start} and p_{end}.
- Set up a function for the head loss:
  - $$\Delta p_{head\ loss} = k \cdot \left(Q_{start}^2 - Q^2\right) \qquad [7]$$
- The constant, k is chosen from the boundary condition:

- $k = \frac{\Delta p_{head\ loss}}{Q_{start}^2}$ [8]

- Calculate the change of flow rate, ΔQ by using equation 9 and 10:
  - $\Delta Q = \frac{g \cdot A_{Pressure\ Shaft}}{L} \cdot \Delta A$ [9]
  - $\Delta A = \sum_{t=t_{i-1}}^{t=t_i} \left(\frac{\Delta p - \Delta p_{Head\ loss}}{g \cdot \rho} \right) \cdot \Delta t$ [10]
- Iterate by changing the flow rate, Q_{start} until the flow rate is zero after closing of the guide vanes. An example of the flow rate curve is shown in Figure 6.
- The turbine efficiency is calculated based on equation 11:
  - $\eta_{Turbine} = \frac{P_{Generatr}}{\eta_{Generator} \cdot Q \cdot \Delta p}$ [11]

Where :

Δp	=	Differential pressure over the turbine	[Pa]
Q	=	Flow rate	[m^3/s]
$P_{Generator}$	=	Generator power	[W]
$\eta_{Generator}$	=	Generator efficiency	[-]

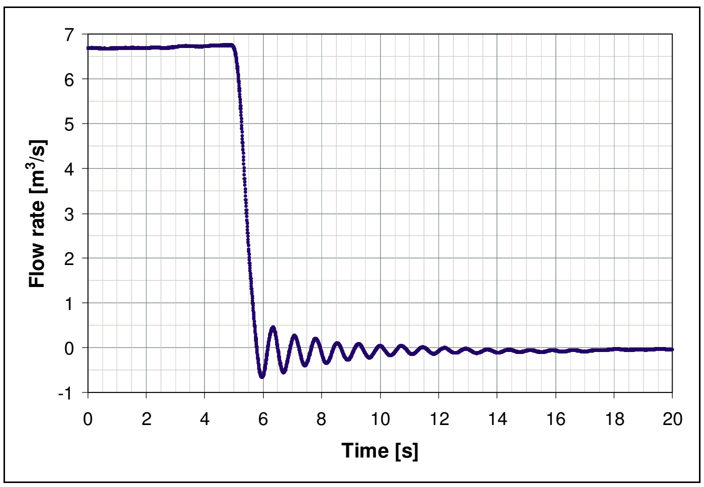

Figure 6. Flow rate during the measurements

The main equipment that was used during the pressure-time measurements:

- Pressure transducers: Druck PTX 610
- Mean pressure transducer: Digiquartz 9002K-105
- Ambient pressure transducer: Digiquartz 9002K-105
- Power meter: Voltek PM3000A

The Thermodynamic measurements

The thermodynamic measurements are carried out according to IEC 41, and will not be described as thoroughly as the pressure-time measurements. Although, the measurements were carried out for 50 meter head, it is a good comparison with the pressure-time measurements.

The temperature measurements were carried out with one probe at the inlet. The length of the tunnel and pressure shaft is long enough to ensure that the temperature is the same all over the inlet cross section of the turbine. At the outlet, samples were taken from 8 different locations at two levels in the draft tube outlet cross section. A pipe system guided the water to a mixing chamber where the temperature probe was located.

The pressure measurements at the inlet of the turbine, p_3 were taken upstream the spiral casing at the same location as for the pressure-time measurements. The pressure at the outlet was measured by the water level at the outlet of the draft tube.

Since the turbine is of the twin-Francis type, no leakage water was taken out of the turbine. Therefore, no measurements had to be carried out for the leakage water.

The main equipment that was used during the thermodynamic measurements:

- Temperature transducers: Seabird SB38
- Pressure transducers: Paroscientific Digiquartz 9002K-105
- Power meter: Voltek PM3000A

Results and conclusions

The measurements were carried out at three turbines. The pressure-time measurements were successful for two turbines. The results from these two turbines are presented in Figure 7 and 8. The maximum efficiency difference between the pressure-time measurements and thermodynamic measurements for turbine 1 and turbine 3 are 1,58% and 2,5%. The large efficiency difference of the measurements on turbine 3 is thought to be du to short period for measurement after the guide vanes was closed. This may give large uncertainty of the mean pressure after the guide vanes are closed.

The uncertainty of the pressure-time efficiency measurements are calculated to be $\pm$0,95 %, and for the thermodynamic efficiency measurements are calculated to be $\pm$1,3 %. The calculation and discussion about the uncertainty are described in Hulaas 2006.

The results show that the thermodynamic and pressure-time efficiency measurements are within the uncertainty bands on Turbine 1, while this is not the case for all measurements on Turbine 3. Therefore, the measurements on Turbine 3 should be rejected.

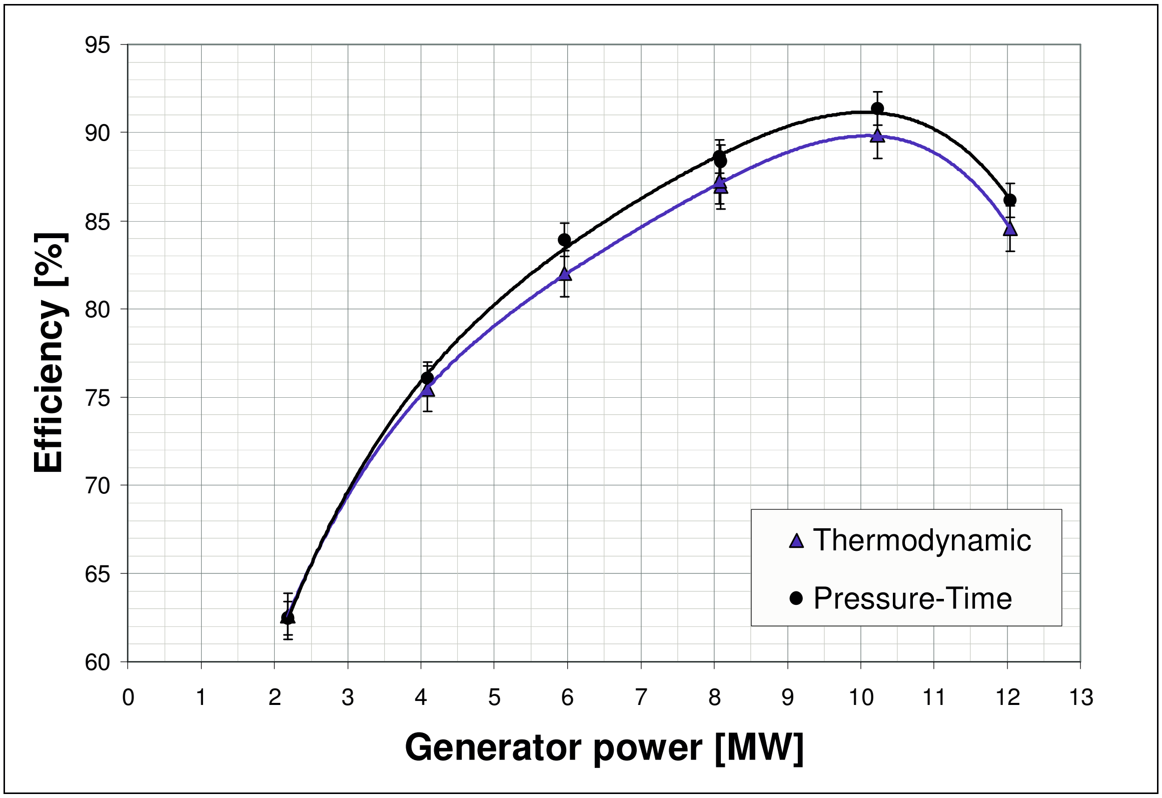

Figure 7. Results from the efficiency measurements on turbine 1.

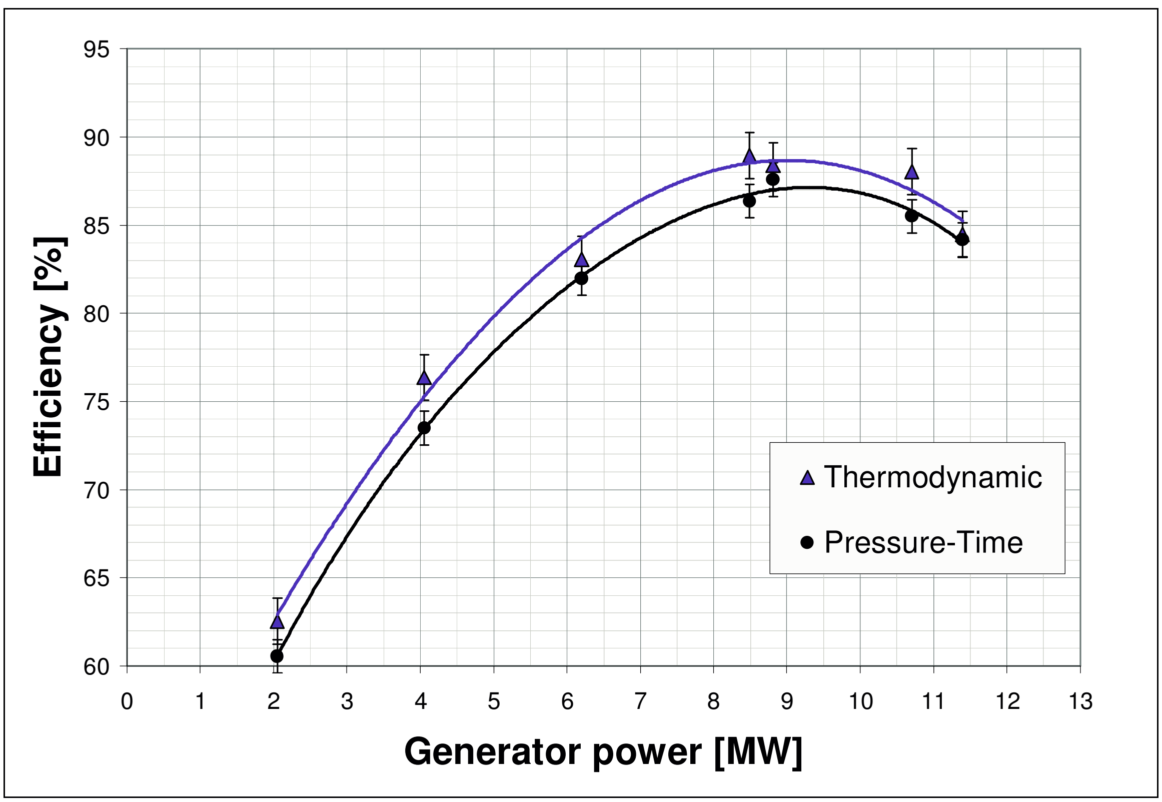

Figure 8. Results from the efficiency measurements on turbine 3.

Discussion

The results show that the thermodynamic and pressure-time efficiency measurements are within the uncertainty bands on Turbine 1, while this is not the case for all measurements on Turbine 3. For Turbine 1, the pressure-time measurement gave the highest efficiency, while the result on Turbine 3 is the other way around.

One can argue that the measurements on Turbine 3 should be rejected. However, it is interesting to compare the two measurements in order to discuss the difference between the two Turbines.

The thermodynamic measurement on Turbine 1 and Turbine 3 show that both have the best efficiency around 89-90%. Since these two turbines are geometrically the same, this is what one could expect. The thermodynamic measurements were carried out exactly the same way on both turbines. Thus, the pressure-time measurements are suspected to be the one with deviations.

The main difference between the two turbines is the pressure shaft. Turbine 1 has a riveted pipe while Turbine 3 has a welded pipe. Here, the change of cross section and surface roughness are parameters that should have been measured more thoroughly.

The measurement of the power is carried out by using the power plant's voltage and current transformers. These transformers are relatively old, and one may expect more uncertainty than a new one. The difference between the transformers on the two turbines may therefore result in difference between the power output measurements.

References

IEC 41, *Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines*. Third edition 1991-11

Hulaas H., Dahlhaug Ole G. (2006) *An Uncertainty analysis of Pressure-Time measurements.* Presented at the IGHEM Symposium in Portland, Oregon, USA., 30. July – 1. August 2006

Lévesque J.-M. Néron J. (1996) *Laforge-1 ComparativeTest* Presented at the IGHEM's Symposium in Montreal, Canada, 1996