Experience from a thermodynamic efficiency test introducing generator cooling water back into the main discharge

E. Nilsen[1], H. Hulaas[2]

[1]*Norconsult AS, erik.nilsen@norconsult.com, Sandvika, Norway*
[2]*Norconsult AS, harald.hulaas@norconsult.com, Trondheim, Norway*

Abstract

What should have been a straightforward thermodynamic efficiency test according to the IEC 60041 [1] to verify the turbine efficiency and the turbine output guarantees after an upgrade of a small vertical Francis unit (300 m, 16 MW), introduced extensive investigations and extra work due to cooling water from the generator coolers and the generator bearings being led back to the main discharge at the start of the draft tube bend upstream of the low pressure measuring section.

Measures taken trying to explain the efficiency shortage, are described. Even performance of a second test was agreed upon. The second test was performed with an extended test arrangement/instrument set up to explore the energy distribution across the measuring sections more closely (multiple sampling probes at the high pressure measuring section and individual temperature recordings at the low pressure measuring section). Observations/findings from the second test is presented.

After the second test it was finally made possible to trace the cooling water return from the generator coolers and the generator bearings back to the draft tube cone/bend. Knowing the generator losses (established at the FAT), it was therefore possible to correct the measurements for the amount of energy added to give the true turbine efficiency. The corrections made are presented.

Based on the measurements performed, the thermodynamic method is characterized as robust when it comes to acquiring reliable data. Even at unfavourable measuring conditions the two different temperature sampling methods produces the same test result.

The main lesson to be learned from the measurements is that you have to know all discharges extracted or added between the high and the low pressure measuring section to avoid unnecessary doubt on the test results. Extraordinary investigations may be time consuming and expensive.

1 Introduction

To verify the turbine efficiency and the turbine output guarantees after an upgrade of a small vertical Francis unit (300 m, 16 MW), a thermodynamic efficiency test according to the IEC 60041 [1] was performed. The measured turbine efficiency was however surprisingly low; well below the guarantee data given by the Contractor; see Figure 1.

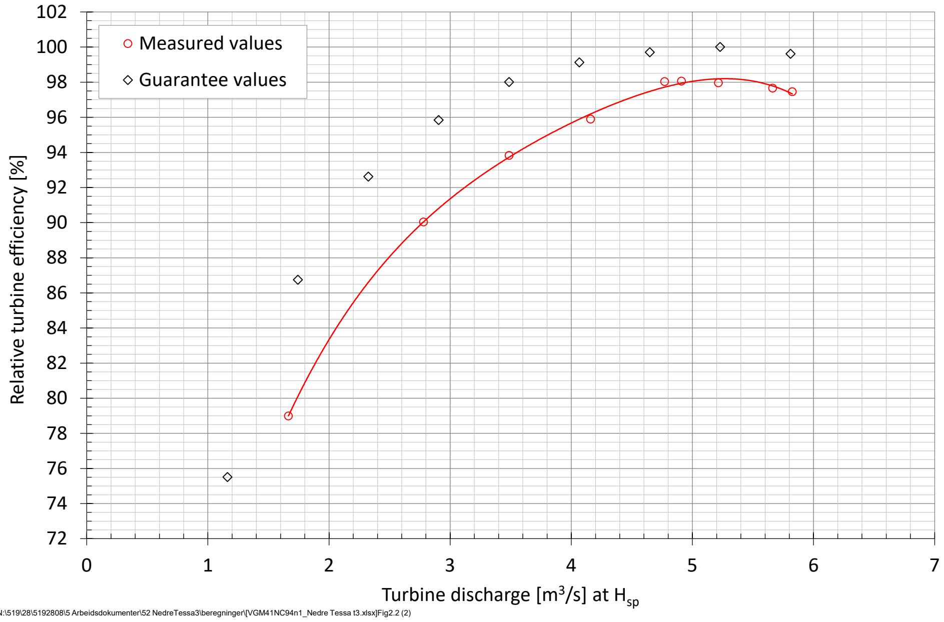


Figure 1 Initial test results compared to guarantee values

The efficiency shortage was later established due to cooling water from the generator coolers and the generator bearings being led back to the main discharge at the start of the draft tube bend upstream of the low pressure measuring section.

This paper describes investigations and further work performed initiated by the initial test result. Findings from a second thermodynamic test with an extended test arrangement/instrument set up is presented. And finally, experiences and lessons to be learned from the tests are given.

2 Investigations and extra work performed

2.1 Investigations during initial test

During the initial test the following were checked/double checked:

- Zero temperature difference – no deviation found
- Valve position for penstock drainage valve – shut
- Valve position for spiral casing drainage valve – shut
- Leakage through the pressure relief (safety) valve. No leakage was observed from the downstream side when pressurising the spiral casing (the turbine initially dewatered)

2.2 Further investigation/work

After returning to office, further work included the following:

- Extra checking of measurement data and calculations – no calculation errors were found. Raw data from the measurements were sent to the Contractor for information/investigation
- Discussions/meetings between Norconsult and the Contractor – no finite reason found
- Analysis of the thermodynamic efficiency test results. Report by Contractor. Point of interest: Interference from the slide valve (MIV) chamber and energy distribution across the measuring sections
- Inspection at site by Contractor. Especially focus on all valves and pipes with connection to the turbine or draft tube. The upgrade included a rebuild of the cooling water and the drainage system. Before the tests it was a consensus that all cooling water was now led to the drainage sump and pumped to the draft tube duct downstream of the low pressure measuring section, see Appendix 2. The inspection could however not verify this 100 %.
- Dimension check by Contractor of the spiral casing and stay vane geometry using by laser scan – no significant deviation was found

2.3 Second thermodynamic test

The initial investigations could not explain the efficiency shortage. It was therefore decided upon to redo the efficiency test with an extended test arrangement/instrument set up to explore the energy distribution across the measuring sections. The extended test arrangement included:

- two sampling probes at the high pressure measuring section (originally one sampling probe was used, d=900 mm), see Appendix 1
- six individual temperature registrations at the low pressure measuring section (originally an averaging collecting frame was used), see Appendix 2

3 Observations/findings from the second thermodynamic test

3.1 High pressure measuring section

Check of pipe wall pressure

At steady state the pressure fluctuations were small. For checking the pressure taps (4 four taps connected through a ring manifold), each tap was read individually (IEC 60041 chapter 11.4.2). The readings from the test are shown in Figure 2. The difference in the pressure readings is quite small and well within the requirements given by the IEC 60041, see Table 1. The quality of the pressure taps is therefore assessed as good.

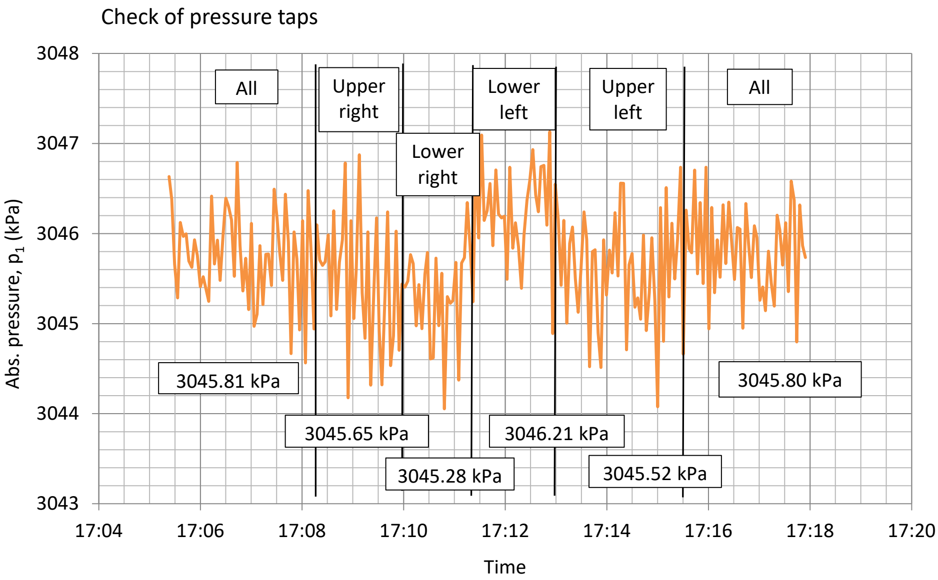


Figure 2 Checking of pressure taps at high pressure measuring section

Table 1 Evaluation of pressure variation at high pressure measuring section

Maximum pressure (kPa)	Minimum pressure (kPa)	Pressure diff. (kPa)	Energy (J/kg)	Hydraulic energy (J/kg)	Part of hydraulic energy (%)	IEC 60041 (%)
3046,21	3045,28	0,93	0,93	2992,69	0,03	<0.5
				Velocity head (J/kg)	**Part of velocity head (%)**	
3046,21	3045,28	0,93	0,93	20,43	4,55	<20

Check of sampling probe pressure

During the test it was observed that the sampling probe pressures differed from each other. The difference also varied throughout the test. Sometimes the sampling probe pressure could even go below the wall pressure. This pressure variation was due to the water quality (organic waste such as leaves, humus etc.) effecting the sample flow rate/pressure tap of the sampling probe. To check the sampling probes, the sampling flow was shut off and the stagnation pressure was measured. The recorded pressures are given in Figure 3. The check is summarized in Table 2. The test does not identify any faults. The stagnation pressure is nearly equal for the two sampling probes and higher than the wall pressure.

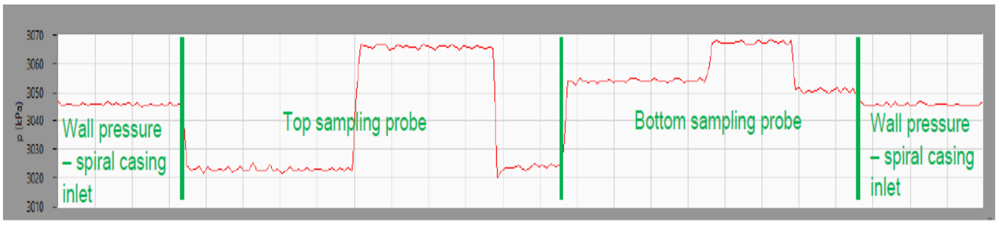


Figure 3 Check of sampling probes; pressure recordings

Table 2 Check of sampling probes; pressure recordings summarized

Measurement location	Sampling flow rate (l/min)	p_1 (kPa abs)	p_{11} (kPa abs)
Spiral casing inlet	-	3045,78	-
Top sampling probe	8 0 8		3023,58 3065,85 3023,57
Bottom sampling probe	7 0 7		3054,05 3067,46 3050,61
Spiral casing inlet	-	3045,79	

Check of interference from the MIV by-pass
During normal operation the MIV by-pass valve is open. To check if this condition interferes with the recordings from the high pressure measuring section, the by-pass valve was shut. The recorded pressures are given in Figure 4. No significant changes in the recorded values were detected. The by-pass valve being open has therefore no effect on the measurements.

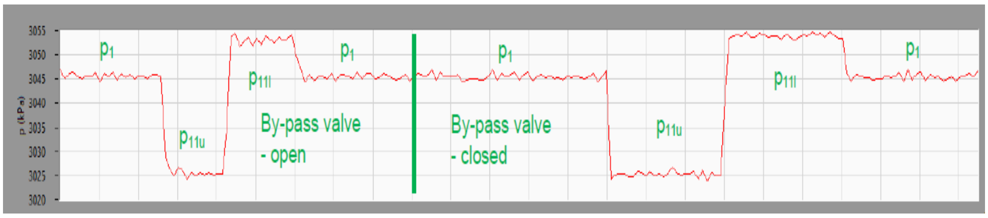


Figure 4 Check of sampling probes; pressure recordings when operating MIV by-pass valve

Water temperature
The water temperature at the turbine inlet did however vary some throughout the day. Both positive and negative gradients were observed, see Figure 5. The temperature gradients were however quite small, no greater than 1 mK/min, during the test runs and therefore well within the limit of 5 mK/min (IEC 60041 chapter 14.6.1). The observed temperature variation was expected (a characteristic for this power plant), the power plant utilizing water from a small intake dam.

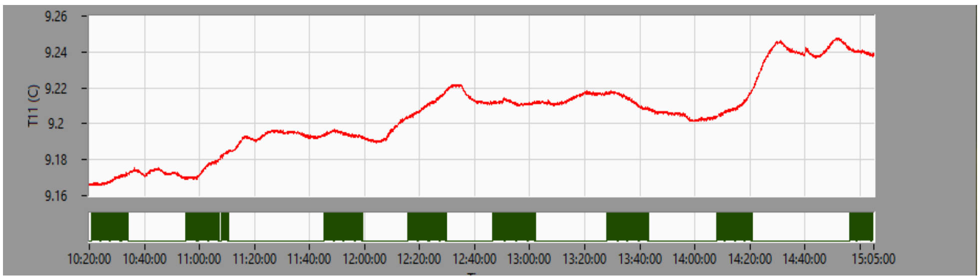


Figure 5 Temperature variation throughout the day at high pressure measuring section

Temperature and pressure being coherent values meant that when the sampling probe pressure dropped due to clogging, the sampling probe temperature would also change. Table 3 gives recorded pressure and temperature values from two different test points; one test point where there is no clogging (test no. 314) and one test point (test no. 318) where there is partly clogging of the upper sampling probe. As can be seen from the table, the temperature change represents the same amount of energy as the pressure drop do. This indicates that the sampling probes are picking up the “right” energy.

Table 3 Sampling probes; simultaneous pressure and temperature recordings

Test no.	Upper sampling probe		Lover sampling probe		Difference			
	p_{11} (kPa)	θ_{11} (°C)	p_{11} (kPa)	θ_{11} (°C)	Δp_{11} (kPa)	Δp_{11} (kJ)	$\Delta\theta_{11}$ (°C)	$\Delta\theta_{11}$ (kJ)
314	2986,6	9,2087	2988,0	9,2083	1,4	1,4	0,0004	1,6
318	3020,9	9,2398	3053,2	9,2321	32,3	32,3	0,0077	32,3

Comparison of specific mechanical energy from each of the sampling probes
The calculated specific mechanical energy, E_{m1-2}, for each of the two sampling probes are given in Table 4. The difference in the resulting efficiency is on average about 0.1 %pp.

Table 4 Sampling probes; specific mechanical energy, E_{m1-2}

Test no.	311	312	313	314	315	316	317
Specific mechanical energy upper probe, E_{m1-2u} (J/kg)	2687.11	2727.92	2705.14	2692.69	2595.65	2344.84	2710.83
Specific mechanical energy lower probe, E_{m1-2l} (J/kg)	2685.07	2724.52	2702.62	2690.49	2594.62	2341.15	2709.12
Specific mechanical energy difference, ΔE_{m1-2} (J/kg)	2.04	3.40	2.52	2.20	1.02	3.69	1.71
Turbine efficiency difference, $\Delta\eta$ (%)	0.07	0.12	0.08	0.08	0.03	0.12	0.06
Test no.	**318**	**318x**	**319**	**320**	**321**	**322**	**323**
Specific mechanical energy upper probe, E_{m1-2u} (J/kg)	2685.70	2684.53	2616.64	2693.33	2723.77	2714.97	2693.97
Specific mechanical energy lower probe, E_{m1-2l} (J/kg)	2683.23	2679.61	2612.11	2690.18	2720.41	2714.00	2691.90
Specific mechanical energy difference, ΔE_{m1-2} (J/kg)	2.47	4.92	4.53	3.15	3.36	0.96	2.07
Turbine efficiency difference, $\Delta\eta$ (%)	0.08	0.16	0.15	0.11	0.11	0.03	0.07

All checks performed, the energy distribution across the high pressure measuring section seems to be even and within the values proposed by IEC 60041 (IEC 60041 chapter 14.7).

3.2 Low pressure measuring section
Water temperature
With the modified sampling frame, it was now possible to record the water temperatures in separate areas of the draft tube. The measuring section was divided into six parts; left (L) or right (R) half and upper (U), middle (M) or lower (L) level. The recordings from the right, upper part (RU) are however omitted due to a temperature sensor mal function. As can be seen from Table 5, the temperature scattering was large, implying an uneven temperature/energy distribution. The measuring conditions were clearly unfavourable according to the IEC 60041 test code (chapter 14.5.4). The scattering is at its largest when the turbine is operating at an opening just below the best efficiency point (i.e. test no. 312, 313, 317, 321 and 322). In this operating range (4-7-5.1 m^3/s), the draft tube swirl is probably absent and therefore the mixing of the water is poor. For operation at lower of larger discharges, the draft tube swirl secures an adequate mixing. The variation in the turbine efficiency based on the individual temperature recordings are given in Table 6.

To check if the position of the sampling frame tapping holes was significant, the tapping hole configuration was changed as shown in Figure 6. The original design was used during test no. 311-318. For test no. 319-323 the hole closet to the centre was blocked and an additional hole was drilled nearer to the draft tube wall. No major changes to the temperature registrations were recorded.

Table 5 Temperature recordings low pressure measuring section

Test no.	**311**	**312**	**313**	**314**	**315**	**316**	**317**
Turbine discharge at H_{sp}, Q (m^3/s)	4.04	5.08	4.77	5.68	2.93	1.76	4.80
Average temperature difference, $\Delta(\theta_{11}-\theta_{21})$ (°C)	-0.0502	-0.0328	-0.0413	-0.0367	-0.0769	-0.1415	-0.0376
Deviation from average temp. diff., pos LU, Δθ (°C)	-0.0006	0.0012	0.0169	0.0010	0.0001	0.0002	0.0136
Deviation from average temp. diff., pos LM, Δθ (°C)	-0.0008	0.0067	0.0067	0.0012	0.0002	0.0002	0.0082
Deviation from average temp. diff., pos LL, Δθ (°C)	-0.0007	0.0108	0.0118	0.0025	0.0001	0.0000	0.0100
Deviation from average temp. diff., pos RU, Δθ (°C)							
Deviation from average temp. diff., pos RM, Δθ (°C)	0.0008	-0.0121	-0.0129	-0.0038	-0.0001	-0.0003	-0.0051
Deviation from average temp. diff., pos RL, Δθ (°C)	0.0014	-0.0066	-0.0225	-0.0009	-0.0004	-0.0001	-0.0267
Test no.	**318**	**318x**	**319**	**320**	**321**	**322**	**323**
Turbine discharge at H_{sp}, Q (m^3/s)	4.00	4.00	2.99	4.18	4.69	5.12	5.67
Average temperature difference, $\Delta(\theta_{11}-\theta_{21})$ (°C)	-0.0465	-0.0544	-0.0793	-0.0539	-0.0424	-0.0419	-0.0425
Deviation from average temp. diff., pos LU, Δθ (°C)	-0.0004	-0.0006	0.0001	-0.0009	0.0057	0.0052	0.0016
Deviation from average temp. diff., pos LM, Δθ (°C)	-0.0007	-0.0007	0.0001	-0.0011	0.0055	0.0101	0.0020
Deviation from average temp. diff., pos LL, Δθ (°C)	-0.0007	-0.0007	-0.0003	-0.0013	0.0127	0.0133	0.0027
Deviation from average temp. diff., pos RU, Δθ (°C)							
Deviation from average temp. diff., pos RM, Δθ (°C)	0.0007	0.0006	0.0000	0.0013	-0.0135	-0.0181	-0.0050
Deviation from average temp. diff., pos RL, Δθ (°C)	0.0011	0.0015	0.0001	0.0019	-0.0105	-0.0106	-0.0013

Table 6 Turbine efficiency deviation from average value, low pressure measuring section

Test no.	**311**	**312**	**313**	**314**	**315**	**316**	**317**
Turbine discharge at H_{sp}, Q (m^3/s)	4.04	5.08	4.77	5.68	2.93	1.76	4.80
Turbine efficiency deviation, pos LU, Δη (%pp)	-0.08	0.17	2.38	0.14	0.01	0.03	1.92
Turbine efficiency deviation, pos LM, Δη (%pp)	-0.11	0.95	0.95	0.18	0.03	0.02	1.15
Turbine efficiency deviation, pos LL, Δη (%pp)	-0.10	1.53	1.66	0.35	0.02	0.00	1.41
Turbine efficiency deviation, pos RU, Δη (%pp)							
Turbine efficiency deviation, pos RM, Δη (%pp)	0.11	-1.71	-1.82	-0.54	-0.01	-0.04	-0.71
Turbine efficiency deviation, pos RL, Δη (%pp)	0.19	-0.93	-3.17	-0.13	-0.05	-0.02	-3.76
Test no.	**318**	**318x**	**319**	**320**	**321**	**322**	**323**
Turbine discharge at H_{sp}, Q (m^3/s)	4.00	4.00	2.99	4.18	4.69	5.12	5.67
Turbine efficiency deviation, pos LU, Δη (%pp)	-0.06	-0.08	0.01	-0.12	0.81	0.74	0.23
Turbine efficiency deviation, pos LM, Δη (%pp)	-0.10	-0.10	0.01	-0.15	0.78	1.44	0.29
Turbine efficiency deviation, pos LL, Δη (%pp)	-0.09	-0.10	-0.03	-0.18	1.80	1.89	0.38
Turbine efficiency deviation, pos RU, Δη (%pp)							
Turbine efficiency deviation, pos RM, Δη (%pp)	0.10	0.08	0.00	0.18	-1.90	-2.56	-0.72
Turbine efficiency deviation, pos RL, Δη (%pp)	0.15	0.21	0.01	0.27	-1.49	-1.50	-0.18

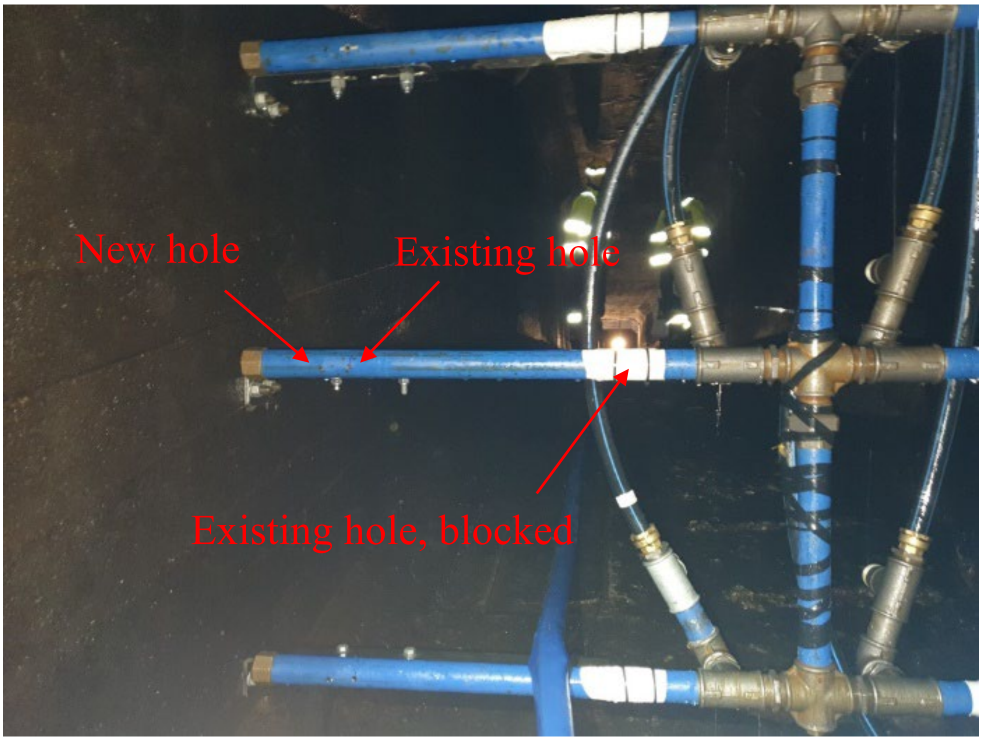


Figure 6 Tapping holes configuration sampling frame low pressure measuring section

3.3 Additional checks

The large temperature scattering recorded at the low pressure measuring section when the draft tube swirl is absent (poor mixing), indicates that there is water added to the main discharge upstream of the low pressure measuring section.

Therefore, further checks on the cooling water system were made. Finally, it was made possible to trace the cooling water return from the generator coolers and the generator bearings back to the draft tube cone/bend.

4 Correction of measured efficiency

Knowing the generator losses (established at the FAT, see Appendix 3 for values), it was possible to correct the measurements for the amount of energy added to give the true turbine efficiency. The corrections were made according to IEC 60041 Appendix H.2 Adding a discharge q (see Equation (1)).

$$E_m = (e_1 - e_2) + \phi \cdot (e_3 - e_2) \tag{1}$$

where $(e_3 - e_2)$ is found from the relation (see Equation (2)):

$$P_{Losses} = (e_3 - e_2) \cdot \varrho \cdot q \tag{2}$$

Based on the data given in Appendix 3, a correction curve for P_{Losses} was made (see Figure 7). The bearings represent a constant loss (friction). The iron losses, the copper losses and the rotor losses will be transferred through the generator coolers.

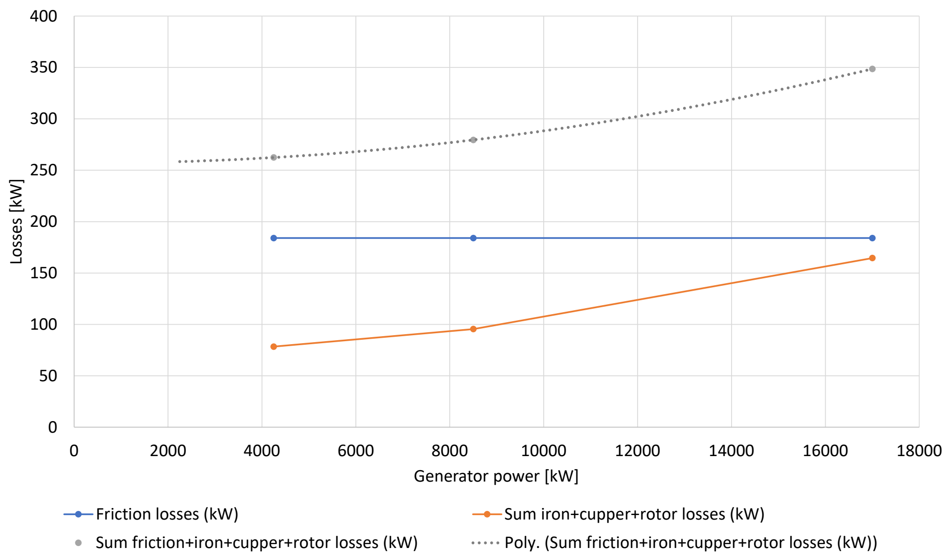


Figure 7 Generator losses as a function of generator output

5 Final test result

Correcting the measurements according to the procedure described in chapter 4, the final test results become as shown in Figure 8. The diagram also includes the test results from the first test also corrected according to the same procedure.

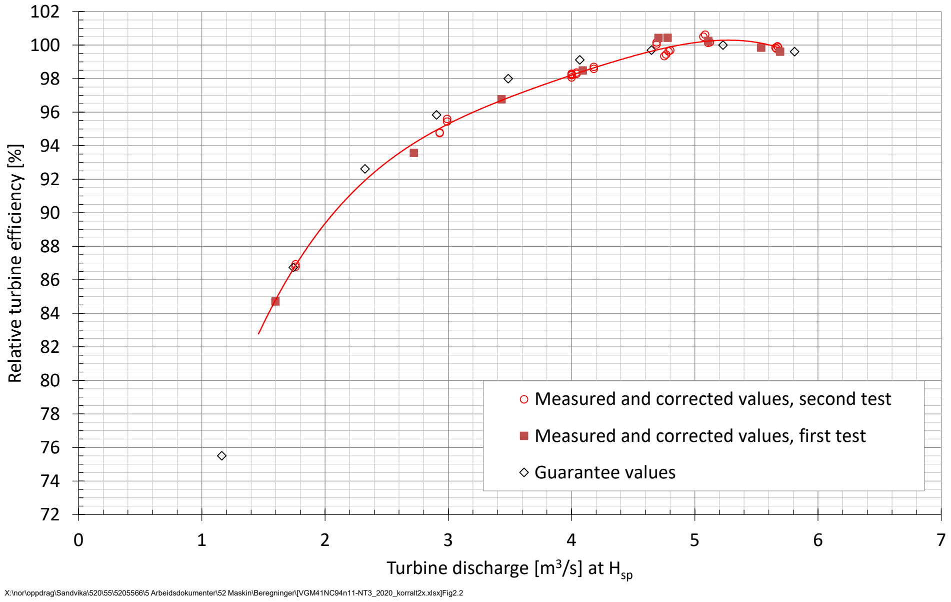


Figure 8 Turbine efficiency, final test results

The corrections made are transposing the turbine efficiency back to expected level, and the turbine efficiency could finally be accepted. It also worth noticing that the first measurement using a collecting sampling frame repeats the second measurement using individual temperature recording even though the measuring conditions are unfavourable.

6 Conclusion/lessons to be learned

The main lesson to be learned from the measurements presented, is that you have to know all discharges extracted or added between the high and the low pressure measuring section to avoid unnecessary doubt on the test results. Extraordinary investigations may be time consuming and expensive.

A test arrangement with several individual temperature sensors at the low pressure measuring section may help you detect any unknown discharge added between the two measuring sections; the temperature distribution will be very uneven.

Knowing all your discharges, the measurements can be corrected according to the amount of energy extracted or added to the main discharge. The correction may be based on data available, or the amount of energy can be determined through temperature and flow measurements at site.

The measurements performed confirms the robustness of the thermodynamic method when it comes to acquiring reliable data.

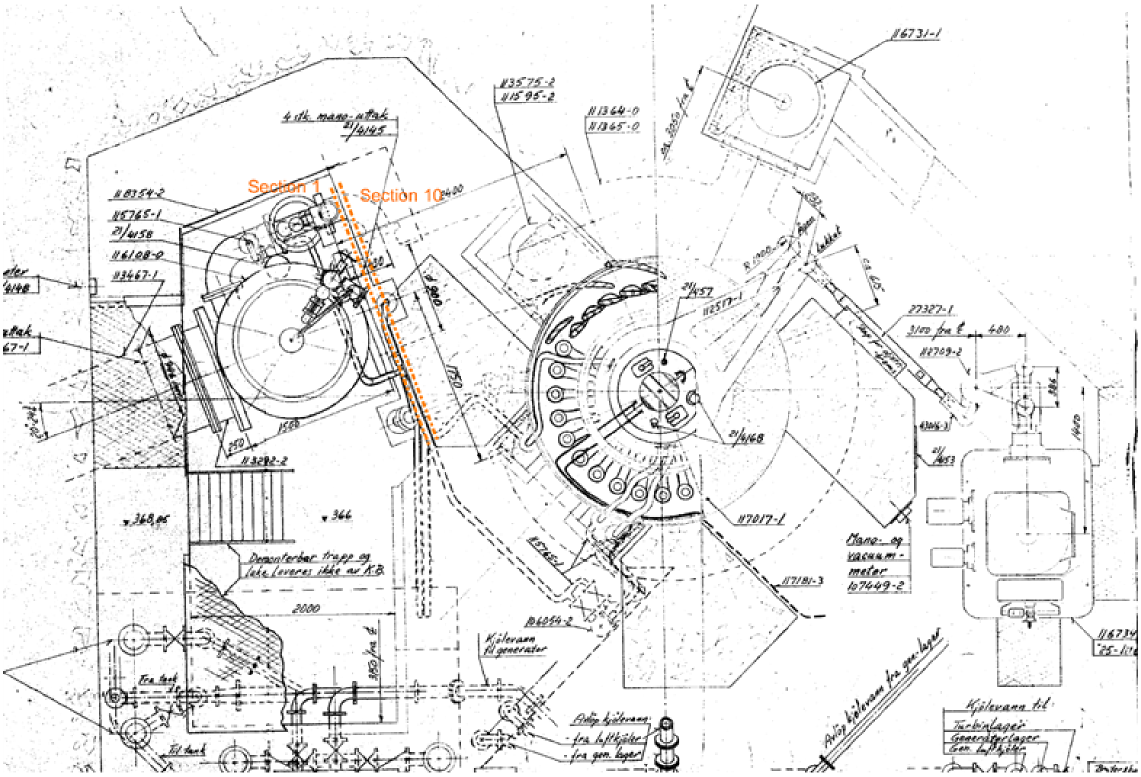
With a uniform flow profile at the high pressure measuring section, the measurements show that the sampling probe position is not of importance for determining the specific mechanical energy when the pipe diameter is small. Positioning of the sampling probe in the immediate wake of a butterfly valve is of course prohibited. The proposed systematic uncertainty due to the energy distribution across the measuring section of ±0.2 % of E_m (IEC 60041 chapter 14.7) seems therefore to be an adequate number.

Even at unfavourable measuring conditions, a simplified test arrangement using an averaging collecting frame seems to produce reliable results compared to individual temperature registrations, at least for small cross-sectional areas.

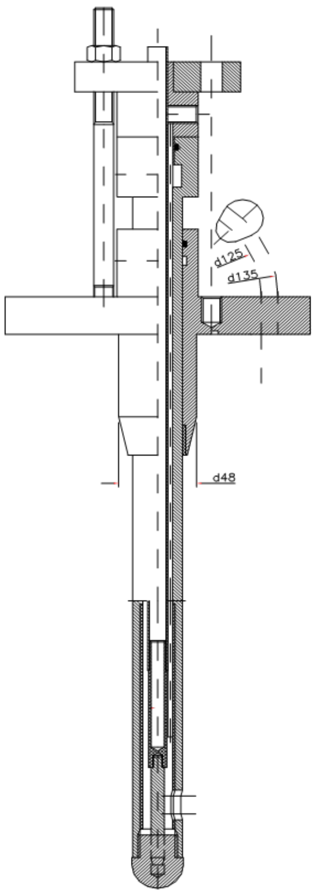
7 References

[1] IEC 60041: *Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines*, 3.ed. 1991-11

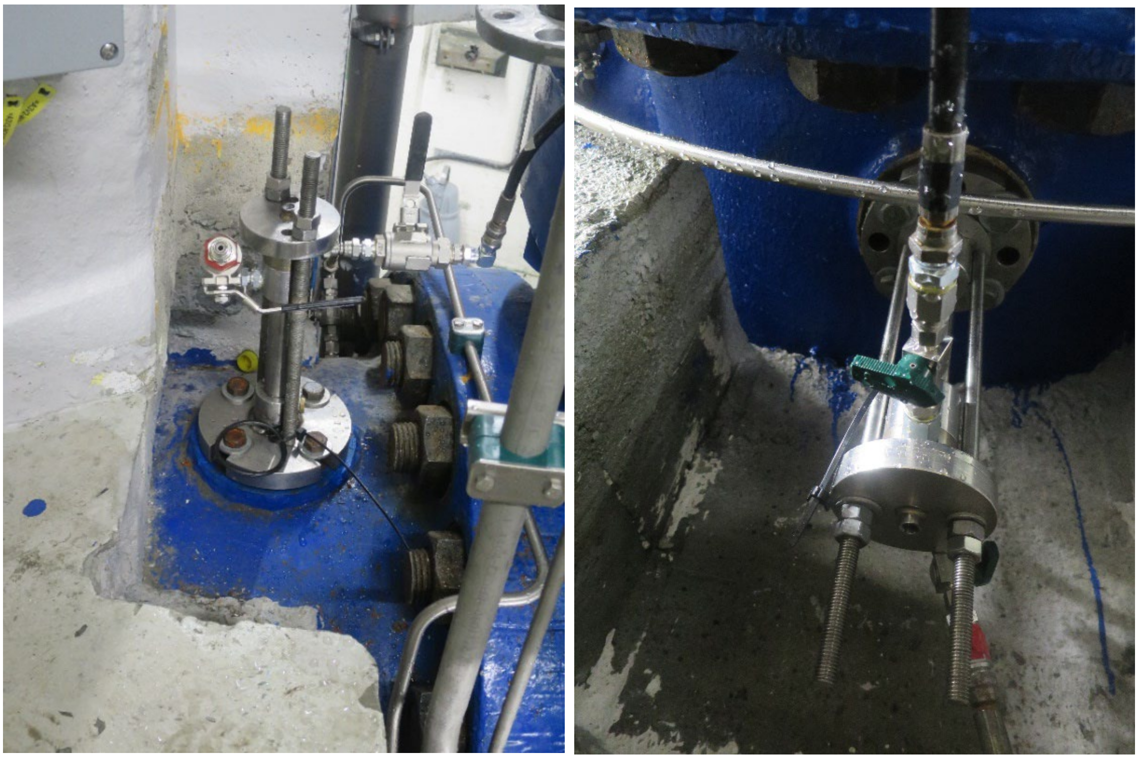
Appendix 1 High pressure measuring section



High pressure measuring section, location



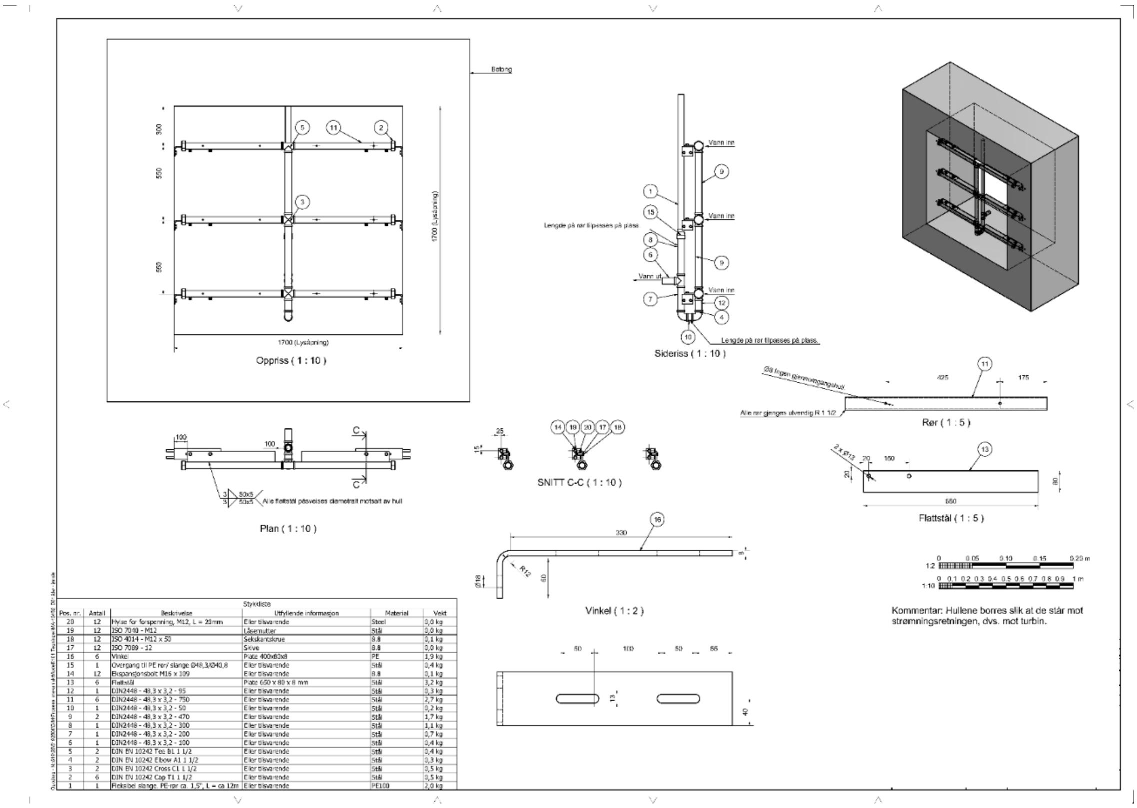
Sampling probe



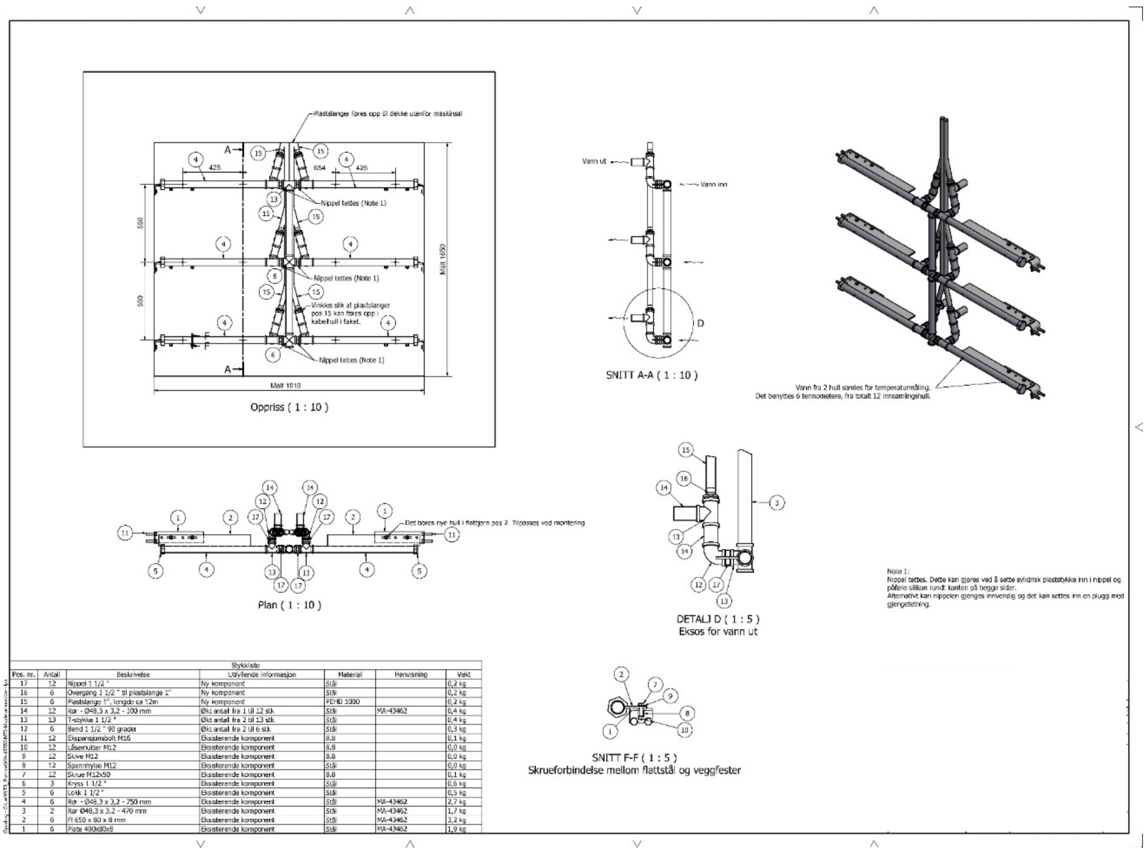
Sampling probe located at top and bottom of spiral casing

Appendix 2 Low pressure measuring section

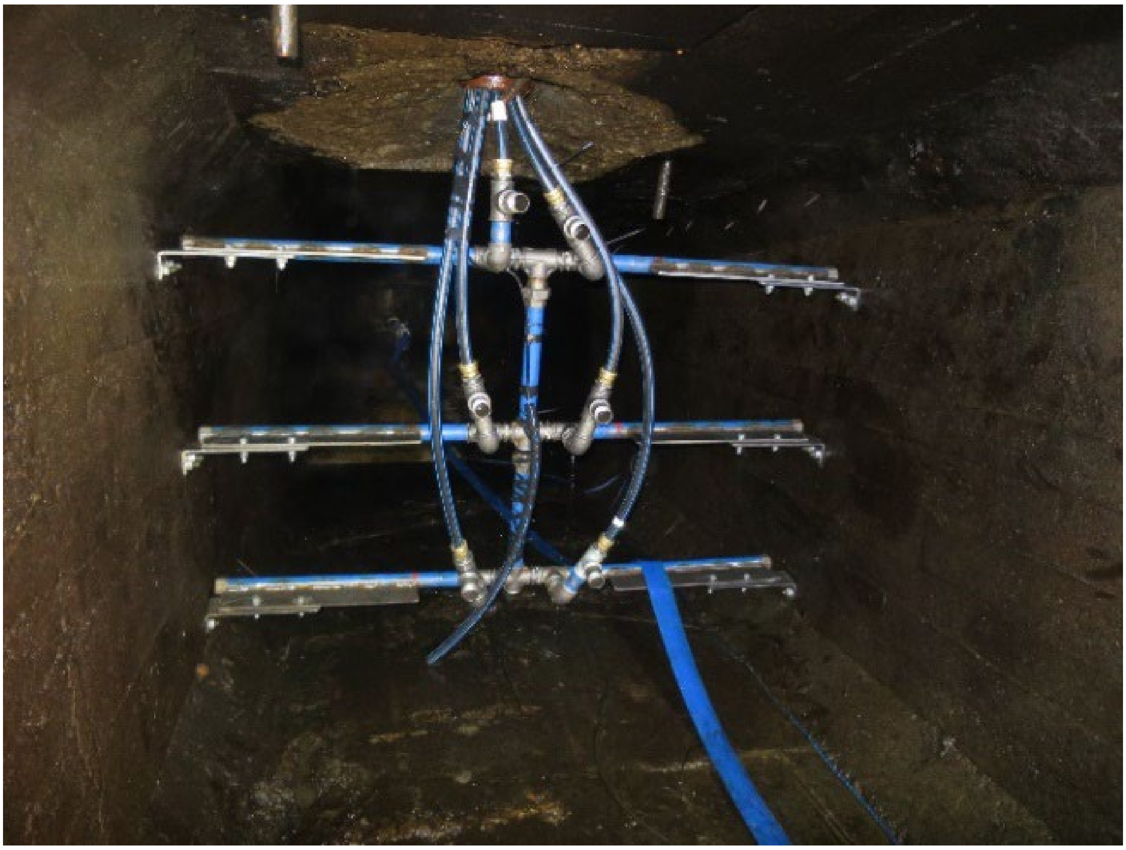
Low pressure measuring section, location



Sampling frame first measurement (average collecting frame)



Sampling frame second measurement (six individual temperature registrations)



Sampling frames first (top) and second (bottom) measurement

Appendix 3 Generator losses

Virkningsgrad.

13 MW. – 1250 H. – 6,3 MW >6,4 MW.
4 MW.

Last	1/1	1/1	1/2	1/2
cos. Ø.	0,8	1,0	0,8	1,0
Tap i KV				
Friksjon	184,0	184,0	184,0	184,0
Jern	58,2	58,2	58,2	58,2
Kobber	78,5	78,5	19,6	19,6
Rotor + börste	50,3	27,92	27,05	17,7
Magn.maskin	7,57	5,25	5,14	4,16
Sum tap	378,57	353,87	293,99	283,66
Avgitt effekt	13600	17000	6800	8500
Virknings-grad %	97,29	97,96	95,85	96,77
Garantert virkningsgrad %	97,3	98,0	96,2	97,0

N. I. form. nr. 560 B. 9000. 2-63. Merkur.

Avleste verdier på strømningsvaktene

Olje til bærelager: 7 x 70 = 490 l/min.
Vann til bærelagerkjølere: 10,5 x 30 = 315 l/min.
" " nedre styrelager: 7,2 x 2 = 15 "
" " luftkjølerne: 8 x 70 = 560 "

Generator losses established at FAT