Thermodynamic Efficiency Measurements of Pelton Turbines. Experience from Investigation of Energy / Temperature Distribution in the Discharge Canal Measuring Section.

by

Harald Hulaas, Erik Nilsen and Leif Vinnogg, Norconsult, Norway
Eirik Bøkko, E-CO Vannkraft, Norway

Abstract

During the last 10 years Norconsult has measured over 350 turbines using the thermodynamic method, and about 40% of the measured turbines were Pelton turbines. Using data from some of the latest measurements we have gathered information about the measured energy distribution from a sample of 25 of these turbines.

There are different ways of taking water samples for temperature measurement from different locations in the measuring section. One way is to use a central mixing chamber with temperature sensor and 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. Another method is to have 3 or more vertical perforated pipes from the canal bottom up to a bridge over the canal, 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.

The importance of doing exploration of temperature distribution in the measuring section becomes obvious from studying these data.
Pelton turbines with horizontal shaft have more even energy distribution than the ones with vertical shaft.
It also appears clearly that sufficient distance from measuring section to turbine centre is important to reduce uncertainty.

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. Thus, the turbine efficiency is

$$\eta = E_m / E$$

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 term "mechanical energy" (E_m) in this special application, is also in general thermodynamics 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 measuring cross section of the flow passage (like in a current meter set-up) to find the real average specific mechanical energy in the flow, but practical experience has fortunately shown that only a rather limited number of sampling points are required. This is specified in the test code, Ref. [1]. 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 article deals with uncertainty of energy / temperature distribution in the open canal flow from Pelton turbines. Previously we have presented uncertainty analyses of test result focusing both on the inlet and the outlet measuring section of Francis and Pelton turbines, Ref. [2] and [3]. However, the data in this article are new and presented in a somewhat different way than before.

Measuring procedure and equipment

The "direct operating procedure" is applied, which means that the turbine inlet temperature and the temperature difference ΔT between turbine inlet and outlet measuring sections are measured / calculated directly (and monitored continuously).

Temperature measurements are done with PT 100 sensors connected to a precision meter with data acquisition / switch capacities "Hewlett Packard 34970 A" and further to the PC.

Pressure measurements (at temperature sensor in inlet probe and at piezometer section of turbine distributor inlet) are done with pressure transducer "Paroscientific Digiquartz Mod.1000 psia or 3000 psia" (depending on the head) connected to the PC.

IEC test code requirements and recommendations

The test code, Ref. [1], specifies measuring conditions to be fulfilled in the measuring sections. For measuring sections with free surface a distance between 4 and 10 runner diameters (OD) has been found satisfactory for Pelton turbines, because this will ensure an adequate mixing of water without having significant heat exchange with surroundings.
In the measuring section exploration of the temperature variation shall be made in at least 6 points, and if the calculated efficiency deviates as much as 1,5 % between any two points, additional actions (as for instance index tests) are required to support the final test result. However, an efficiency difference of 1,5 % for a Pelton turbine with for instance 800 m head is equivalent with 12 m hydraulic head difference or about 30 mK temperature difference. Such an uneven temperature distribution is very rare.
Further the test code, Ref. [1], states that systematic uncertainty due to absence of exploration of energy distribution can amount to ± 0,6 % of specific mechanical energy, independent of turbine type, but that large deviation is also very unusual for high-head turbines. Nevertheless, for practical reasons and to avoid discussions this figure is often used in the analysis of uncertainty of acceptance tests, even if an exploration of temperature variation is made.

Ways of taking samples

The primary parameter for determination of energy distribution is the water temperature. If the temperature variation is small, the velocity distribution does not matter.
There are different ways of taking water samples for temperature measurement from different locations in the measuring section. One way is to use a horizontal "sampling beam" with a central mixing chamber with temperature sensor and sampling pipes from 4 or 6 points distributed over the canal width, which has proved to give a good average over the width, see **Fig.1**. The "beam" is then held in different depths to get the vertical temperature variation.

Another method is to have three or more vertical perforated pipes standing from the canal bottom up to a bridge over the canal, with temperature sensors that are placed in various elevations in each of the pipes to get the temperature variation over the measuring section, see **Fig. 2**.
Special concern for both methods has been possibilities of secondary flow phenomena in the pipes, and the extra time needed for the flow to reach the temperature sensor (important when there is a variation of water temperature over time and a correction is needed). A comparison between a horizontal sampling beam and a large array of fixed thermometers (and current meters) is described in Ref. [4]. Only a systematic deviation of about 1 mK could be seen, but that is insignificant related to high head turbines.
The upper layer of the canal flow from a Pelton turbine has entrained air, which means that heat exchange with the air takes place, and therefore temperature measurements in the upper layer with air entrainment are not representative for the water temperature (which often can be seen as unstable temperature and a steep temperature gradient in the vertical section).

Figure 1 Horizontal "sampling beam"

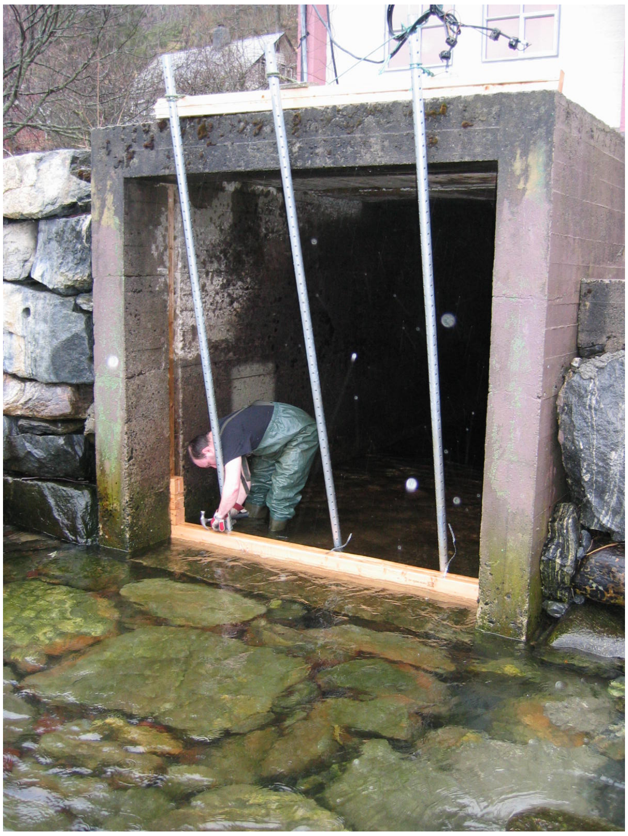

Figure 2 Vertical perforated pipes

Units tested and test results

During the last 10 years Norconsult has measured over 350 turbines using the thermodynamic method, and about 40% of the measured turbines were Pelton turbines. From efficiency measurements of 25 different Pelton turbines the temperature variation in the measuring section has been collected and investigated to find typical patterns and "normal" temperature variations, - if any. The types vary from small horizontal shaft machines with 2 injectors to large vertical shaft machines with 6 injectors. Power varies in the range 9 to 280 MW and head varies from 316 to 1034 m. The water sampling system in the discharge canal was horizontal pitot branch pipes for 10 turbines and perforated standing pipes for 15 turbines, see **Table 1** below.

Table 1 Number of units in each group

	Horizontal pitot pipes	Perforated standing pipes
Horizontal shaft	4	6
Vertical shaft	6	9

There are not so many in each group, so the statistical analyses are to some extent questionable, but trends are clearly seen. Unfortunately the distance from the turbine centre to the measuring section is too short for some tests, so some "outliers" are found.

The mechanical energy E_m is found based on measured mechanical energies (e_{m1} - e_{m2}) in the two measuring sections. A series of E_m vales is calculated, - one for each position of the temperature sensor in the outlet measuring section. The temperature and pressure in the inlet sampling probe is measured for each temperature sensor position in the outlet. The average E_m for all temperature sensor positions is then calculated, and the variation of E_m over the measuring section relative to $E_{m\ average}$ appears. It is presented in percent, and max deviation between any two positions is found, and the standard deviation (σ) is also calculated. Based on this an uncertainty of E_m "due to absence of exploration of energy distribution" can be found. We propose using $\pm 2 \cdot \sigma$, i.e. 95 % confidence level.

"Maps" showing E_m distribution for all 25 turbines at full load (max), best efficiency point (BEP) and part load (~ 30%) are shown in **Appendix 1** and **Appendix 2**. The turbine data and test data are presented in two tables, one for tests with standing perforated pipes and one for tests with horizontal pitot branch pipes.

It was of interest to see if the E_m uncertainty did have any correlation with:

1. turbine head
2. distance from turbine centre to measuring section
3. turbine shaft direction (horizontal / vertical)
4. turbine opening (full load, best efficiency and part load)
5. water velocity in measuring section
6. water depth in measuring section

We first look at the measurements with <u>perforated standing pipes</u>. The plants / units named "A" to "I" have vertical turbine shaft, and the plants / units "J" to "O" have horizontal shaft. The first pair of diagrams, **Fig. 3 a** and **b**, shows E_m uncertainty ($2 \cdot \sigma$) in percent versus turbine head. The vertical shaft turbines show a much more uneven E_m distribution than the horizontal shaft turbines, and this must be due to the more symmetrical discharge pattern into the pit from a horizontal shaft turbine. The E_m uncertainty (in percent) decreases with increasing head, which has been stated in previous papers, Ref. [3].

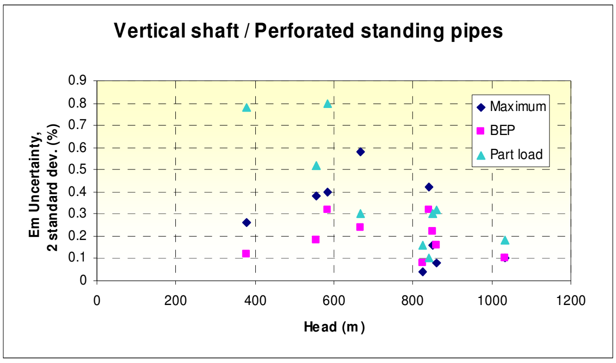

Figure 3a E_m uncertainty in % ($2\ \sigma$)

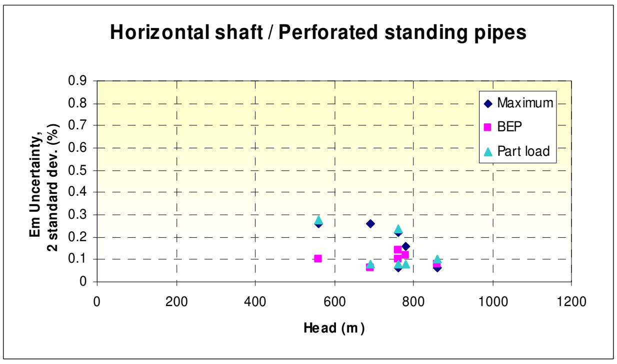

Figure 3b E_m uncertainty in % ($2\ \sigma$)

The second pair of diagrams, **Fig. 4 a** and **b**, shows E_m uncertainty versus the relative distance from turbine centre to measuring section (L / D_{max}). The horizontal shaft turbines show little E_m scatter in the distance range L/D from 4 to 10. Some vertical shaft turbines are showing a larger deviation at part load and full load even if the measuring sections are about 6 D from the turbine centre (plants / units C and E). It is also obvious that when the distance is down to 4 D and less, the uncertainty increases. At best efficiency point (BEP) the discharge flow pattern should be close to ideal, and the E_m uncertainty at BEP in **Fig. 4** a is moderate, 0,3 % and less. From looking at the influence of canal depth or average flow velocity no significant correlation with E_m uncertainty was found.

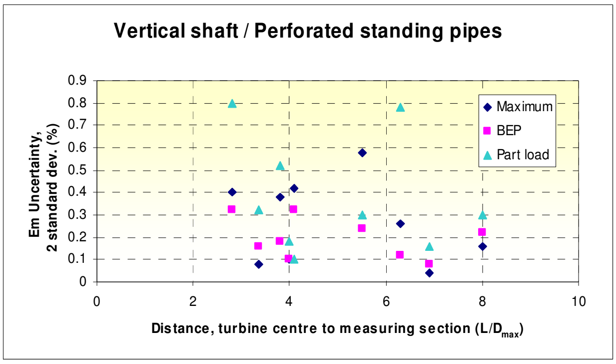

Figure 4a E_m uncertainty in % (2 σ)

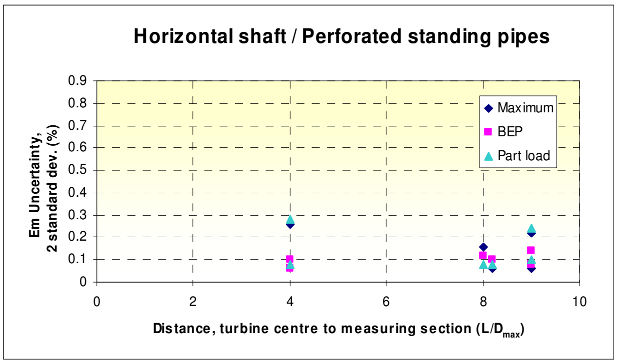

Figure 4b E_m uncertainty in % (2 σ)

We then look at the measurements with horizontal sampling pitot pipes. The plants / units named "P" to "U" have vertical turbine shaft, and the plants / units "V" to "Y" have horizontal shaft. The first pair of diagrams, **Fig. 5 a** and **b**, shows E_m uncertainty (2·σ) in percent versus turbine head. **Fig. 5 a** has two plants / units, "R" and "T" with head 700 m and 640 m, but they show a relatively high E_m uncertainty. The reason for this is a short distance from the turbine centre (3,2 D and 4,1 D). **Fig 5 b** (horizontal shaft units) shows relatively small E_m uncertainties except for one plant / unit, "V", with 610 m head and distance from turbine centre 4,5 D. Unit "V" is actually in the same power plant as unit "W", and the discharge canals are identical. The only difference is that "V" had lost a guide shield in the turbine housing, and it was also clearly seen on efficiency.

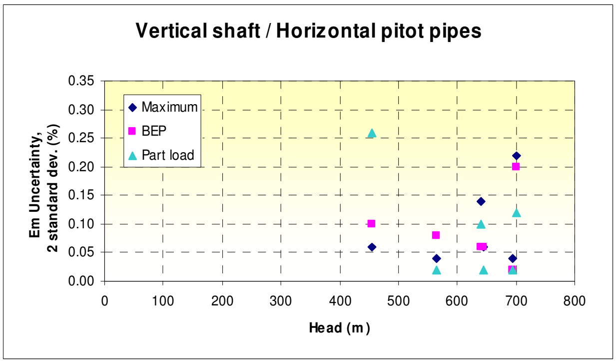

Figure 5a E_m uncertainty in % (2 σ)

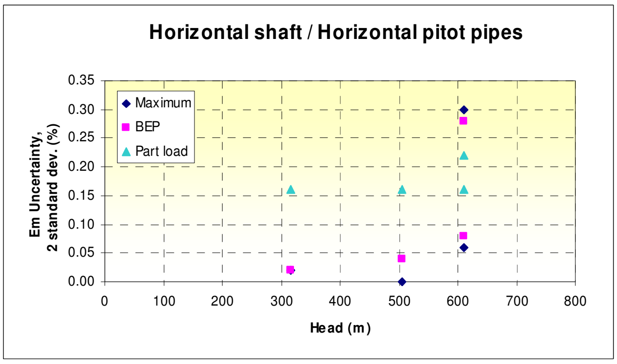

Figure 5b E_m uncertainty in % (2 σ)

The second pair of diagrams, **Fig. 6 a** and **b**, shows E_m uncertainty versus the relative distance from turbine centre to measuring section (L / D_{max}). **Fig. 6 a** (vertical shaft units) demonstrates clearly the importance of distance from measuring section to turbine. Here are two groups, one with distance 3 to 4 D with large E_m uncertainty, and one with distance 10 to 12 D with small E_m uncertainty. **Fig 6 b** (horizontal shaft units) shows about the same E_m uncertainty for units near the turbine (4,5 D). However, one turbine ("Y") shows a relatively large E_m uncertainty at part load even if the distance from the turbine is 8 D. The reason for this is that the canal is wide (7 m split in two by a mid-pier, i.e. two pitot beams with mixing chambers), and the flow is shallow at part load, only 0,3 m and the average velocity was high 1,64 m/s. This is the only measurement where the water depth in the canal obviously creates extra uncertainty.

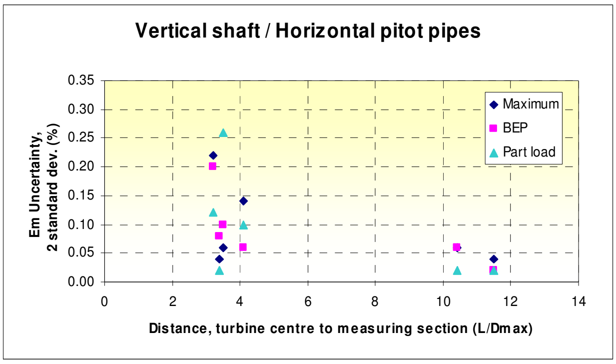

Figure 6a E_m uncertainty in % (2 σ)

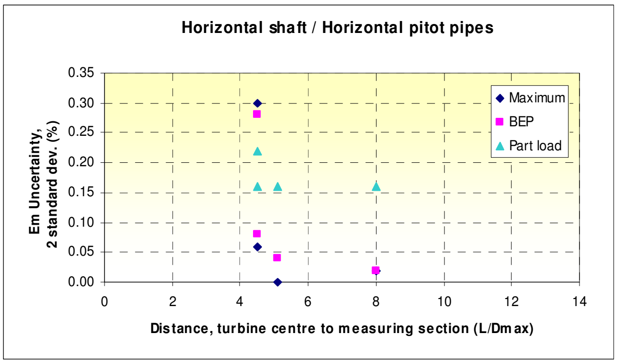

Figure 6b E_m uncertainty in % (2 σ)

The average of the 2·σ deviation of the energy distribution is calculated for each of the 4 groups listed in Table 1, and the results are shown in **Table 2** below.

Table 2. Average 2·σ deviation

	Perforated Standing Pipes		Horizontal Pitot Pipes	
	Vertical shaft	Horizontal shaft	Vertical shaft	Horizontal shaft
Maximum [%]	0.27	0.17	0.09	0.13
BEP [%]	0.19	0.10	0.09	0.11
Part Load [%]	0.38	0.14	0.09	0.18
Average [%]	0.28	0.14	0.09	0.14

Vertical shaft units show about twice the deviation found for horizontal shaft units when both types are measured with standing perforated pipes.
For vertical units measured with horizontal pitot pipes the deviation is smaller (about 1/3) compared to when standing perforated pipes are used, because the energy is already averaged in the mixing chamber for the sampling pitots. In the energy distribution maps in Appendix 1 (perforated standing pipes) the average deviation in each level is calculated, and it is interesting to see that it brings the deviation down to about the same as measured with horizontal pitot pipes.
For horizontal units the average energy deviation is the same for measurements with perforated standing pipes and measurements with horizontal pitot pipes, which clearly tells that for most horizontal shaft Pelton turbines the energy distribution in the flow in the outlet canal is quite uniform over the width.
Surprisingly the energy distribution using horizontal pitot pipes is identical for all loads on the vertical units, - probably a coincidence.

Conclusions

1. To make a full exploration of the E_m uncertainty in the measuring section, the standing perforated pipes are well suited, - often 9 points (3 x 3) are used in order to get the full pattern. This is most important for vertical shaft Pelton turbines where the energy distribution can be quite uneven over the canal width, in particular for operation away from the best efficiency point. By doing this full mapping a representative figure for systematic uncertainty of energy distribution is found, most probably well below the ± 0,6 % of specific mechanical energy indicated in the test code, Ref. [1].

2. The average $2 \cdot \sigma$ of the energy distribution at vertical units, measured in vertical perforated pipes, is about twice of that for horizontal units. For horizontal shaft turbines the discharge into the pit and further to the canal is quite symmetrical so the vertical gradient of energy in the measuring section is more important, and then a horizontal pitot pipe beam (with 4 or 6 orifices) will be sufficient. It averages "automatically" the measurements over the canal width.

3. The distance from the turbine centre to the measuring section is important. The minimum distance set in the test code, Ref [1], is 4 runner diameters, and the measurements show that it should be the absolute minimum. A bit longer distance will improve the energy distribution.

4. When turbine head increases the % uncertainty of energy measurement decreases.

5. In this study neither the water depth in the measuring section of the canal nor the flow velocity seems to have any impact on the uncertainty of the energy measurements. Only one extreme case with shallow water (0,3 m) at part load and relatively high velocity (1,6 m/s) showed increased uncertainty.

6. Our data — together with Ref. [4] — indicates that using horizontal sampling branch pipes give a good average of the energy distribution, but the extremes are not mapped as with perforated standing pipes.

References

[1] IEC Publication 60041 “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

[3] Bøkko, Nilsen, Vinnogg: "Thermodynamic Efficiency Measurements. The Uncertainty of Efficiency versus Hydraulic Head", IGHEM Conference, Kempten, June 2000.

[4] Bryhni, Dahlhaug, Hulaas: "Multipoint Thermodynamic measurements - A Statistical Approach to Uncertainty Levels", IGHEM Conference, Kempten, June 2000.

Appendix 1 Standing perforated pipes

Data:

Unit no.:		A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
Rated output, P =	MW	280	2x127	117	103	11.2	188	90	106.7	66.6	9.2	38	61.1	29.6	15.6	15.5
Rated head, H =	m	840	825	668	585	378	1034	860	850	555	860	780	760	760	690	560
Rated speed, n =	rpm	500	500	450	428.6	720	428.6	600	500	428.6	1000	500	428.6	500	750	500
Shaft orientation:		Vertical	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical	Vertical	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal	Horizontal
No. of jets:		6	6	6	6	6	5	5	4	4	2	2	2	2	2	2
Canal width:	m	5.00	5.40	6.10	3.80	3.00	4.50	2.90	3.80	3.60	2.20	3.50	4.00	3.00	1.86	1.86
Distance from turbine:	runner diameters	4.10	6.90	5.50	2.80	6.30	4.00	3.35	8.00	3.80	9.00	8.00	9.00	8.20	4.00	4.00
Turbine opening:		Maximum	Maximum	Maximum	Maximum	Maximum	Maximum	Maximum	Maximum	Maximum	Maximum	Maximum	Maximum	Maximum	Maximum	Maximum
No. of jets:		6	6	6	6	6	5	5	4	4	2	2	2	2	2	2
Turbine flow	m3/s	37.72	37.18	22.41	19.10	3.05	21.39	12.24	14.05	13.94	1.23	5.60	9.00	4.38	2.64	3.27
Water depth:	m	3.65	3.81	2.45	2.20	0.70	4.40	3.97	2.10	1.76	0.75	1.25	1.00	1.10	2.00	2.14
Average flow velocity	m/s	2.07	1.81	1.50	2.28	1.45	1.08	1.06	1.76	2.20	0.75	1.28	2.25	1.33	0.71	0.82
Difference in extreme values:	%	0.55	0.06	1.10	0.56	0.44	0.19	0.11	0.24	0.60	0.10	0.26	0.31	0.11	0.36	0.43
Standard deviation:	%	0.21	0.02	0.29	0.20	0.13	0.05	0.04	0.08	0.19	0.03	0.08	0.11	0.03	0.13	0.13
2 x Standard deviation	%	0.42	0.04	0.58	0.4	0.26	0.1	0.08	0.16	0.38	0.06	0.16	0.22	0.06	0.26	0.26
Turbine opening:		BEP	BEP	BEP	BEP	BEP	BEP	BEP	BEP	BEP	BEP	BEP	BEP	BEP	BEP	BEP
No. of jets:		6	6	6	6	6	5	5	4	4	2	2	2	2	2	2
Turbine flow	m3/s	27.66	25.31	12.57	15.21	2.22	17.31	8.91	11.45	9.41	1.02	4.02	6.43	3.55	1.94	2.42
Water depth:	m	3.13	2.96	2.43	2.20	0.64	4.27	3.83	1.95	1.61	0.65	1.20	1.00	1.00	1.85	1.97
Average flow velocity	m/s	1.77	1.58	0.85	1.82	1.16	0.90	0.80	1.55	1.62	0.71	0.96	1.61	1.18	0.56	0.66
Difference in extreme values:	%	0.49	0.12	0.48	0.44	0.21	0.22	0.28	0.32	0.30	0.11	0.22	0.25	0.16	0.09	0.17
Standard deviation:	%	0.16	0.04	0.12	0.16	0.06	0.05	0.08	0.11	0.09	0.04	0.06	0.07	0.05	0.03	0.05
2 x Standard deviation	%	0.32	0.08	0.24	0.32	0.12	0.1	0.16	0.22	0.18	0.08	0.12	0.14	0.1	0.06	0.1
Turbine opening:		Part load	Part load	Part load	Part load	Part load	Part load	Part load	Part load	Part load	Part load	Part load	Part load	Part load	Part load	Part load
No. of jets:		6 (3)	6 (4)	6 (3)	6 (3)	6 (6)	5 (3)	5 (3)	4 (2)	4 (2)	2 (1)	2 (2)	2 (2)	2 (2)	2 (2)	2 (2)
Turbine flow	m3/s	13.49	15.42	7.57	5.74	1.05	10.78	4.35	4.41	5.08	0.47	2.06	2.99	1.44	0.98	1.30
Water depth:	m	3.11	2.44	2.44	2.10	0.58	4.20	3.63	1.90	1.61	0.65	1.18	1.00	0.77	1.85	1.68
Average flow velocity	m/s	0.87	1.17	0.51	0.72	0.60	0.57	0.41	0.61	0.88	0.33	0.50	0.75	0.62	0.28	0.42
Difference in extreme values:	%	0.14	0.22	0.45	1.21	1.40	0.28	0.55	0.45	0.87	0.16	0.11	0.35	0.14	0.11	0.37
Standard deviation:	%	0.05	0.08	0.15	0.40	0.39	0.09	0.16	0.15	0.26	0.05	0.04	0.12	0.04	0.04	0.14
2 x Standard deviation	%	0.1	0.16	0.3	0.8	0.78	0.18	0.32	0.3	0.52	0.1	0.08	0.24	0.08	0.08	0.28

Energy distribution "maps":

Plant no.: **Deviation from average temperature difference in % of specific mechanical energy, E_m**

A

Maximum			Level avg.	BEP			Level avg.	Part load			Level avg.
0.24 %	0.09 %	-0.19 %	0.05 %	0.09 %	-0.09 %	-0.24 %	-0.08 %	0.04 %	0.03 %	-0.06 %	0.00 %
0.27 %	-0.14 %	-0.20 %	-0.02 %	0.21 %	0.01 %	-0.16 %	0.02 %	0.05 %	0.03 %	-0.06 %	0.01 %
0.28 %	-0.09 %	-0.27 %	-0.03 %	0.26 %	0.05 %	-0.14 %	0.06 %	0.04 %	0.02 %	-0.09 %	-0.01 %
Largest difference:		0.55 %		Largest difference:		0.49 %		Largest difference:		0.14 %	
Standard deviation:		0.21 %		Standard deviation:		0.16 %		Standard deviation:		0.05 %	

B

Maximum			Level avg.	BEP			Level avg.	Part load			Level avg.
0.04 %	-0.02 %	-0.01 %	0.00 %	0.05 %	0.02 %	-0.01 %	0.02 %	-0.10 %	-0.07 %	0.05 %	-0.04 %
0.01 %	-0.01 %	0.00 %	0.00 %	0.04 %	-0.02 %	-0.04 %	-0.01 %	-0.07 %	-0.02 %	0.10 %	0.00 %
0.00 %	-0.02 %	0.00 %	-0.01 %	0.06 %	-0.04 %	-0.06 %	-0.01 %	-0.03 %	0.03 %	0.12 %	0.04 %
Largest difference:		0.06 %		Largest difference:		0.12 %		Largest difference:		0.22 %	
Standard deviation:		0.02 %		Standard deviation:		0.04 %		Standard deviation:		0.08 %	

C

Maximum			Level avg.	BEP			Level avg.	Part load			Level avg.
0.00 %	0.33 %	0.53 %	0.29 %	-0.28 %	-0.07 %	-0.02 %	-0.12 %	-0.06 %	0.26 %	-0.12 %	0.03 %
-0.17 %	-0.03 %	0.07 %	-0.04 %	0.20 %	0.10 %	0.02 %	0.11 %	0.01 %	0.19 %	-0.19 %	0.00 %
-0.03 %	-0.57 %	-0.14 %	-0.25 %	-0.01 %	0.02 %	0.04 %	0.02 %	-0.10 %	0.15 %	-0.13 %	-0.03 %
Largest difference:		1.11 %		Largest difference:		0.48 %		Largest difference:		0.45 %	
Standard deviation:		0.29 %		Standard deviation:		0.12 %		Standard deviation:		0.15 %	

D

Maximum			Level avg.	BEP			Level avg.	Part load			Level avg.
-0.14 %	0.22 %	0.35 %	0.14 %	-0.02 %	0.10 %	0.20 %	0.09 %	-0.20 %	0.05 %	0.50 %	0.12 %
-0.21 %	-0.01 %	0.22 %	0.00 %	-0.18 %	-0.11 %	0.22 %	-0.02 %	-0.56 %	-0.04 %	0.33 %	-0.09 %
-0.20 %	-0.16 %	-0.06 %	-0.14 %	-0.22 %	-0.12 %	0.13 %	-0.07 %	-0.71 %	0.27 %	0.36 %	-0.03 %
Largest difference:		0.56 %		Largest difference:		0.44 %		Largest difference:		1.21 %	
Standard deviation:		0.20 %		Standard deviation:		0.16 %		Standard deviation:		0.40 %	

E

Maximum			Level avg.	BEP			Level avg.	Part load			Level avg.
0.02 %	-0.02 %	0.10 %	0.03 %	0.09 %	0.06 %	-0.04 %	0.04 %	-0.33 %	-0.27 %	-0.79 %	-0.47 %
0.02 %	0.02 %	0.10 %	0.05 %	0.07 %	0.05 %	-0.01 %	0.04 %	-0.15 %	-0.04 %	-0.03 %	-0.07 %
0.05 %	0.02 %	-0.34 %	-0.09 %	-0.03 %	0.05 %	-0.12 %	-0.04 %	0.45 %	-0.04 %	0.60 %	0.34 %
Largest difference:		0.44 %		Largest difference:		0.21 %		Largest difference:		1.40 %	
Standard deviation:		0.13 %		Standard deviation:		0.06 %		Standard deviation:		0.39 %	

F

-0.07 %	-0.01 %	0.12 %	0.01 %	-0.11 %	0.00 %	0.10 %	0.00 %	0.12 %	0.05 %	0.16 %	0.11 %
-0.04 %	0.00 %	0.02 %	-0.01 %	-0.02 %	0.00 %	0.01 %	0.00 %	-0.07 %	-0.01 %	-0.01 %	-0.03 %
-0.02 %	0.00 %	0.00 %	0.00 %	0.01 %	0.00 %	0.01 %	0.01 %	-0.12 %	-0.06 %	-0.05 %	-0.08 %
Largest difference:		0.19 %		Largest difference:		0.22 %		Largest difference:		0.28 %	
Standard deviation:		0.05 %		Standard deviation:		0.05 %		Standard deviation:		0.09 %	

G

0.04 %	0.04 %	-0.01 %	0.02 %	0.06 %	0.05 %	0.14 %	0.08 %	0.21 %	0.11 %	0.12 %	0.15 %
0.04 %	0.03 %	-0.04 %	0.01 %	0.03 %	-0.04 %	0.02 %	0.01 %	0.07 %	-0.21 %	0.08 %	-0.02 %
0.00 %	-0.03 %	-0.07 %	-0.03 %	-0.01 %	-0.12 %	-0.14 %	-0.09 %	-0.06 %	-0.33 %	0.01 %	-0.13 %
Largest difference:		0.11 %		Largest difference:		0.28 %		Largest difference:		0.55 %	
Standard deviation:		0.04 %		Standard deviation:		0.08 %		Standard deviation:		0.16 %	

H

0.08 %	0.14 %	-0.10 %	0.04 %	0.14 %	-0.01 %	-0.13 %	0.00 %	-0.20 %	-0.03 %	0.04 %	-0.06 %
0.03 %	0.06 %	-0.09 %	0.00 %	0.14 %	0.02 %	-0.13 %	0.01 %	-0.20 %	0.01 %	0.11 %	-0.03 %
0.01 %	-0.03 %	-0.10 %	-0.04 %	0.11 %	0.03 %	-0.17 %	-0.01 %	-0.15 %	0.17 %	0.24 %	0.09 %
Largest difference:		0.24 %		Largest difference:		0.32 %		Largest difference:		0.45 %	
Standard deviation:		0.08 %		Standard deviation:		0.11 %		Standard deviation:		0.15 %	

I

0.16 %	0.13 %	0.31 %	0.20 %	0.04 %	0.12 %	0.06 %	0.07 %	0.52 %	0.04 %	-0.35 %	0.07 %
-0.03 %	-0.18 %	0.20 %	0.00 %	-0.01 %	0.09 %	-0.03 %	0.02 %	0.30 %	-0.04 %	-0.33 %	-0.02 %
-0.18 %	-0.29 %	-0.11 %	-0.19 %	-0.05 %	-0.18 %	-0.03 %	-0.09 %	0.02 %	-0.04 %	-0.12 %	-0.05 %
Largest difference:		0.60 %		Largest difference:		0.30 %		Largest difference:		0.87 %	
Standard deviation:		0.19 %		Standard deviation:		0.09 %		Standard deviation:		0.26 %	

J

0.02 %	-0.01 %	-0.08 %	-0.02 %	0.03 %	-0.03 %	-0.07 %	-0.02 %	0.11 %	0.06 %	-0.03 %	0.05 %
0.03 %	0.02 %	-0.01 %	0.01 %	0.04 %	0.01 %	-0.06 %	0.00 %	0.02 %	0.00 %	-0.05 %	-0.01 %
0.01 %	0.03 %	-0.01 %	0.01 %	0.05 %	0.03 %	0.00 %	0.03 %	-0.03 %	-0.03 %	-0.06 %	-0.04 %
Largest difference:		0.10 %		Largest difference:		0.11 %		Largest difference:		0.16 %	
Standard deviation:		0.03 %		Standard deviation:		0.04 %		Standard deviation:		0.05 %	

K

-0.03 %	-0.05 %	0.19 %	0.04 %	0.04 %	0.00 %	-0.13 %	-0.03 %	-0.03 %	-0.06 %	0.05 %	-0.01 %
-0.03 %	-0.08 %	0.03 %	-0.02 %	0.03 %	-0.03 %	0.10 %	0.03 %	0.01 %	-0.03 %	0.04 %	0.01 %
-0.03 %	-0.05 %	0.04 %	-0.01 %	0.03 %	-0.03 %	-0.01 %	0.00 %	0.01 %	-0.03 %	0.04 %	0.01 %
Largest difference:		0.26 %		Largest difference:		0.22 %		Largest difference:		0.11 %	
Standard deviation:		0.08 %		Standard deviation:		0.06 %		Standard deviation:		0.04 %	

L

0.01 %	-0.15 %	0.16 %	0.01 %	0.09 %	-0.12 %	0.03 %	0.00 %	0.14 %	-0.21 %	0.13 %	0.02 %
-0.08 %	-0.14 %	0.12 %	-0.04 %	0.13 %	-0.07 %	-0.03 %	0.01 %	0.08 %	-0.17 %	0.01 %	-0.03 %
0.00 %	0.06 %	0.15 %	0.07 %	0.01 %	-0.02 %	-0.01 %	-0.01 %	0.14 %	-0.04 %	0.04 %	0.04 %
Largest difference:		0.31 %		Largest difference:		0.25 %		Largest difference:		0.35 %	
Standard deviation:		0.11 %		Standard deviation:		0.07 %		Standard deviation:		0.12 %	

M

0.00 %	-0.07 %	0.00 %	-0.02 %	-0.06 %	0.09 %	-0.01 %	0.01 %	-0.06 %	-0.01 %	0.00 %	-0.02 %
0.03 %	-0.03 %	0.01 %	0.00 %	-0.03 %	0.06 %	-0.04 %	0.00 %	-0.04 %	0.02 %	0.00 %	-0.01 %
0.02 %	0.01 %	0.04 %	0.02 %	-0.01 %	0.06 %	-0.07 %	-0.01 %	0.00 %	0.08 %	0.00 %	0.03 %
Largest difference:		0.11 %		Largest difference:		0.16 %		Largest difference:		0.14 %	
Standard deviation:		0.03 %		Standard deviation:		0.05 %		Standard deviation:		0.04 %	

N

-0.17 %	-0.20 %	-0.16 %	-0.18 %	0.05 %	-0.02 %	0.02 %	0.02 %	0.06 %	-0.03 %	0.03 %	0.02 %
0.04 %	0.02 %	0.04 %	0.03 %	0.04 %	-0.02 %	0.02 %	0.01 %	0.02 %	-0.02 %	0.01 %	0.00 %
0.16 %	0.13 %	0.15 %	0.15 %	-0.02 %	-0.04 %	-0.03 %	-0.03 %	-0.04 %	-0.05 %	0.01 %	-0.02 %
Largest difference:		0.36 %		Largest difference:		0.09 %		Largest difference:		0.11 %	
Standard deviation:		0.13 %		Standard deviation:		0.03 %		Standard deviation:		0.04 %	

O

0.04 %	0.10 %	0.09 %	0.07 %	0.04 %	-0.05 %	-0.05 %	-0.02 %	0.23 %	-0.06 %	-0.09 %	0.02 %
0.10 %	0.07 %	-0.07 %	0.04 %	0.05 %	-0.02 %	-0.06 %	-0.01 %	0.24 %	-0.05 %	-0.12 %	0.02 %
0.06 %	-0.07 %	-0.32 %	-0.11 %	0.10 %	0.02 %	-0.03 %	0.03 %	0.08 %	-0.08 %	-0.14 %	-0.05 %
Largest difference:		0.43 %		Largest difference:		0.17 %		Largest difference:		0.37 %	
Standard deviation:		0.13 %		Standard deviation:		0.05 %		Standard deviation:		0.14 %	

Appendix 2 Horizontal pitot branch pipes

Data:

Unit no:		P	Q	R	S	T	U	V	W	X	Y
Rated output, P =	MW	95.6	65	40.8	109	60	47	44	36	15.9	26.5
Rated head, H =	m	645	456	700	695	640	565	610	610	504.6	316
Rated speed, n =	rpm	500	300	750	500	600	500	500	500	600	300
Shaft orientation:		Vertical	Vertical	Vertical	Vertical	Vertical	Vertical	Horizontal	Horizontal	Horizontal	Horizontal
No. of jets:		6	6	6	6	6	5	2	2	2	2
Canal width:	m	4.50	5.80	2.50	3.00	3.42	3.00	2.70	2.70	2.00	2x3.50
Distance from turbine:	runner diameters	10.40	3.50	3.20	11.50	4.10	3.40	4.50	4.50	5.10	8.00
Turbine opening:		Maximum	Maximum	Maximum	Maximum	Maximum	Maximum	Maximum	Maximum	Maximum	Maximum
No. of jets:		6	6	6	6	6	5	2	2	2	2
Turbine flow:	m3/s	17.92	20.26	6.83	18.76	11.05	9.84	8.65	6.86	3.74	9.00
Water depth:	m	2.84	2.12	2.33	2.01	1.90	1.45	1.97	1.95	1.02	0.60
Average water vlocity	m/s	1.40	1.65	1.17	3.11	1.70	2.26	1.63	1.30	1.83	2.14
Difference in extreme values:	%	0.06	0.05	0.26	0.05	0.16	0.04	0.37	0.08		0.02
Standard deviation:	%	0.03	0.03	0.11	0.02	0.07	0.02	0.15	0.03		0.01
2 x Standard deviation	%	0.06	0.06	0.22	0.04	0.14	0.04	0.3	0.06	0	0.02
Turbine opening:		BEP	BEP	BEP	BEP	BEP	BEP	BEP	BEP	BEP	BEP
No. of jets:		6	6	6	6	6	5	2	2	2	2
Turbine flow:	m3/s	10.77	11.76	5.22	10.38	5.72	6.84	6.51	5.78	2.36	6.77
Water depth:	m	2.77	1.92	2.22	2.00	1.40	1.35	1.90	1.95	0.87	0.50
Average water vlocity	m/s	0.86	1.06	0.94	1.73	1.19	1.69	1.27	1.10	1.36	1.93
Difference in extreme values:	%	0.07	0.10	0.24	0.03	0.07	0.10	0.33	0.09	0.05	0.02
Standard deviation:	%	0.03	0.05	0.10	0.01	0.03	0.04	0.14	0.04	0.02	0.01
2 x Standard deviation	%	0.06	0.1	0.2	0.02	0.06	0.08	0.28	0.08	0.04	0.02
Turbine opening:		Part load	Part load	Part load	Part load	Part load	Part load	Part load	Part load	Part load	Part load
No. of jets:		6 (3)	6 (3)	6 (6)	6 (3)	6 (3)	5 (5)	2 (2)	2 (2)	2 (1)	2 (2)
Turbine flow:	m3/s	5.42	5.99	2.66	5.96	3.32	2.36	2.38	2.07	1.25	3.44
Water depth:	m	2.73	1.86	2.07	1.76	1.05	1.20	1.75	1.85	0.87	0.30
Average water vlocity	m/s	0.44	0.56	0.51	1.13	0.92	0.66	0.50	0.41	0.72	1.64
Difference in extreme values:	%	0.03	0.31	0.14	0.01	0.11	0.03	0.18	0.24	0.19	0.15
Standard deviation:	%	0.01	0.13	0.06	0.01	0.05	0.01	0.08	0.11	0.08	0.08
2 x Standard deviation	%	0.02	0.26	0.12	0.02	0.1	0.02	0.16	0.22	0.16	0.16

Energy distribution "maps":

Deviation from average temperature difference in % of specific mechanical energy, E_m

Plant no.:		Maximum	BEP	Part load
P		0.02 %	0.03 %	-0.01 %
		0.01 %	0.01 %	0.00 %
		-0.03 %	-0.04 %	0.02 %
	Largest difference:	0.06 %	0.07 %	0.03 %
	Standard deviation:	0.03 %	0.03 %	0.01 %
Q		0.04 %	-0.07 %	-0.17 %
		-0.02 %	0.03 %	0.03 %
		-0.02 %	0.03 %	0.14 %
	Largest difference:	0.05 %	0.10 %	0.31 %
	Standard deviation:	0.03 %	0.05 %	0.13 %
R		0.14 %	0.10 %	0.06 %
		-0.01 %	0.04 %	0.02 %
		-0.12 %	-0.14 %	-0.08 %
	Largest difference:	0.26 %	0.24 %	0.14 %
	Standard deviation:	0.11 %	0.10 %	0.06 %
S		0.02 %	-0.01 %	0.01 %
		0.01 %	0.00 %	0.00 %
		-0.03 %	0.01 %	0.00 %
	Largest difference:	0.05 %	0.03 %	0.01 %
	Standard deviation:	0.02 %	0.01 %	0.01 %
T		0.09 %	-0.01 %	-0.07 %
		-0.01 %	-0.03 %	0.04 %
		-0.08 %	0.04 %	0.03 %
	Largest difference:	0.16 %	0.07 %	0.11 %
	Standard deviation:	0.07 %	0.03 %	0.05 %
U		0.01 %	-0.06 %	-0.02 %
		-0.02 %	0.02 %	0.00 %
		0.02 %	0.04 %	0.01 %
	Largest difference:	0.04 %	0.10 %	0.03 %
	Standard deviation:	0.02 %	0.04 %	0.01 %
V		0.19 %	0.19 %	0.06 %
		0.00 %	-0.04 %	0.05 %
		-0.19 %	-0.14 %	-0.11 %
	Largest difference:	0.37 %	0.33 %	0.18 %
	Standard deviation:	0.15 %	0.14 %	0.08 %
W		0.01 %	-0.04 %	0.08 %
		0.03 %	0.06 %	-0.16 %
		-0.04 %	-0.02 %	0.07 %
	Largest difference:	0.08 %	0.09 %	0.24 %
	Standard deviation:	0.03 %	0.04 %	0.11 %
X			0.02 %	0.00 %
			0.02 %	0.09 %
			-0.03 %	-0.09 %
	Largest difference:		0.05 %	0.19 %