EXPERIMENTS WITH THE THERMODYNAMIC METHOD

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SUMMARY

The thermodynamic method was recently used for efficiency testing in a high-head plant in northern Québec, and the results were compared with results obtained with the acoustic transit-time method. Uncertainty caused by energy distribution was evaluated, and experiments were performed to find answers to unresolved questions and to verify hypotheses so that application of the thermodynamic method at Hydro-Québec could be improved.

Four total-head probes were used to extract sample discharges upstream of the spiral casing. Water temperature was measured directly in the probe, while pressure was measured at the probe ports. One of the probes was longer than the others, to check the impact of wall proximity on the measurements obtained. Possible environmental heating of the water and friction heating of the thermometer sensor (friction with the sampling discharge) were also tested by varying the sampling discharge for a given turbine operating point. An adiabatic measuring chamber was also installed downstream of one of the sampling probes to validate that specific mechanical energy measured would be the same in quasi-stagnant conditions.

Eight thermometers (with current meters for weighting purposes) were placed on a frame to scan flow vertically at the end of the draft tube. All but one of these thermometers were equipped with an aluminum cylinder that completely surrounded the temperature sensor and reduced water velocity around it. The remaining thermometer was equipped with a protector that allowed flow to circulate freely around the temperature sensor. A measuring vessel was also installed on the frame to measure total temperature and pressure in reduced-velocity conditions.

The results obtained with the thermodynamic method corresponded very well with those obtained with the acoustic method, and the additional testing and analyses answered many ongoing questions about the thermodynamic method. Environmental heating of the sampling probes was greater than anticipated, while no friction heating of the temperature sensors was detected. Downstream measurements in the main flow were confirmed in quasi-stagnant conditions, but higher temperatures were measured in the absence of a flow-reducing protector around the temperature sensor. This paper describes and analyzes the testing methods, results and additional experiments conducted in this case study.

SITE AND OBJECTIVES

The thermodynamic method uses the principle of conservation of energy to determine the efficiency of a hydraulic turbine from measurements of performance variables (such as pressure, temperature, velocity and level) and the thermodynamic properties of water. The accuracy of the method increases with the amount of specific hydraulic energy measured, and the method is thus preferably used to assess high-head turbines (head ≥ 100 m), as stated in the IEC 41 standard.

For this case study, thermodynamic tests were carried out on a Francis turbine with a specified net head of 330 m in an underground two-unit power plant in northern Québec, Canada. As shown in Figure 1, spiral cases are supplied with water by an 8.5-km headrace tunnel that leads to a surge tank and then a manifold, a converging section and a ball valve. Specified unit output is 440 MW at a flow of about 150 m³/s.

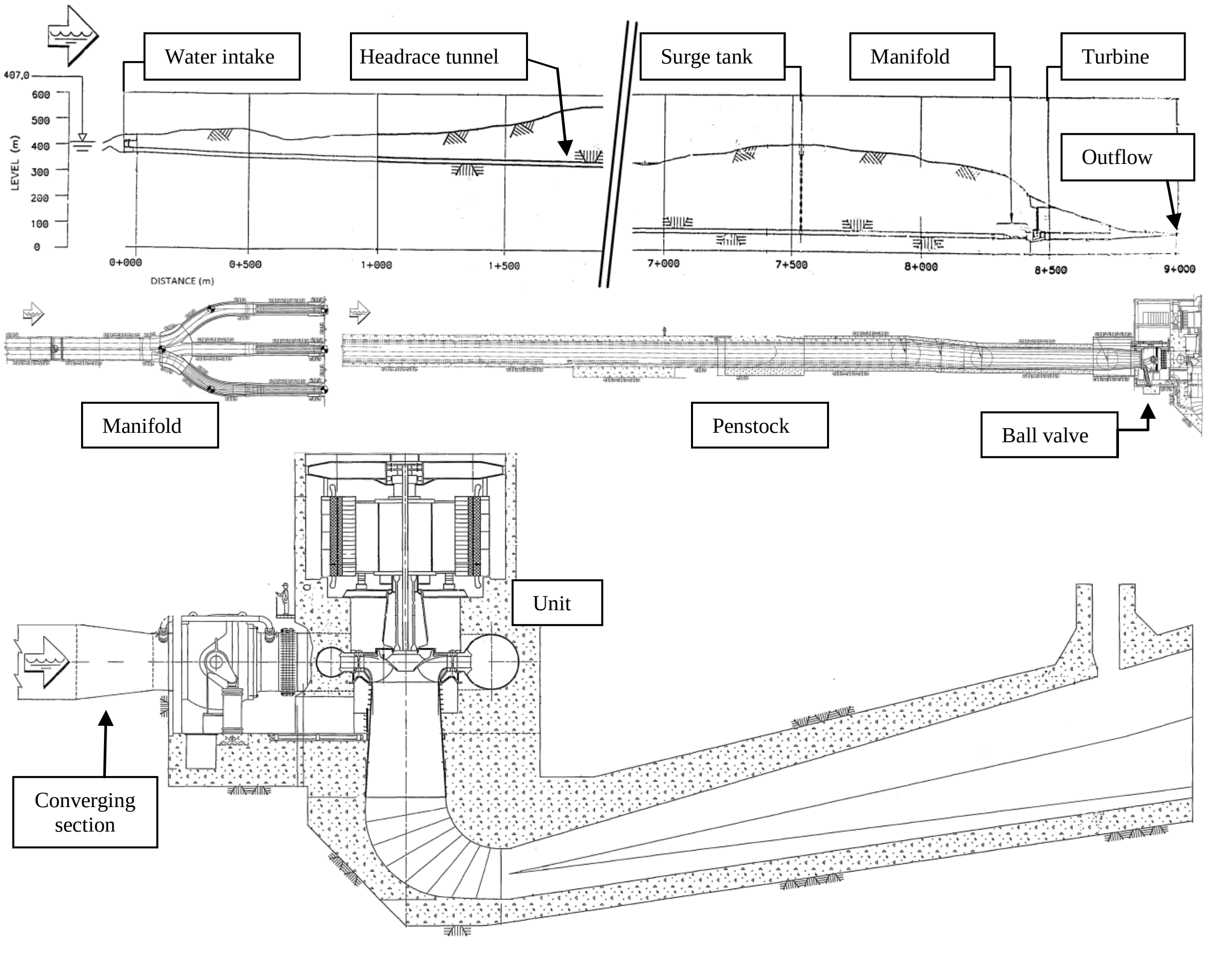

Figure 1: Cross section of site and unit

Following the commissioning of the units, efficiency tests were performed for contractual and operating purposes. To increase the level of confidence of the results, two methods were used: thermodynamic and acoustic transit-time. To reduce the uncertainty of the thermodynamic method and answer several questions, about temperature measurement in particular, additional measures were taken. Details and results of these measures are discussed in the additional experimentation section.

THERMODYNAMIC METHOD

With the thermodynamic method, efficiency is defined as the ratio of specific mechanical energy to specific hydraulic energy. Both these specific energies are measured differences between a high-pressure section upstream and a low-pressure section downstream of the turbine. Figure 2 shows the locations of these sections.

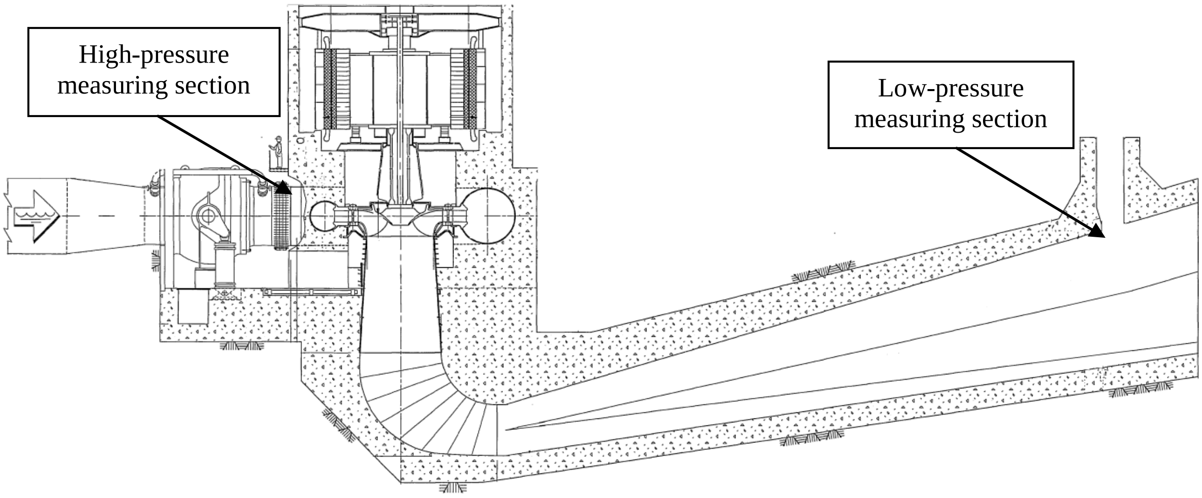

Figure 2: Positioning of the measuring sections

Specific hydraulic energy is commonly measured for efficiency testing, and good precision is relatively easy to achieve. However, computing specific mechanical energy with accuracy requires measuring water temperature differences of only a few mK. To do this, sampling discharges were extracted by four probes installed in the high-pressure section while the low-pressure section was scanned with thermometers and current meters on a frame in motion.

High-Pressure Section

Figure 3 shows the installation of one of the four sampling probes. The cylindrical total-head probe facing the flow inside the conduit is shown on the left, and the piping and insulation are shown in the center and on the right respectively.

Figure 3: Installation of sampling probe

When a sampling discharge is extracted, temperature is immediately measured in the probe. A pressure sensor is positioned just outside the conduit at the outside end of the probe. After passing by the temperature and pressure sensors, water circulates around the thermometer, to insulate it from ambient temperature, and finally crosses a small propeller flow meter before discharge to the drain. All piping is insulated to minimize heat exchanges with ambient air.

Low-Pressure Section

Figure 4 shows the measuring frame: CAD representation on the left, picture in the centre and zoom on one of the eight thermometers with its current meter on the right.

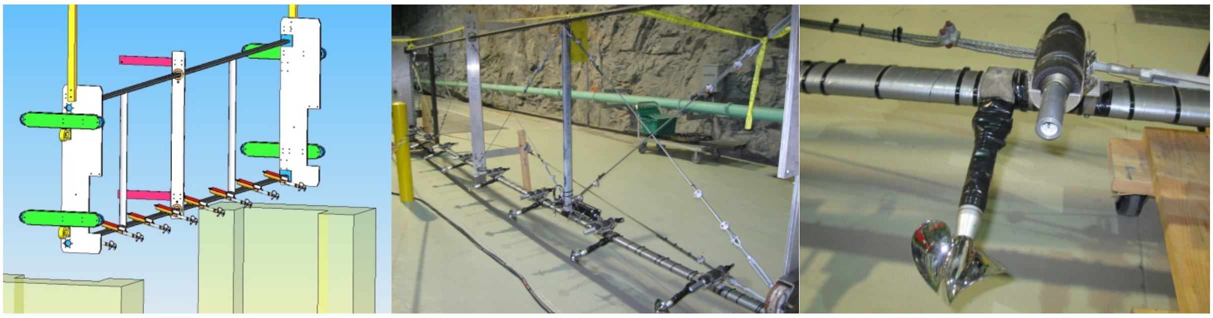

Figure 4: Low-pressure measuring frame

For each operating point, the frame scans the flow vertically in the stoplog gates at the end of the draft tube. The frame is equipped with eight thermometers equally spaced along the lower horizontal profiled rod. A current meter beside each thermometer measures water velocity. Gathering data over the entire measuring section allows computation of temperature and velocity profiles. Temperature is then integrated and weighted with the velocity profile to obtain average temperature for the low-pressure section. Pressure is read on the two static pressure taps located on the side walls.

Specific Mechanical Energy Corrections

The corrective term for specific mechanical energy was calculated taking three factors into account, in accordance with IEC 41:

1. Water temperature variation during travel between the two measuring sections.
2. Heat exchanges with the sampling probes
3. Heat exchanges with ambient air introduced by aeration

TRANSIT-TIME ACOUSTIC METHOD

The transit-time acoustic method of discharge measurement uses the difference in time of travel of acoustic pulses transmitted downstream versus upstream on a given path crossing the conduit to determine the average velocity of water along that path. Discharge is computed by integrating the velocity of multiple paths, assuming a fully-developed velocity profile.

To increase the accuracy of the results, the velocity profile at the measuring section should be stable, axisymmetric and fully developed. Therefore, the section should be as far as possible from any disturbance. IEC 41 recommends ten conduit diameters of straight length upstream and three downstream. The location of the measuring section is shown in Figure 5. As the figure shows, it was not possible to follow the recommendation, but the disturbance of a slightly converging section is usually small.

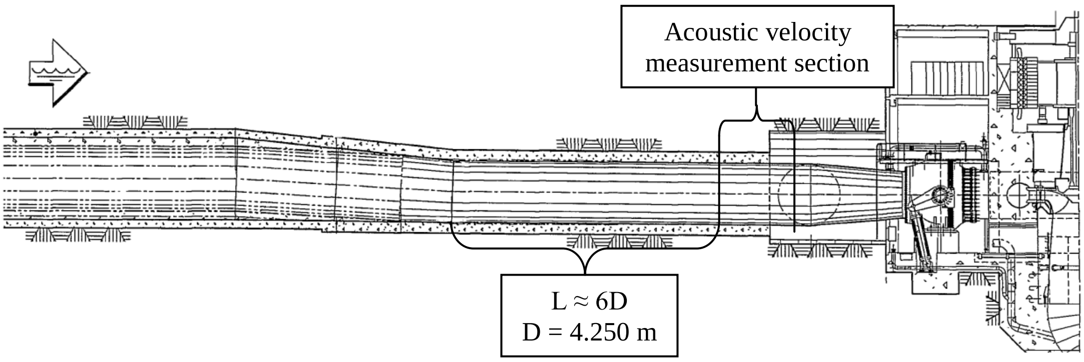

Figure 5: Acoustic measurement section

Like most systems meeting IEC 41 requirements, the layout of the transducers consists of two four-path planes at 65°, for a total of 16 transducers. With four-path planes, quadrature integration methods can be used, and use of two planes eliminates the effect of traverse velocity components.

COMPARISON OF RESULTS

Figure 6 shows the efficiency curves resulting from thermodynamic testing of units 2 and 1 and acoustic method testing of unit 2.

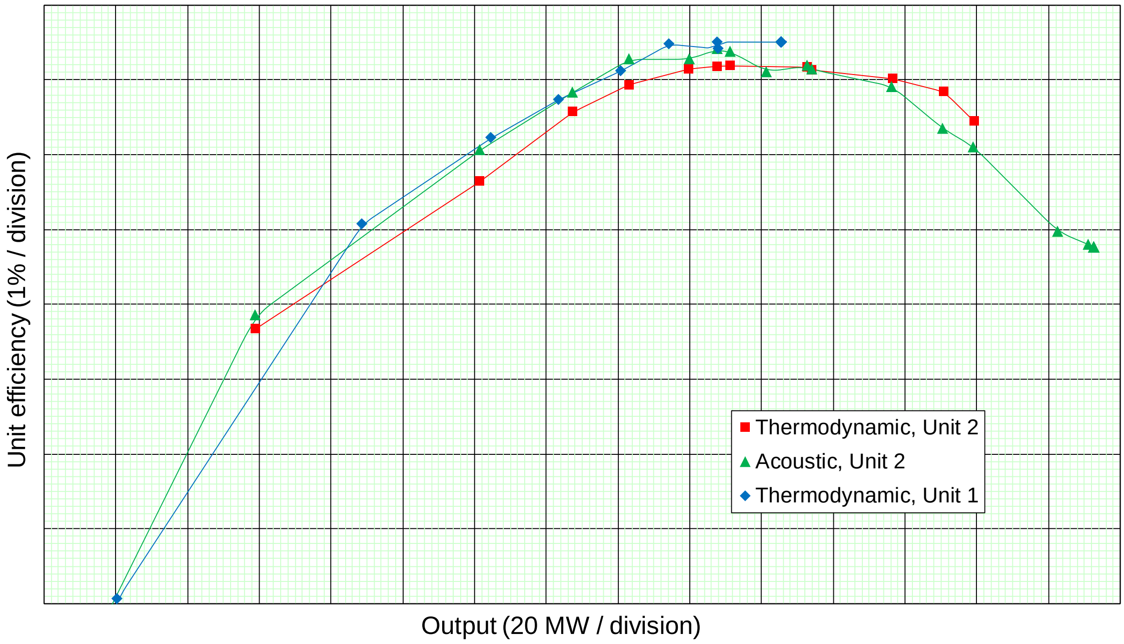

Figure 6: Comparison of thermodynamic on both units and acoustic testing

The two thermodynamic curves are of quite similar shape, with peak efficiency located at about the same output. Unfortunately, no data are available at higher discharges for unit 1, since the thermodynamic testing was stopped once peak efficiency was reached. However, results indicate that unit 1 is about 0.3% more efficient than unit 2 over most of the operating range. These measured differences are what justifies testing every unit. Mean weighted efficiency was very close to guaranteed efficiency in both units.

Figure 6 also shows that the thermodynamic method yields a lower efficiency than the acoustic method in unit 2 when discharge is low, but a higher efficiency after optimal discharge is reached. Comparison with the index curve of static pressure difference in the converging section suggests the efficiency value obtained via the acoustic method is slightly overvalued before the peak. However, the efficiency value yielded by the thermodynamic method seems to be overvalued for the three runs at highest output, with the discrepancy starting at a discharge of about 120 m^3/s, or 80% wicket gate opening.

A 120-m^3/s discharge gives an average velocity of about 15 m/s at the upstream sampling section. At such velocities, friction can heat the probe slightly, causing the temperature of the sampling water to rise by a few mK. Though difficult to validate, this seems the most plausible explanation of what appears to be a slight overvaluation of efficiency by the thermodynamic method at high velocity. In future testing, this will be checked using a sampling probe shaped more like a Pitot tube.

Nonetheless, all efficiency deviations remained small and within the expected uncertainty margin for these methods of efficiency testing.

ENERGY DISTRIBUTION AND NUMBER OF SAMPLINGS

IEC 41 suggests that uncertainty due to the absence of exploration of energy distribution can amount to ±0.2% and ±0.6% for the high- and the low-pressure sides respectively. Energy distribution is shown for both sides and uncertainty estimated by plotting standard deviation as a function of the number of samplings.

High-Pressure Section

Figure 7 presents the energy distribution of the samplings on the high-pressure side. Left and right are referenced looking downstream.

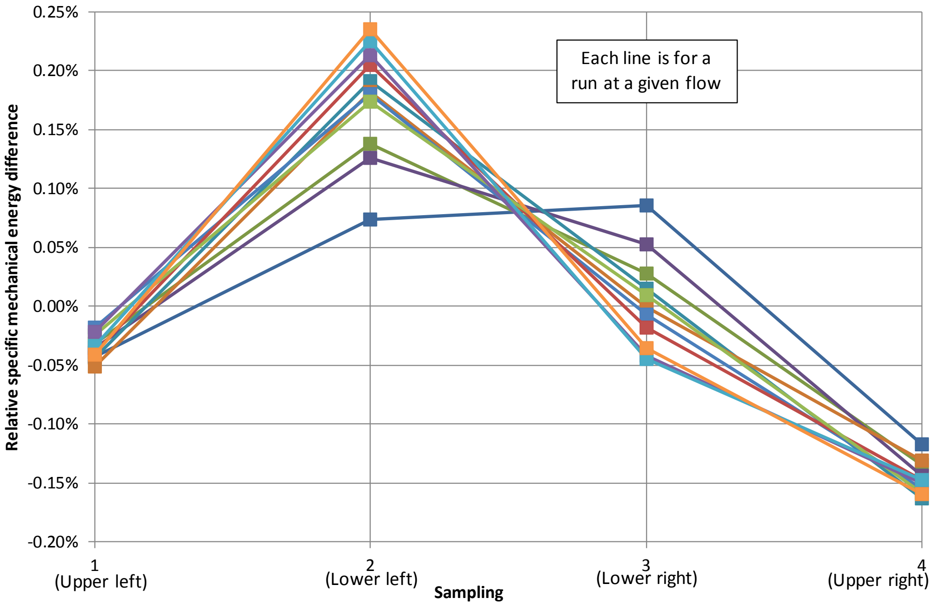

Figure 7: High-pressure energy distribution

Deviations were about +0.20% and -0.15% respectively for the lower-left and upper-right samplings. Figure 8 shows standard deviation of specific mechanical energy versus number of samplings.

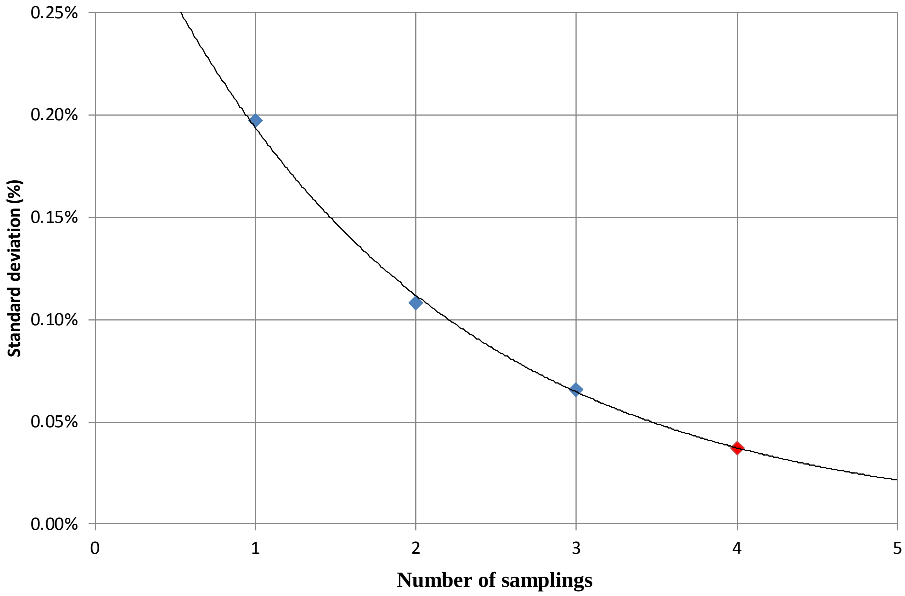

Figure 8: Uncertainty for high-pressure exploration

Based on Student's "t" distribution, the estimated 0.037% standard deviation for four samplings gives an uncertainty of 0.059% on average with a 95% level of confidence. The 0.2% uncertainty estimate for sampling without exploration seems accurate in the present case.

Low-Pressure Section

Figure 9 shows temperature distribution of the eight thermometers on the low-pressure side.

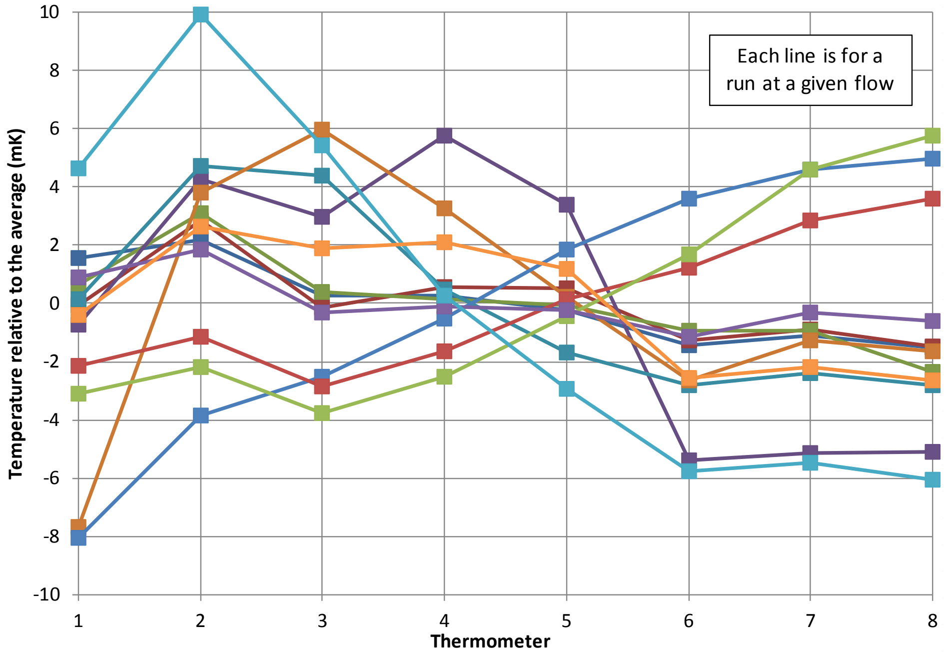

Figure 9: High-pressure energy distribution

Temperature distribution fluctuates greatly with flow. The average standard deviation of temperature distribution is 3 mK. Figure 10 shows standard deviation of specific mechanical energy versus the number of thermometers taken into account.

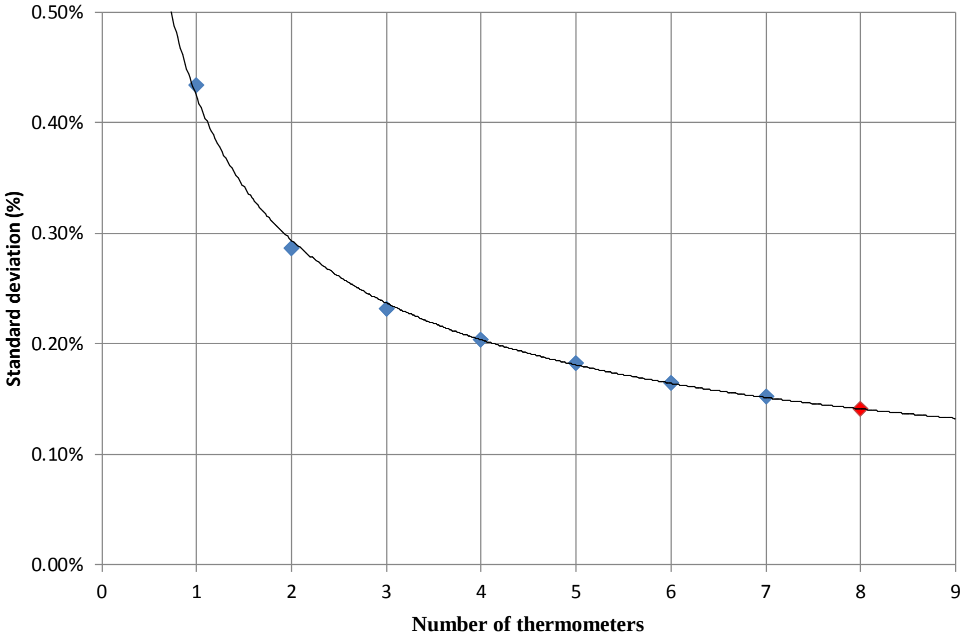

Figure 10: Uncertainty for high-pressure exploration

Based on Student's "t" distribution, the estimated 0.14% standard deviation gives an uncertainty of 0.12% on average with a 95% level of confidence. The 0.6% uncertainty estimate for sampling without exploration is close, but slightly higher than these results.

ADDITIONAL EXPERIMENTATION WITH THE THERMODYNAMIC METHOD

To validate different theories and increase the confidence level of the results obtained with the thermodynamic method, additional verifications were performed.

Upstream Expansion Chamber

To test the influence of water velocity on temperature measurement, a measuring chamber was installed downstream of one of the sampling probes. This second measurement of specific mechanical energy was made at much lower velocity (16 times slower, since the pipe diameter is four times larger). Figure 11 shows the measuring vessel, supplied by sampling water downstream of the installation shown in Figure 3.

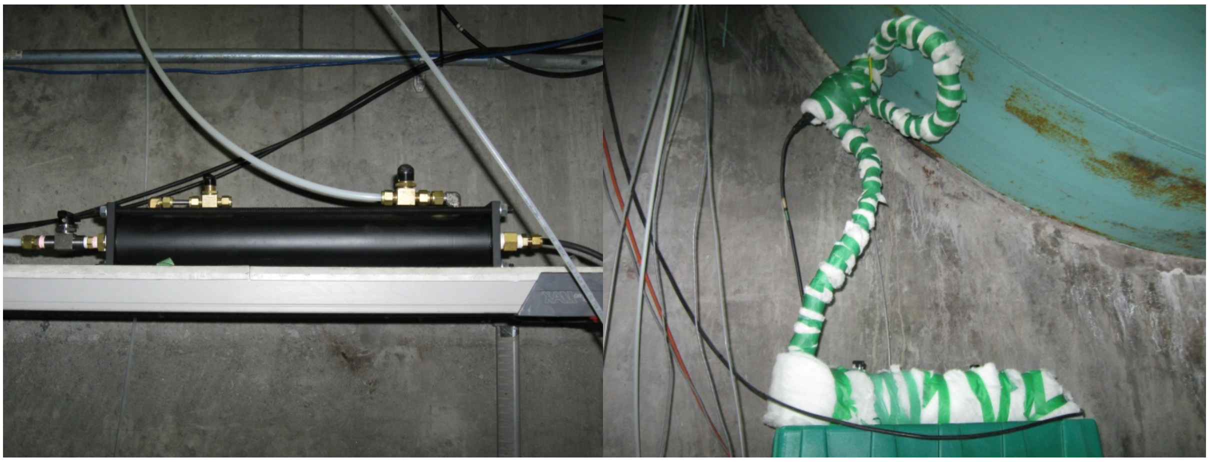

Figure 11: Upstream measuring vessel

If there is no heat exchange with the ambient air, the specific mechanical energy measured at both locations should be the same. Therefore, mineral wool was installed to insulate the tubes carrying the sampling discharge.

Efficiencies computed using the data collected in the measuring vessel were all at least 1.75% too high. The variation in specific mechanical energy as a function of sampling flow suggests the insulation was not sufficient to prevent heat exchanges with the ambient environment.

Sampling Probe Length

To test the impact of the distance between the wall and the location where the sampling is done, one of the four probes was slightly longer. IEC 41 specifies only that sampling must be done more than 5 cm from the wall. Figure 12 shows the two types of probes.

Figure 12: Sampling probes (two lengths)

No significant difference was found between the results obtained with the longer probe and those obtained with the other probes. The differences between the results obtained with probes of different length were small and not greater than those obtained with probes of the same length.

Sampling Discharge

IEC 41 recommends a sampling discharge between 6 and 30 L/min. A lower discharge reduces the risk of heating the thermometer probe by friction, while a higher discharge reduces the risk of influence from an external source of energy. Since water temperature is measured directly in the sampling probe, the risk of external sources of energy influencing the measure seemed virtually nonexistent and a discharge of 6 L/min was targeted.

To test its influence on results, sampling discharge was altered from 2 to 16 L/min and four runs of data were taken at the same point of operation of the turbine. Figure 13 shows the specific mechanical energy measured (before correction for external heat exchange) as a function of the inverse value of the sampling discharge.

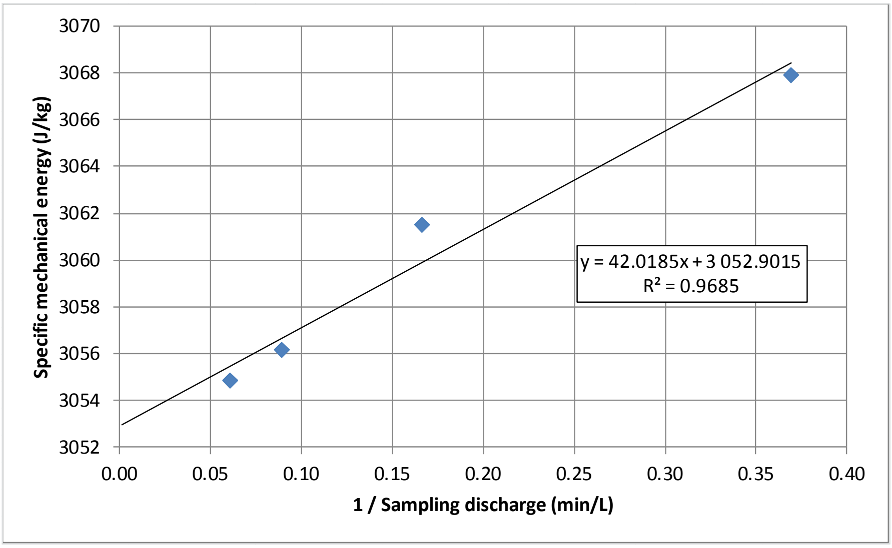

Figure 13: Influence of sampling discharge on specific mechanical energy

Since environmental heating is inversely proportional to sampling discharge, the intercept point of the linear regression gives the specific mechanical energy that would have been measured if the sampling discharge were infinite, meaning the measure is not influenced by external heating. Even though water temperature is measured immediately in the sampling probe and all conduits are insulated, specific mechanical energy is still influenced by environmental heating in the range of 0.3 % depending on the sampling discharge.

On the other hand, no additional heating that could have come from water friction on the temperature sensor was demonstrated at the maximum sampling discharge measured. A discharge of 16.4 L/min gives a velocity of 1.7 m/s at the sensor, within the recommendations of IEC 41 (<2.0 m/s). A greater increase in sampling discharge would have been necessary to start observing heating by friction.

In short, the correction for heat exchange gives accurate results. However, the correction could have been smaller without introducing friction heating of the temperature sensor if the sampling discharge had been increased so velocity approached 2.0 m/s at the thermometer.

Downstream Thermometer Protectors

Seven of the eight thermometers installed on the downstream measuring frame had a cylindrical protector covering the temperature sensor in its entirety. In addition to protecting the sensor, this cylinder also controls the flow of water circulating around it; two small holes drilled near the downstream end of the cylinder allowed circulation of water while reducing the velocity of the flow on the sensor. The protector on the remaining thermometer protected the sensor from being hit by objects while allowing free circulation around it. Figure 14 shows the two types of protectors.

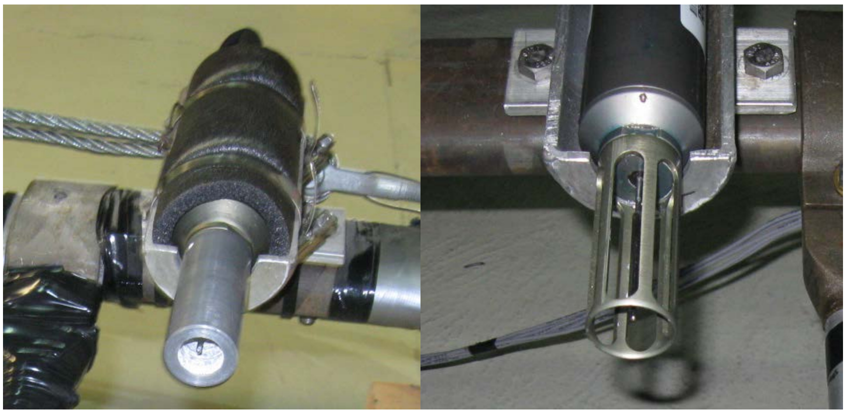

Figure 14: Two types of protectors

To test the flow-reducing cylinders, the second thermometer (T2) was installed with the simple protector allowing free flow around the sensor. Table 1 shows temperature measurements of thermometer T2 in comparison with those of its neighbors (T1 and T3).

Table 1: Temperature comparisons

Run	Downstream Temperature (°C) Mean(T1,T3)	T2	Water Velocity V2 (m/s)	Deviation (mK) T2 - Mean(T1,T3)
57	6.8492	6.8505	1.72	1.3
43	6.9040	6.9070	1.07	3.0
56	6.8219	6.8245	1.19	2.6
44	6.7886	6.7917	2.15	3.1
39	6.9031	6.9056	2.17	2.5
55	6.8051	6.8098	2.23	4.7
59	6.8302	6.8316	2.04	1.5
49	6.7847	6.7860	1.79	1.3
45	6.7037	6.7049	1.85	1.3
48	6.7937	6.7953	2.31	1.6
47	6.7607	6.7656	2.63	4.9
46	6.7194	6.7214	2.98	1.9
			Mean Deviation:	2.5

Temperature measured by thermometer T2 is always a little higher than the average of the temperatures measured by its two neighbors. Results do not show correlation between the deviation and water velocity. Other thermometers also showed similar trends.

Downstream Measuring Chamber

To verify the downstream measure of specific mechanical energy directly in the flow, a measuring vessel (Figure 15) was installed on the frame with the thermometers and current meters. Water from the main flow enters the vessel through a Pitot tube-type total head input and exits through a small hole on the opposite side that controls circulation. Total temperature and pressure are thus measured in the vessel in quasi-stagnant conditions. Static pressure is also measured at the same elevation outside the vessel.

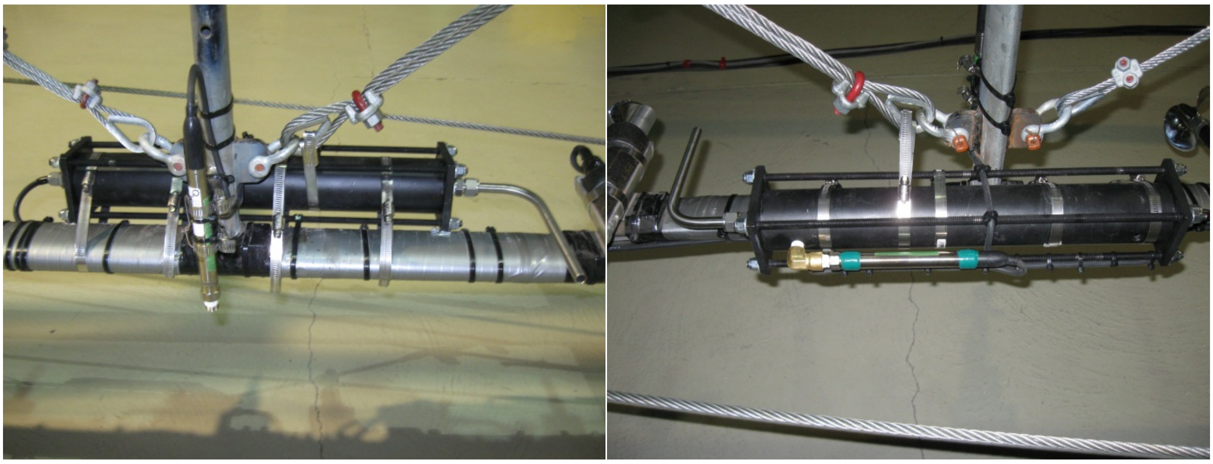

Figure 15: Downstream measuring vessel

Since pressure sensor signals become saturated when the sensor is too deeply submerged, only data from the higher part of the draft tube could be analyzed. It was still possible, nonetheless, to compare temperatures and energies measured by both methods. Table 2 shows the results of these comparisons.

Table 2: Comparison between measurements in the flow and in the vessel

	Downstream Temperature (°C)			Specific Mechanical Energy (J/kg)		
Run	T7 (°C)	Tv (°C)	Deviation (mk)	Em,T7 (J/kg)	Em, Vessel (J/kg)	Deviation (%)
57	6.8470	6.8481	1.0	2980.84	2977.21	-0.12%
43	6.9029	6.9036	0.8	3052.24	3049.25	-0.10%
56	6.8175	6.8180	0.5	3071.08	3069.38	-0.06%
44	6.7737	6.7749	1.2	3083.97	3083.07	-0.03%
39	6.8967	6.8979	1.2	3093.43	3092.02	-0.05%
55	6.8026	6.8038	1.2	3064.29	3062.79	-0.05%
59	6.8349	6.8363	1.3	3057.79	3055.05	-0.09%
49	6.7875	6.7878	0.4	3058.32	3057.97	-0.01%
45	6.7068	6.7069	0.1	3054.83	3055.26	0.01%
48	6.7931	6.7941	1.0	3051.37	3049.92	-0.05%
47	6.7506	6.7514	0.8	3039.94	3039.73	-0.01%
46	6.7156	6.7171	1.5	3031.65	3030.44	-0.04%

Even though specific mechanical energy is slightly lower when measured using the vessel, the mean deviation of 0.05% is minimal and confirms the validity of temperature measurement in the flow.

CONCLUSIONS

Efficiency measured by the thermodynamic method averages 0.07% higher than efficiency measured with the acoustic transit-time method. Though the shapes of the curves of these measured efficiencies are somewhat different, the deviation never exceeds 0.5% at any given operating point. There seems to be a slight overvaluation of thermodynamic efficiency at higher discharges, where friction heating of the sampling probes is possible. There is a 0.33% difference in efficiency between the two units of the plant and efficiency uncertainty on unit 2 is evaluated at 0.35%.

With four sampling probes in the high-pressure section and eight thermometers in the low-pressure section, uncertainties for energy distribution exploration are evaluated at 0.037% and 0.12% for the high- and low-pressure sections respectively.

External heating of the sampling probes was greater than anticipated. An approximate 0.3% correction of the specific mechanical energy value obtained was necessary due to heating of the sampled water by the external environment before temperature measurement in the sampling probes.

On the other hand, no friction heating of the temperature sensors was detected. Maximum sampling discharge gave a velocity of only 1.7 m/s at the temperature sensor, which is probably too slow to generate significant friction heating.

Downstream measurements with a frame in motion in the main flow were confirmed in quasi-stagnant conditions. Mean deviation between specific energy measured directly in the flow and specific energy measured by a total-head expansion chamber was only 0.05%.

However, higher temperatures were measured when there was no flow-reducing protector around the thermometer sensor; mean deviation was 2.5 mK and did not correlate with water velocity.

REFERENCE

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

BIOGRAPHIES

Emmanuel Côté, Eng., graduated in Mechanical Engineering from the University of Sherbrooke in 2007. He has worked for Hydro-Québec Production’s testing department since 2008 and has conducted many tests of hydraulic turbine performance using the department’s main test methods—including the current-meter, acoustic transit-time, pressure-time and thermodynamic methods as well as different index tests.

Gilles Proulx, Eng., graduated in Mechanical Engineering from the École Polytechnique de Montréal in 1989 and has worked for Hydro-Québec’s test department since then. He has worked on the commissioning of major Hydro-Québec power plants and has performed many performance tests using different methods. He is responsible for the R&D team of the testing department and is the convenor of Maintenance Team 28 of the TC4 of IEC and a member of the ASME PTC 18 revision committee.