CASE STUDY OF BULB TURBINE EFFICIENCY TESTING

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SUMMARY

A new hydraulic generating station was commissioned in northern Québec, Canada, in 2013. The plant's output is generated by three bulb units, each unit consisting of a horizontal axis generator located in a bulb coupled to an axial flow Kaplan turbine. The combination of low head and high discharge that characterize bulb turbines makes efficiency testing more difficult and expensive than with other types of turbine. That these turbines are less common and their output is lower for their size also contributes to the paucity of prototype efficiency testing of bulb units shared with the community.

This paper describes the efficiency testing that was performed after the commissioning of the three units, using the current-meter method to measure discharge at the water intake. In addition to describing the methodology and results in detail, the paper also contains complementary analyses, from the preparation of the tests to the processing of the data collected, making this case study particularly complete. The analyses includes a CFD simulation of the water intake velocity profile; the design of the 16-m wide current-meter structure; the effect of measuring behind a central pillar, studied with a Doppler velocimeter; the effect of the angle of incidence and the upper end of the measuring section, also using a Doppler velocimeter; cam curve optimization; and comparison of the three units with their model.

CONFIGURATION, OBJECTIVES AND METHODOLOGY

Figure 1 shows the configuration of the units. Each unit has a 20-m wide water intake separated by a central pillar that holds the trash racks. Immediately downstream of the pillars are the stoplog gate slots. The cut-off valve is located in the draft tube. Specific energy was measured at both the "hi" and "low" sections using four static pressure taps located on the side walls at two elevations (two per wall). Specified output of the unit is 53.1 MW for a net head of 13 m, which requires a discharge close to 500 m³/s.

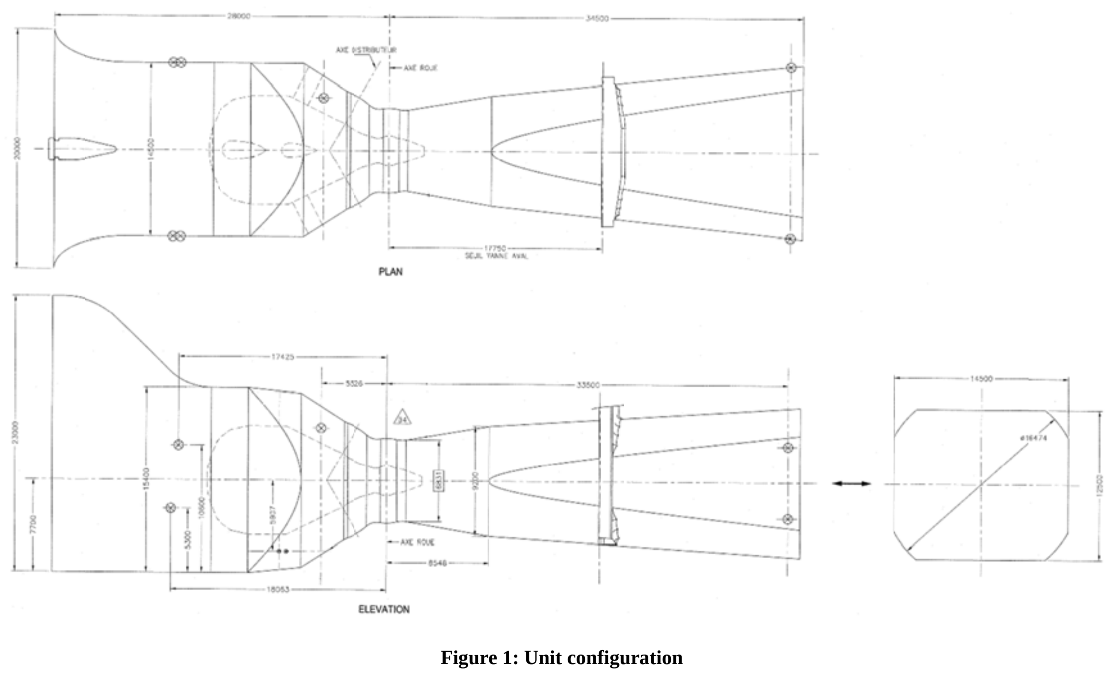


Figure 1: Unit configuration

The main objective of the efficiency testing was to verify the contract guarantee and the optimization of powerhouse efficiency. Accurate knowledge of the performance curves of each unit allows optimal use of hydraulic resources by operating the units at their own peak efficiency and with their individual cam curves.

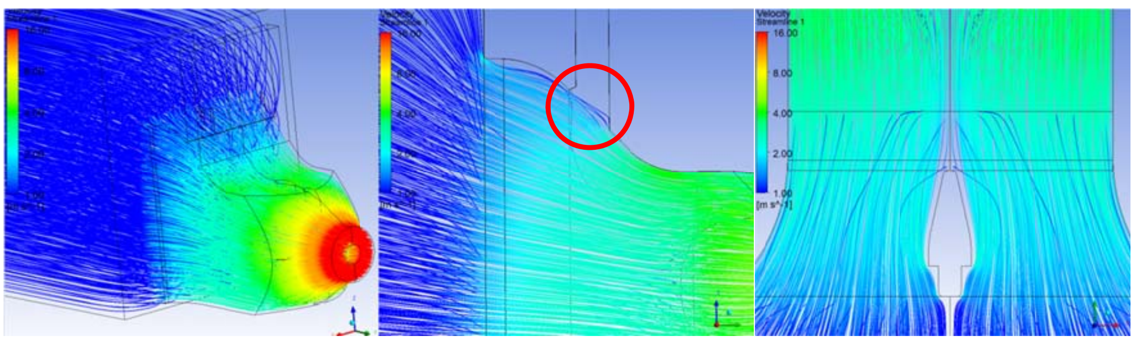
As with most efficiency testing, the main challenge was to find the best way to measure the discharge accurately despite budget and time constraints. Given the low head, the high discharge and the dimensions of the hydraulic passageways, it was determined that the most convenient way to measure the discharge was to use a current-meter structure to scan the flow down the stoplog gate slots. In addition, to compute the cam curves and find the best efficiency point, an index of the discharge was measured while slowly moving the wicket gates with fixed blades after each "on cam" discharge measurement with the current meters.

CFD SIMULATION OF THE FLOW

A CFD simulation of flow between the upstream reservoir and the runner was performed to validate measurement feasibility and to help in positioning the current meters, designing the current-meter structure and interpreting the results. The objective of the simulation was to obtain a general idea of the velocity profile and the flow angle at the measuring section. It was not intended to be an exhaustive and complete study.

The geometry was drawn in accordance with the plans, except that wicket gate and trash rack details were not taken into account. Water surface boundary was set as symmetric, walls were set to "no slip" and the runner section was set as an opening. The K-Epsilon model was used for the boundary layer. Different discharges were simulated in steady state with 5°C water using the ANSYS-CFX solver.

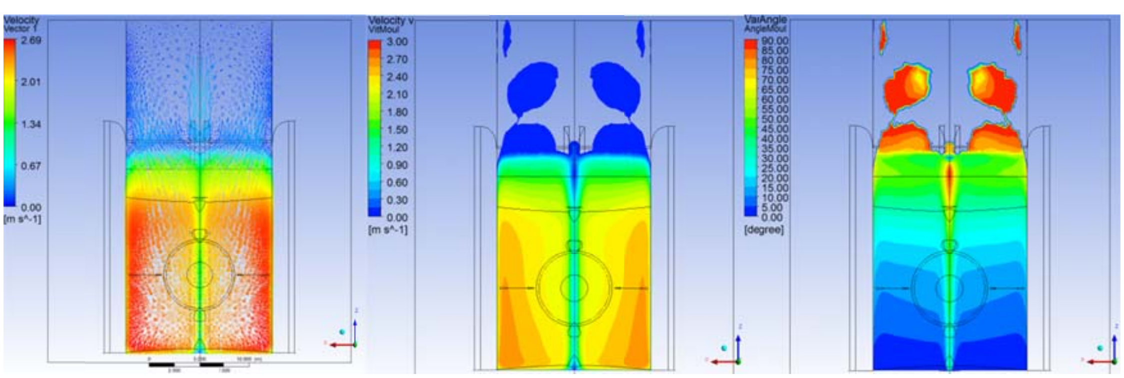
Figure 2 shows streamlines at 300-m³/s (near peak efficiency) in three different views. The flow downstream of the central pillar is particularly interesting because it is where the current meters measure local water velocity.



a) Isometric view b) Side view c) Top view

Figure 2: CFD Streamlines

The streamlines show low velocity flow going down at a high angle of incidence with a recirculating zone behind the pillar. The red circle on figure 2 b) also shows that part of the flow enters the stoplog gate slot before hitting the wall and continuing down to the runner. This is normal flow behavior in an intake and must be taken into account when determining the height of the measuring section for integration of the velocity profile. Figure 3 shows the velocity vectors, the axial velocity profile and the angle of incidence of the flow at the measuring section.



a) Velocity vectors b) Axial component of velocity c) Flow angle relative to a straight line

Figure 3: CFD flow at measuring section

The vectors show that the flow converges horizontally toward the centre of the section, particularly in the wake of the central pillar, because of the depression. The flow also goes down, since the ceiling converges while the floor stays horizontal. Angles of incidence above 45° are mainly in the upper part of the section and behind the pillar. Another observation about the velocity profile is that the major part of the flow at the measuring section is concentrated in the lower corners. This is due to convergence of the ceiling and the side walls and presence of the bulb, which deflects the flow to the periphery of the conduit. A central line about the width of the pillar indicates low velocity and possible presence of recirculation vortices. The very pronounced downward angle of the flow at this location indicates that the water flows down the stoplog gate slots towards the downstream end of the central pillar.

CURRENT METERS, DOPPLER VELOCIMETER AND HOLDING STRUCTURE

Based on the CFD analysis, it was decided to increase the concentration of current meters behind the central pillar and to install a Doppler velocimeter on the upper row of the structure to measure the wake of the pillar. Thus 31 current meters where distributed along the 14.5-m lower beam of the structure in a 360° cosine distribution (figure 4). The current meters have 120-mm propellers that return water velocity in their rotating axes within a ±1% margin of uncertainty when the angle of incidence of the flow is below 45°. The acquisition system allows measurement of reverse flow (negative velocities). The Doppler velocimeter is a Vectrino model from Nortek that uses microparticles in the flow to measure water velocity along three axes in a small control volume allowing computation of the angle of the flow. The sensor was fixed on a rail, allowing exploration of the entire wake of the pillar. Figure 4 shows photos of a self-compensating current meter and the Doppler velocimeter and plots the distribution of the current meters along the holding structure.

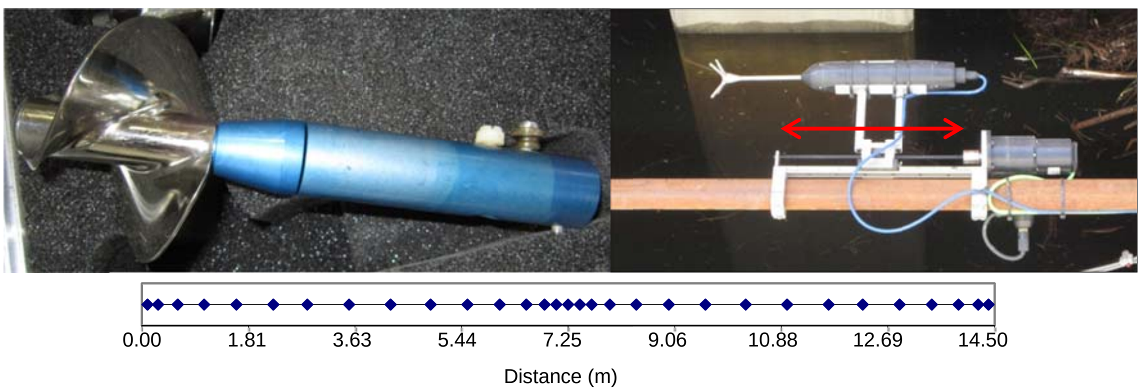


Figure 4: Current-meter distribution

Several factors were taken into account in the design of the holding structure. It needed to support its own weight as well as the drag forces and the downlift caused by maximum discharge coming at the worst angle (roof at 45°). In doing so, the deformation and the blockage factor of the structure needed to be minimal. The design is illustrated in figure 5, which shows a CAD representation (without strengthening wires) and a photo taken on site.

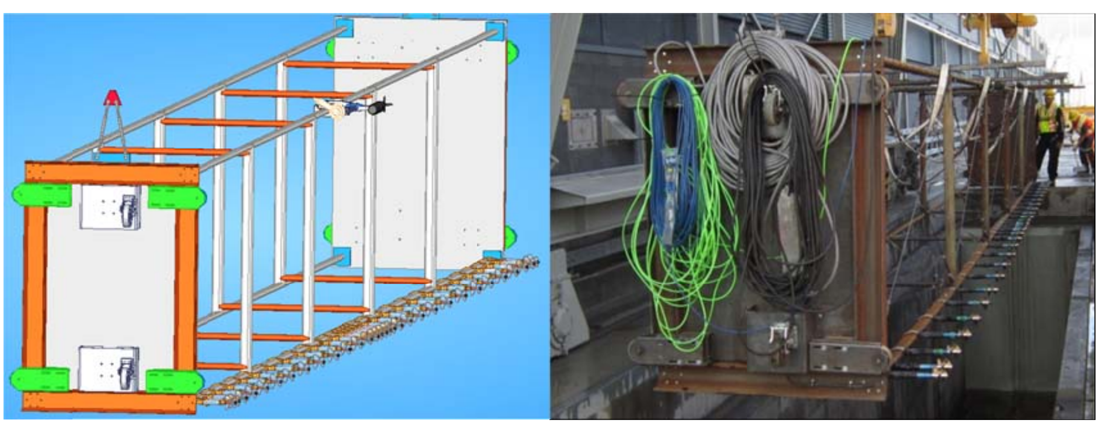


Figure 5: Drawing and photo of the current-meter structure

The rods facing the flow are of neutral hydrofoil-shaped steel (35 X 73 mm) and the axial rods are of round pipe. The same type of profiled rods was used for calibration of the current meters. Wire ropes with 3.5 kN of pretension were used to add rigidity to the structure. A finite element analysis was performed to confirm the design, and it showed that maximum deflection of the structure under the worst conditions would be 6.5 mm—compared to 760 mm without the strengthening wires.

The structure was moved up and down in the stoplog gate slots using an automated chain hoist. The major part of the 21 m of vertical movement needed to cover the water intake in its entirety was at a speed of 20 mm/s, that is, less than 2% of the average velocity of the discharge. Slower speeds were programmed near the floor and in the upper part of the section to obtain greater resolution where the velocity profile changes more steeply.

EFFICIENCY RESULTS

Figure 6 shows the efficiency curves obtained for the three turbines and the prototype curve anticipated by model testing. All results were normalized to a 13-m net head using the hill chart of the model and assuming a constant discharge. Measured net heads were all higher than 12.9 m and only the very low discharge points had net heads above 13.5 m. Consequently, most of the normalization represented less than 0.2% of the net head. Turbines 1 and 3 were not tested at maximum wicket gate opening.

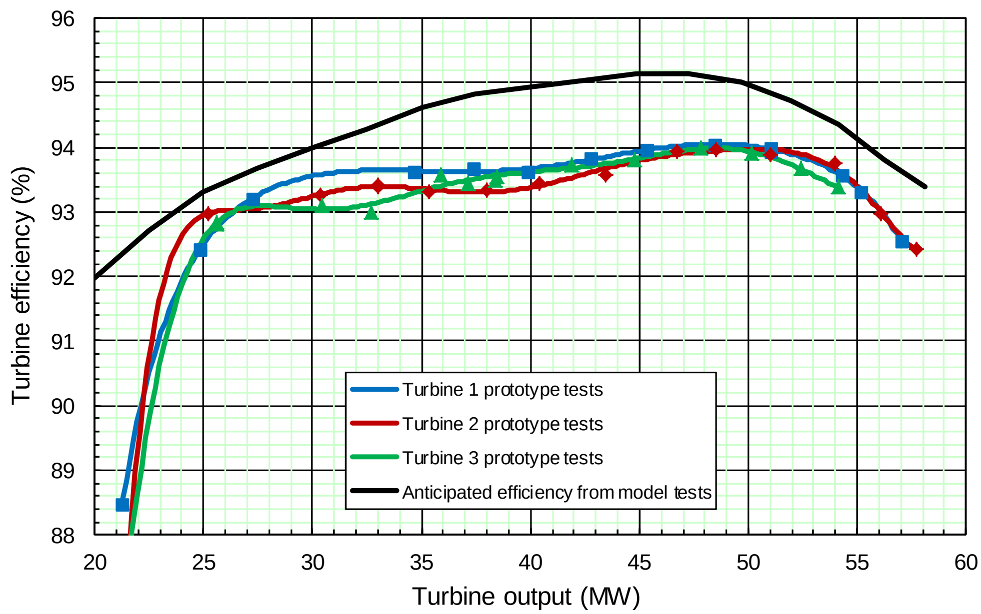
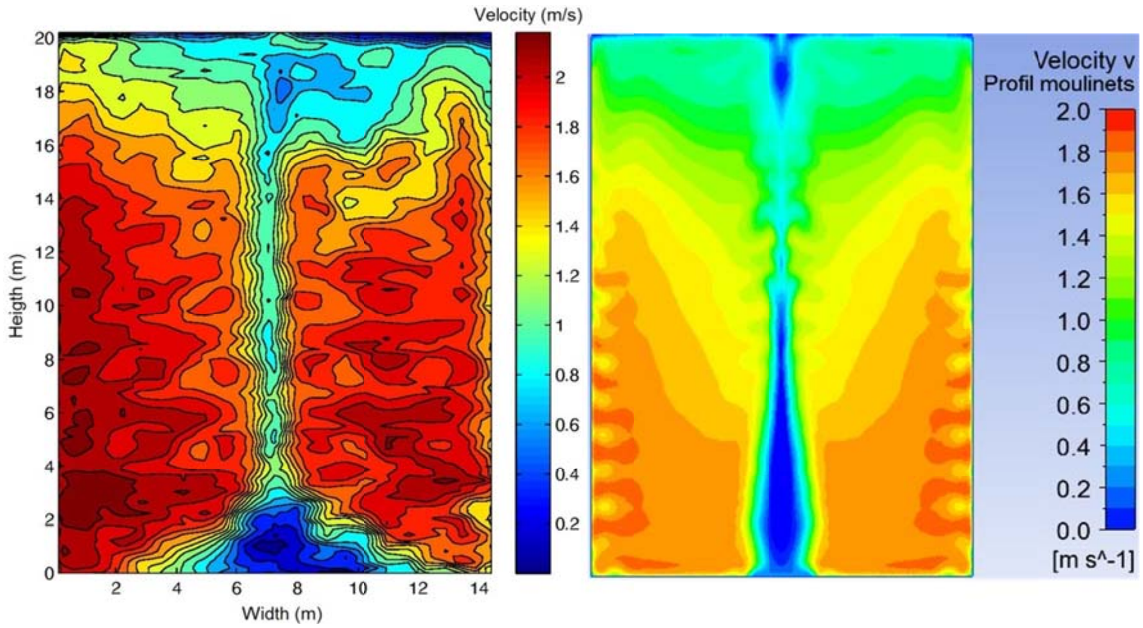


Figure 6: Efficiencies of the three turbines

Efficiencies measured for the three turbines are more than 1% below the expected curve for the major part of the turbine operating range. The three turbines have their differences, but all are in a 0.5% efficiency band over the full operating range, with peak efficiencies near 94% and less than 0.1% apart. It is common to find differences in the efficiencies of new units despite low tolerance in the manufacturing of modern turbines. Though the shapes of the efficiency curves for the three turbines differ from that of the model tests, they are all similar: efficiency plateaus as the blades start to open near 25 MW, with a 0.5% bump at about 90% rated output and 80% blade opening.

VELOCITY PROFILE

Figure 7 shows, on the left, a typical measured velocity profile for unit 2 at rated output with the blades at maximum opening. On the right is the CFD simulation of the velocity profile at the rated discharge.



a) Measured velocity b) CFD results

Figure 7: Velocity profile comparison

The most noticeable difference is that the simulated velocity profile is smoother, whereas the measured profile is more turbulent. There may be several reasons for this difference, since the numerical simulation is not exhaustive. Additional simulations would have to be done to evaluate the influence of the turbulence model, trash rack refinements, the meshing method, element size, boundary layer and more. However, the higher level of turbulence helps the boundary layer stay attached to the central pillar, which decreases the influence of its wake and improves current-meter measurement by limiting negative velocities.

On the other hand, the two profiles have several points in common, including the effect of the pillar, the influence of the trash racks and the overall distribution of velocity. Neither the current meters nor the Doppler velocimeter measured negative velocity or recirculation in the measuring section during the tests. Confidence in the measured velocity profile is also increased by its similarity to the simulation in showing no angle of incidence above 45° outside the wake of the central pillar.

EFFECT OF THE CENTRAL PILLAR

In addition to increasing the concentration of current meters in the central part of the current-meter structure, a 3-axis Doppler velocimeter was installed on the upper part of the structure to validate velocities and angles of the flow. Figure 8 shows the installation as well as the central pillar, indicated by the red arrow.

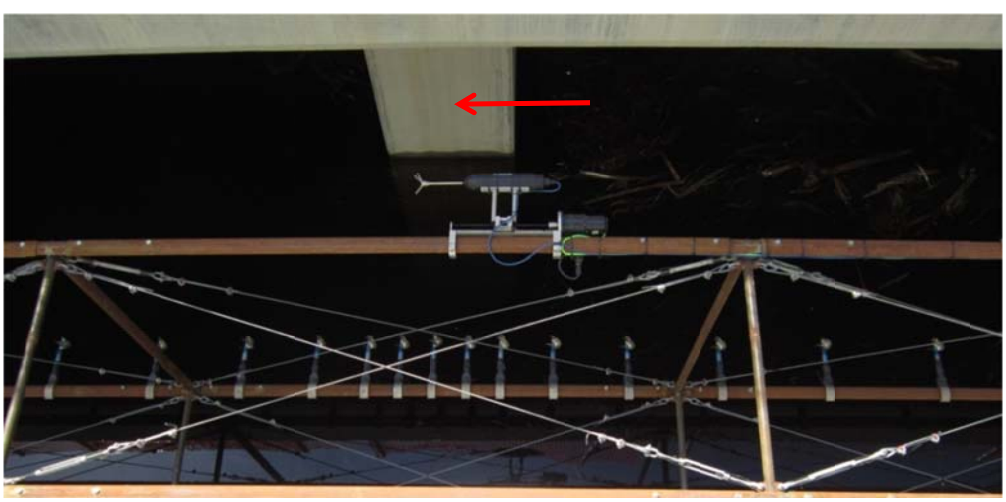


Figure 8: Photo of current-meter structure and downstream end of the pillar

Figure 9 compares velocities measured by the central current meter and the Doppler velocimeter as a function of elevation in the measuring section in a typical test (unit 2, 80% blade opening). Since the sensors are not at the same level at the same time, the plots cannot be expected to match perfectly because of turbulence. Also, the bottom of the section cannot be analyzed since the velocimeter is fixed on the upper part of the structure, which does not descend lower than 1.7 m.

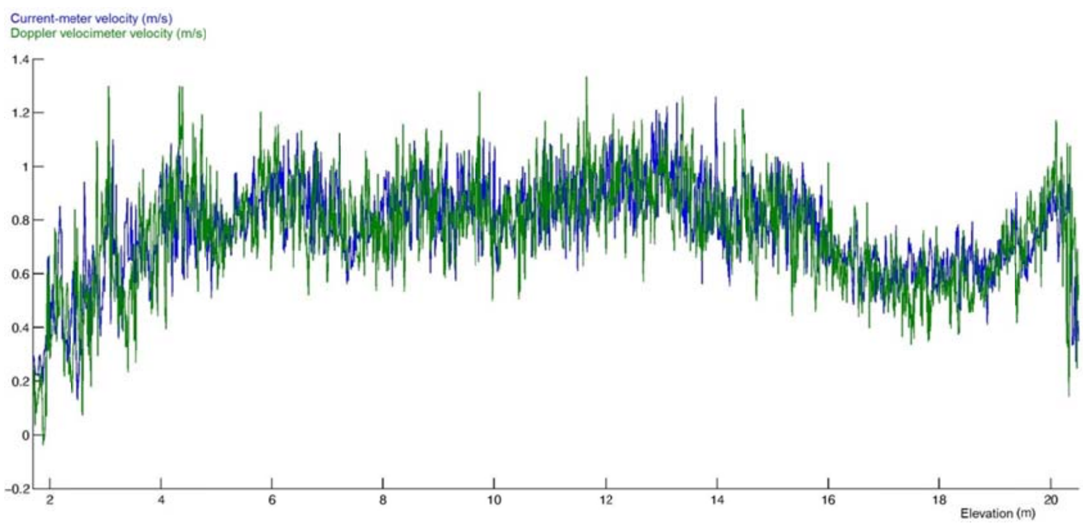


Figure 9: Velocity (horizontal component) measured by current meter and Doppler velocimeter

Though there is good agreement between the plots, the velocimeter measurements were 1.5% lower in this test. When all tests with valid data are considered, the velocimeter yields velocities 2.5% lower than those obtained with the central current meter. It is important to note that the absolute precision of the velocimeter under these conditions was not validated. However, the velocimeter measures in 3 axes, allowing computation of the angle of the flow in its control volume. Figure 10 shows the angle of incidence of the flow relative to the central current meter as a function of elevation in the measuring section. This flow essentially comes from the top going downward.

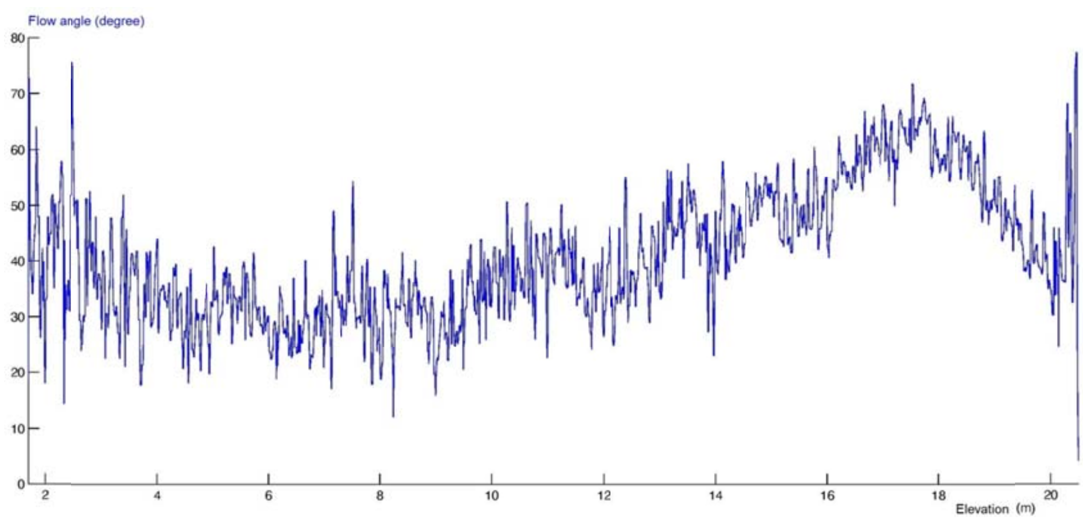


Figure 10: Angle of incidence of the flow behind the central pillar

The flow angle increases up to 70° behind the central pillar, mainly in the upper part of the section, but the current meters self-compensate for angles of incidence up to 45° only. This could explain the slower velocities measured by the Doppler velocimeter, but the discrepancy does not seem to increase as the flow angle increases. Consequently, no correlation was found between flow angle and velocity difference. The impact of the central pillar on the measurements was evaluated by looking at an extreme case in which the velocity of the three central current meters was overestimated by 5% for the entire measuring section, but this only increased the calculated discharge by 0.12%.

UNCERTAINTY

Uncertainty of measurement was assessed according to IEC-60041 recommendations. In this case, the uncertainty in prototype efficiency comes essentially from the discharge measurement, which relies on the local velocities measured by the current meters. The uncertainty in local axial velocities is largely caused by the angle of incidence of the flow. Several factors were considered in evaluating this uncertainty:

- The self-compensating current meters measure axial velocity in a ±1% band for any angle of incidence lower than 45°. This is a general uncertainty declared by the manufacturer.
- The current meters were calibrated at a 0° angle of incidence, so no uncertainty should be added when the flow is straight.
- The ceiling angle is 45° while the floor is flat at 0° and more flow passes through the lower part of the measuring section.
- Based on CFD simulations, the area where the angle of incidence is over 45° is about 8%, but only about 2% of the discharge crosses the measuring section in this area.

With these factors taken into account, the uncertainty caused by the angle of the flow is evaluated at 0.7%. When other factors that influence discharge measurement uncertainty (turbulence and section area, for example) are taken into account, the figure rises to 0.94%. With all factors considered, including head and output, the total uncertainty of measurement of bulb unit efficiency is evaluated at 1.02%.

CAM CURVE OPTIMIZATION

To make sure the turbine is always operated at best efficiency for a given discharge or output, one of the objectives of the test campaign was to optimize the cam curves. To do this, once the “on cam” discharge was measured, the “off cam” efficiency was explored with an index pressure of the discharge while the wicket gates were moved slowly with the blades fixed. The movement was made at 0.01%/s from -5% to +5% of the “on cam” position. The index used was the difference in static pressure between two sections of the upstream hydraulic passageways, which is proportional to the square of the discharge. Figure 11 shows the curves obtained for unit 1. The 20% blade opening curve was repeated twice at different times of the day and concordance was excellent.

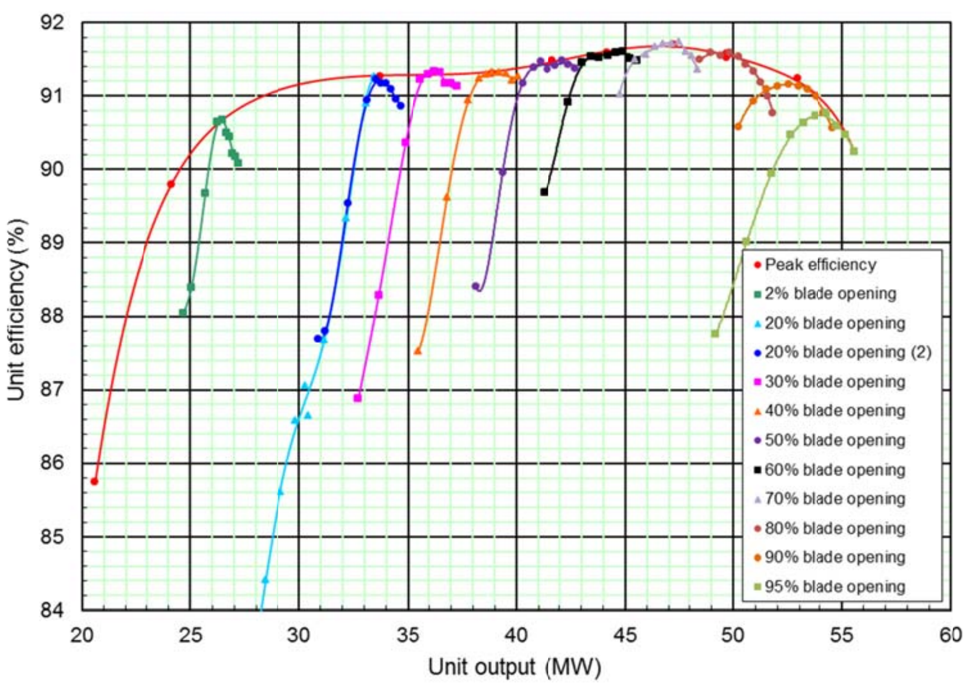


Figure 11: Unit efficiency with "off cam" curves

The peak efficiency curve is the envelope of the summits of the fixed-blade curves, which is how the turbine is meant to be operated according to the cam charts. This efficiency curve relies on well-adjusted and calibrated sensors as well as proper cam charts for every condition of output and head. The charts give the position command to the blade as a function of gate opening and difference in static pressure between the upstream and downstream sides of the turbine.

Several problems were found regarding blade positioning during the testing. Unit 1 was substantially off, leading to up to a 5% loss in efficiency. Unit 2 was almost perfect during the tests, while unit 3 was mildly off, but not on the same side as unit 1. Our first reaction was to try to adjust the tables, but testing was only done at one head and the differences between the units did not seem right. Investigations showed that some of the static pressure sensors, on which cam charts rely, were not calibrated properly, but this did not entirely explain the differences. Further investigation showed that unit 1 was giving more output for a given blade and gate position than the other units, and comparisons with the model tests showed that none of the units were giving the right output in accordance with their openings. In other words, the problem was incorrect adjustment of the blade-positioning sensor. Even unit 2, which seemed right at first, in fact had two problems which cancelled each other out for the head concerned.

CONCLUSIONS

In conclusion, efficiency testing was successfully done on the three bulb units with reliable results at an acceptable level of uncertainty.

Numerical tools were very helpful in the process. Simple modeling was a big help in optimizing the current meter holding structure, and CFD flow simulation helped throughout the process, from structure design to result interpretation and uncertainty evaluation.

Efficiency of the three units was lower than expected from model testing, but the difference was within the uncertainty band of the tests and the step-up of the model. The uncertainty of the prototype testing was evaluated at 1.02%, which is relatively low for current-meter testing at water intake. The size of the measuring section reduces the relative weight of the boundary layers, floor and upper end of the section, which are harder to measure. The large number of current meters used, their self-compensation up to 45° and the fact that no negative velocity was found are other factors that contributed to keeping uncertainty relatively low.

Both the scanning of the water intake with the current meters and the index testing of the fixed-blade curves to find the best efficiency point were done with a constant slow movement rather than static measurements. As changing the direction did not affect the results, this technique meant more efficient testing, as more measurements were taken within a given time period and the measuring section and efficiency curves could be completely explored.

Measuring immediately behind a pillar did not affect the accuracy of the results. The CFD simulation, the higher concentration of current meters and the use of a Doppler velocimeter were all important factors that helped to mitigate uncertainties in the measured velocity profile and increase the level of confidence in the results.

The most important outcome of the tests was the correction of blade positioning. The three units needed intervention for different reasons, such as position-sensor misconfiguration. Blade positioning charts were optimized and the gains in efficiency will mean a rapid return on the investment in the test campaign.

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