Axial Flow turbine development for Ultra Low-Head (ULH) Hydro projects

by
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Synopsis

The paper presents the process implemented to develop an Axial Flow turbine, designed specifically for hydropower sites having Net Head below 3m. Engineering design optimization criteria were derived from an economic analysis, as the ultimate goal is to open ultra low-head hydropower market to commercial investors. Extensive computer flow simulations were conducted as the basis for the hydraulic design. General economic analysis and major engineering challenges that the development team had to face are presented in the paper.

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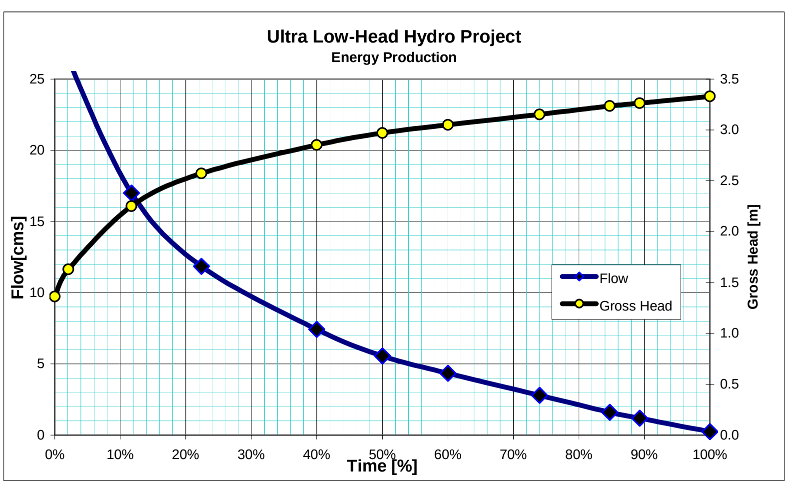
Preamble

This article presents a general approach used to develop a new water turbine, which should allow for the construction of an economically viable hydro power plant having Net Head below 3 m. The concept to undertake such a task was created as a result of discussions between CANMET (Natural Resources Canada) and Swiderski Engineering. For most of those, involved in the hydropower industry, it has been well known that under normal investment circumstances, development of a hydropower project with less than 3 m of Net Head has been a non-economically sound investment. However, if we take look at the global hydropower potential of those sites and taking into account today's desire for sustainable development, it becomes clear that – an effort to develop a method of utilizing this energy potential should be undertaken. Furthermore, recent technological advancements within the industry and modern financial mechanisms designed to help renewable energy developments make it easier to decide about risking capital expenditure, supporting research, and developing this subject.

Ultra Low Head (ULH)

The Ultra Low-Head (ULH) hydropower plant usually operates in the "run-of-the-river" mode, which causes that the prediction of the energy production, and therefore project's cash flow is a function of probability of hydraulic conditions. Looking more closely at the Flow Duration Curve (Graph 1) we notice large variations of the Gross Head: from 50% to 100%.



Graph. 1 Typical flow-head duration curves for Ultra Low-Head hydro project.

Modern techniques

Most recent advances in the hydropower design of hydropower schemes, especially due to computerized methods of water flow simulation for powerhouse intakes and internal turbine components design, uncover new potential within existing power plants, and create very good circumstances for new turbine developments. Most recently completed upgrade projects as ell as new developments undertaken demonstrate enormous potential for advancement in improving overall energy efficiency within the hydropower industry. Improvements by 15% to 25% of the installed capacity and 3% to 8% hydraulic efficiency result in incremental energy production of 5% to 15% annually. This fact significantly changes the projects cash flow.

Is economical viability reachable?

Predicted project cash flow determines the payback ability.

After conducting detailed cost analysis of the project development, we conclude, in general terms, that the economic viability can be achieved by lowering the capital investment amount. It is reasonable to make an assumption that following values are constant and beyond influence:

- energy selling price
- cost of financing

Therefore in the overall scheme, the capital investment becomes the only component, we can possibly change. As we assume that the most significant cost components are civil works and the electro-mechanical equipment, the general conclusion is that in order to influence the capital cost of the project we should lower cost of:

a) civil structure
b) mechanical structure,

while controls and electrical equipment still represent noticeable costs are not within a scope of this phase of development of the project.

Design optimization criteria

The cost of the civil structure is directly related to the size of the turbine – a larger turbine represents higher cost, and can be expressed by the following equation:

$$\text{Cost} = \zeta * D^{\lambda} \qquad (1)$$

where:

D – turbine throat diameter
ζ - constant coefficient
λ ~2.0 to 2.3 – constant

Equation (1) can be easily assumed to be valid as the cost equation for the whole investment including civil works, equipment supply and installation.
The benefit, in case of the hydroelectric facility, is measured by the energy sale. The energy production depends on the capacity of the plant as well as the plant factor (this is the usage factor of the equipment that relates to the availability of water and therefore the flow duration curve). The benefit equation can be written as follows:

$$Benefit = Pr * \sum (P(t) * t) \qquad (2)$$

where:
Pr [$/kWh] – selling price of the energy
P(t) [kW] – turbine output at instant t

Considering that:

turbine power output: $P = \eta * g * Q * H$
turbine unit flow: $Q11 = Q/(D^2 * H^{0.5})$

Equation (2) can be presented as:

$$Benefit = \tau * Q11 * D^2 * H^{1.5} * \eta \qquad (3)$$

where:
τ – constant (cost/kWh).
η – turbine efficiency
$g = 9.807\ m/s^2$

The Cost – Benefit (CBR) ratio can be expressed by combining Equations (1) and (3):

$$CBR = (\zeta * D^{\lambda}) / (\tau * Q11 * D^2 * H^{1.5} * \eta)$$

Assuming that $\lambda = 2.0$, and H = constant, the CBR equation will appear in the form:

$$CBR = \gamma / (Q11 * \eta) \qquad (4)$$

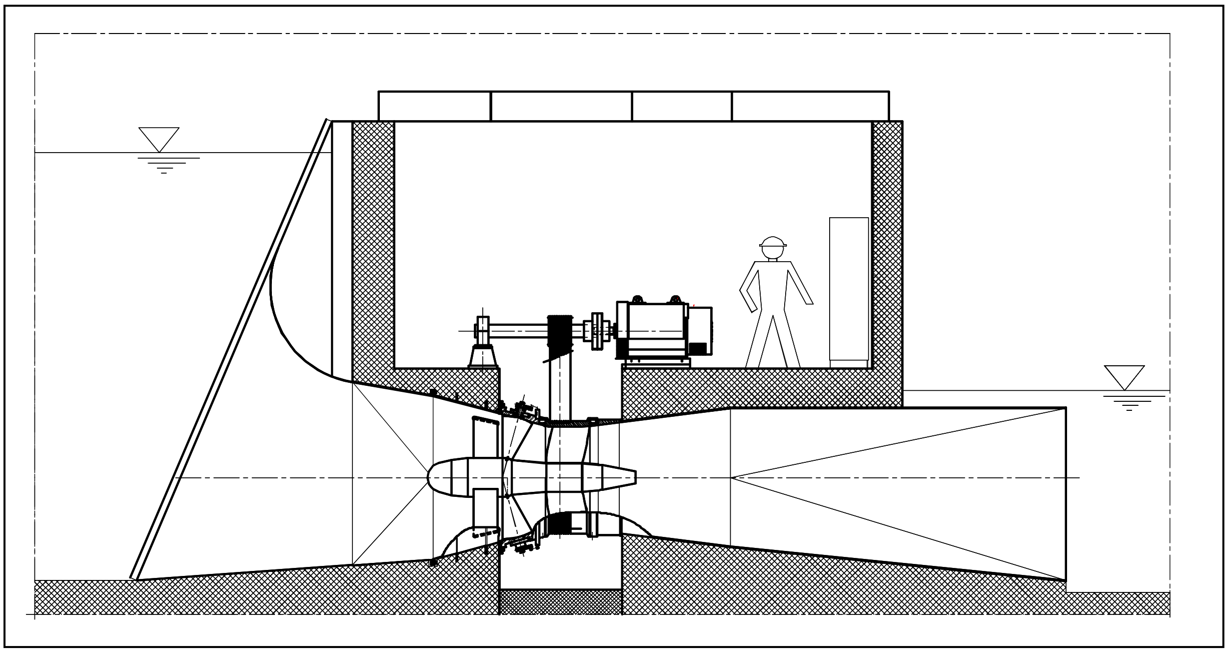
Equation (4) and the conclusions derived from it will be used in further considerations as design criteria of the most economic turbine unit for the ultra low-head hydro projects. Minimizing Cost-to-Benefit Ratio (CBR), which is a normal practice for any investment, will be achieved by maximizing the value of product of the unit flow (Q11) and the turbine efficiency (η). Therefore the design optimization criteria can be, written as:

$$\delta(Q11 * \eta)/\delta(Q11) = 0 \qquad (5)$$

Equation (5) will be used to define desired turbine design parameters.

Turbine concept

The Cost – Benefit considerations conducted were based on an assumption that the power plant is for the reaction turbine, which has a characteristic dimension D – the throat diameter. In order to satisfy the derived optimization criteria (equation 5), the turbine should have a high flow capacity (Q11), while maintaining high efficiency (η). This led to selection of the turbine type: Axial Flow. In order to create flow passages with gentle change in direction of flow and considering small scale, the power transmission and the generator had to be moved away from the flow passage and the draft tube was assumed to be conical for most of its length. The arrangement developed to satisfy these requirements is presented in Drawing 1.



Dwg. 1 General concept of an Ultra Low-Head Turbine

Design Methodology

Based on the design practice described in [1] and [2], as well as the optimization criteria (Eq. (5)), the following schedule was developed:

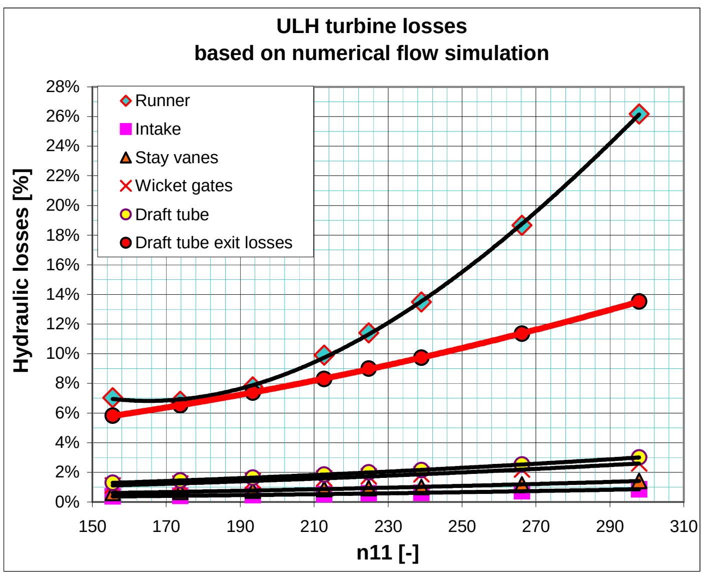
1) Determine hydraulic losses factor for:
   a) Intake,
   b) Draft Tube,
   c) Stay Vanes,

   based on the flow analysis for the flow relevant to turbine Q11 = 3.9 and the Hnet = 2.8m.

2) For the same flow as above, find the hydraulic profile of the Wicket Gates (WG) that will result in lowest hydraulic losses for the WG position of approximately 75 deg.
3) Design the optimum runner blade for the determined conditions, by following the procedure:
   a) Repeat the analysis for at least four different rotational speeds, selected to give the results in neighborhood of the peak of the (Q11* η) function
   b) Record the results (turbine efficiency, Q11, n11, Hnet)
   c) Evaluate the hydraulic quality of the blade by visual analysis of the static pressure distribution on both blade surfaces and the flow distribution at the runner exit. Acceptance criteria at this stage are:
      (i) pressure iso-lines (blade surface) perpendicular to the flow and parallel-like to the leading and trailing edges of the blade
      (ii) minimal flow non-uniformity at the draft tube outflow
      The decision about the necessity of further blade modification (for this operating point) is left to the designer at this stage they are one of the objectives of the project.
   d) Modify blade shape based on the above.
   e) Repeat analysis starting with a).
4) Stress analysis based on the pressure distributions on the runner blades and the wicket gates, stay vane load calculations. Modifications if necessary and flow analysis.

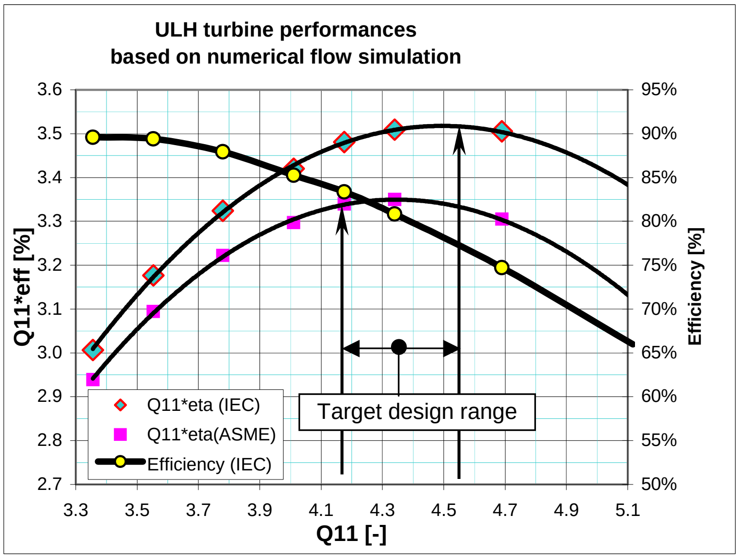
Target design parameters - preliminary results of the flow analysis

According to the described methodology, several runs of the CFD software were conducted to evaluate the quality of the flow passages and to provide necessary modifications. As soon as the results looked acceptable (pressure distribution on blades, lack of extreme pressure peaks in the flow passage etc.), they were recorded and are shown on Graph 2.



GRAPH 2. <u>CFD test preliminary results</u>

Analysis of the results was done to verify what the design operating range for the ultra low-head turbine unit should be. As soon as this was defined, the area of exploration was narrowed so the design process would be streamlined towards geometry modifications only. Such an approach makes the process faster and it assures that the "to-be-designed" turbine unit will be properly optimized for its specific purpose.



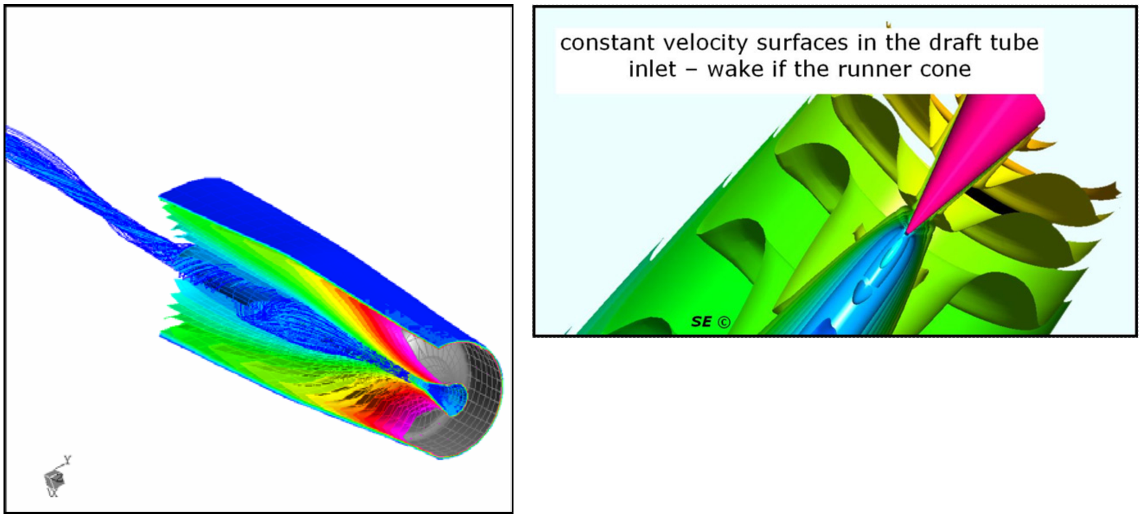
GRAPH 3. Target design range

The first goal was to verify the design parameters in the Equation (5).
As this is shown on the Graph 3 above, the function Q11 = f(Q11$*$ η) reaches its maximum value for Q11 ~ 4.3 , which corresponds to n11 ~ 220.

Difficulties encountered

Draft tube flow

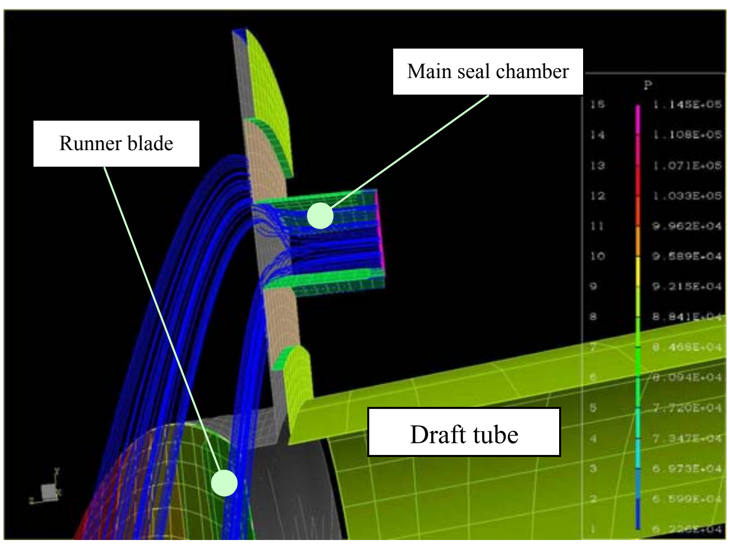
Set, at the very high Q11 level , design target point was very difficult to achieve. Very high velocity of turbine flow made turbine performances design very sensitive to even minima changes in runner blade geometry. After several blade modifications, when reasonable efficiencies were achieved, the draft tube flow pattern still was not acceptable (Dwg. 2).
In order to overcome this problem many more CFD simulations for various runner blade geometries were conducted.



Dwg. 2 Ultra Low-Head Turbine development – draft tube flow: constant velocity surfaces (design iteration Nr 15 and Nr 21)

Main seal design

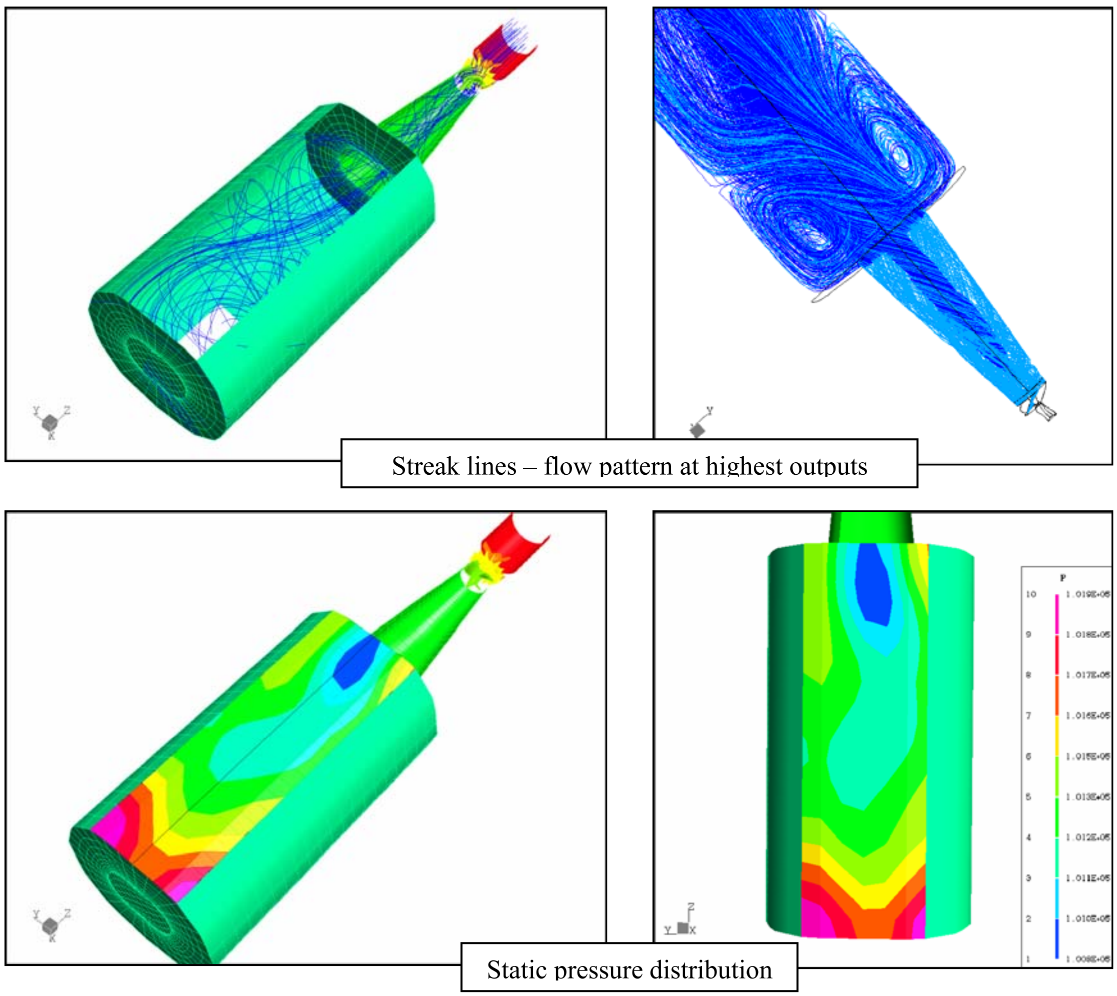
During the first phase of model tests, the main runner seals were not operating sufficiently at very high turbine flows. As it was not certain if poor performance of the seal was caused by structural problems, or the seal's operational parameters (flow rate to the main chamber, back pressure positioning seal element and others), a decision was made to conduct full CFD simulation of the seal as an integral part of the turbine. In cooperation with CANMET, the seal grid was connected to the turbine grid and the flow simulation was completed for various operating points of the turbine as well as for various seal gaps and flow rates. Results enable the modification of the seal design and the determination of operational parameters.



Dwg. 2 Ultra Low-Head Turbine development – visualization of flow simulation in the turbine main seal.

Draft tube – low pressure tank interaction

During very high flows rate operation, mechanical instability was observed. It was difficult to determine specific reason; the turbine performance (?), laboratory system operating at the edge of acceptable range (?) or malfunctioning seals (?) could be amongst reasons. The CFD domain was then extended to include the low pressure so the flow simulation for various operating points was conducted and careful observation of the draft tube – tank transition flow. At the expected turbine maximum power point, the flow pattern at the tank become significantly disturbed, so the static pressure at the top water elevation has shown difference of approx. 5% of the Net Head.



Dwg. 3 Ultra Low-Head Turbine development – visualization of flow simulation in the turbine main seal.

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