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Quantifying Extractable Power in a Stretch of River Using an Array of Marine Hydrokinetic Turbines

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CONTEXT

Between fall 2015 and spring 2016, a collaborative research project involving academics, industry and government researchers was conducted with funding support from Natural Resources Canada through the Eco Energy Innovation Initiative.

Main goals

- to help accelerate the development of the IEC-TC114 standards related to the assessment of turbine performances and hydrokinetic resource in rivers;
- to contribute to the development of marine hydrokinetic projects in Canada and abroad.

General approach

Develop a numerical methodology to predict the actual performances of an array of cross-flow type turbine (CFT) in a given stretch of river.

Project steps

1. Development of a numerical model of a Canadian river suitable for turbine array deployment;
2. Characterization and analysis of the wake and performance curves of an actual CFT;
3. Development of a novel simplified turbine model that can generate the same impact on the flow as the actual CFT and predict its performance;
4. Analysis of the actual extractable power of three different array configurations using the complete river model and several simplified turbine representations.

1. RIVER MODEL

Goal

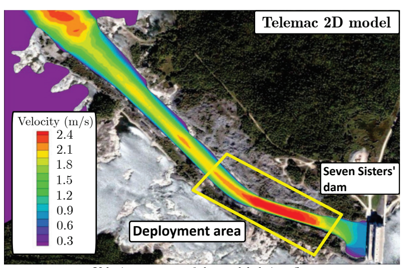
Provide an accurate prediction of how a real river responds to a turbine array deployment.

Site characteristics

- located along the Winnipeg River, downstream of the Seven Sisters' dam in Manitoba (Canada)
- man-made open-channel
- home of the Canadian Hydrokinetic Turbine Test Center (CHTTC) run by the University of Manitoba

Model characteristics

- Telemac-2D and StarCCM+ simulation software
- model calibration used bathymetric data, ADCP flow measurements and flow rate data at the dam



Velocity contours of the modeled river flow

2. TURBINE WAKE AND PERFORMANCE CHARACTERIZATION

Goal

Provide accurate reference data regarding the performances and wake recuperation length of an actual CFT operating in different channel blockage conditions to verify and tune the simplified turbine model.

Methodology

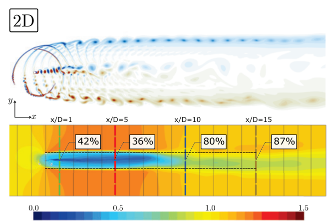
- 2D and 3D CFD study
- CD-Adapco's StarCCM+ simulation software
- URANS flow resolution
- 2-equation k-w SST turbulence modeling

Turbine specifications

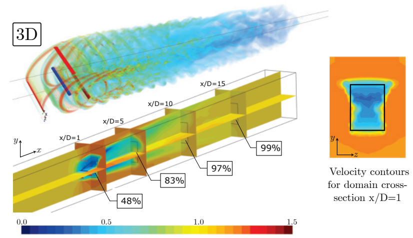
- Scaled-up version (6.56:1) of a model-scale turbine previously investigated by Mavi Innovations Inc.
- High-solidity three-bladed cross-flow type turbine with NACA 63-021 blade profile

Wake characterization

Investigation of the wake topology and recuperation length of the CFT operating at maximum power extraction in a confined channel ($\lambda = 3.0, \epsilon = 20\%$):



z-vorticity contours (red=positive, blue=negative) (top)
Contours of normalized streamwise velocity (bottom)



Volume rendering of vorticity magnitude (top)
Contours of normalized streamwise velocity (bottom)

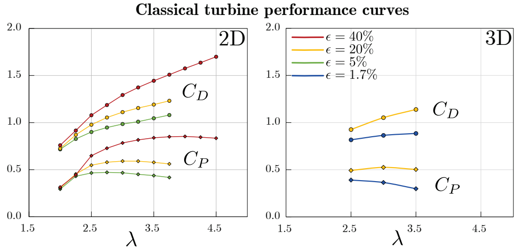
Velocity contours for domain cross-section x/D=1

- 2D CFT models produce unreliable wake recuperation predictions.
- Wake recovery length is significantly shorter in 3D than in 2D because of the enhanced wake mixing and inward convection generated by the spanwise bypass flow.

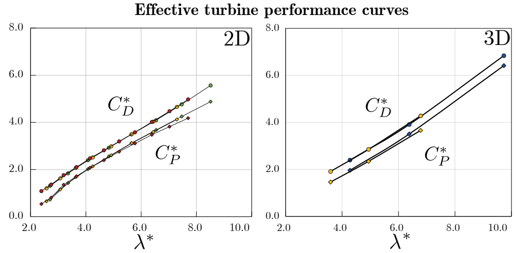
Performances characterization

Investigation of channel blockage level ($\epsilon = \frac{A_T}{A_{\text{channel}}}$) and operating conditions (λ) effects on turbine performances :

Classical turbine performance curves



Effective turbine performance curves



Traditional performance curves strongly depend on channel blockage level ϵ.

- ϵ needs to be precisely quantified before referencing to classical C_D and C_P curves.
- The choice of V_{ref} is often tricky in array deployment circumstances.

Effective performance curves are **independent of channel blockage level.**

- Performances only depend on effective flow conditions at the turbine through V^*.

Classical and effective (*) performance metrics

Tip speed ratio

$\lambda = \frac{\omega R}{V_{\text{ref}}}$ $\qquad$ $\lambda^* = \frac{\omega R}{V^*}$

Mean drag coefficient

$C_D = \frac{\overline{D}}{\frac{1}{2}\rho V_{\text{ref}}^2 A_T}$ $\qquad$ $C_D^* = \frac{\overline{D}}{\frac{1}{2}\rho {V^*}^2 A_T}$

Mean power coefficient

$C_P = \frac{\overline{P}}{\frac{1}{2}\rho V_{\text{ref}}^3 A_T}$ $\qquad$ $C_P^* = \frac{\overline{P}}{\frac{1}{2}\rho {V^*}^3 A_T}$

with V^* being the mean flow velocity passing through the turbine

3. SIMPLIFIED TURBINE MODEL

Goals

- Provide a reliable prediction of the mean performances of the CFT once it is deployed in a river;
- Generate the same mean impact on the resource as the actual turbine.

Key concepts behind the Effective Turbine Model (ETM)

- The turbines are represented by thin prism regions of same frontal area as the CFT in which a streamwise volumic force $\boldsymbol{f_T}$ acts.
- The ETM imposes both effective performance coefficients of the actual CFT (C_D^* and C_P^*).
  - achieved through a non-uniform spatial distribution of $\boldsymbol{f_T}$

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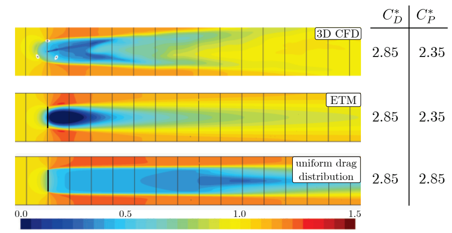
- drastic reduction of computational cost compared to 3D unsteady CFD;
- independent of channel blockage level;
- accurate energy loss induced on the river flow.

Results

- When C_D^* and C_P^* both match that of the CFT, turbine performance coefficients (C_D and C_P) are predicted within 5% irrespective of blockage level.
- Without the spatial distribution of the drag-elements leading to the right energy extraction (right C_P^*), both wake and performance predictions are off.



Contours of the normalized streamwise velocity

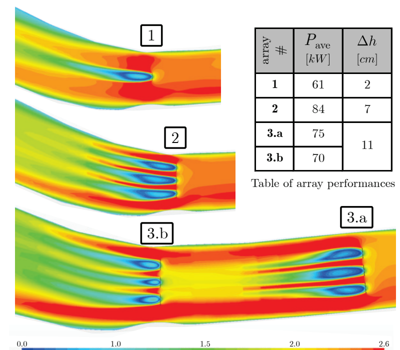
4. COMPLETE ARRAY MODEL

Goal

Provide insight regarding the global effects of a turbine array deployed in a stretch of river.

Observations

- Deploying a row of turbines across the river instead of a single turbine increases the power production per turbine (P_{ave}). This is due to the increased in channel blockage.
- Deploying turbines upstream of an other row of turbines decreases the power production of the downstream turbines. This is due to the momentum deficit generated by the upstream turbines.
- The estimated change in water elevation (Δh) at the dam (upstream) increases as more turbines are placed in the channel. This is due to the increased global flow resistance by the array.



Velocity magnitude contours for the three array configurations using the complete turbine array model (StarCCM+, 3D)

array #	P_{ave} [kW]	Δh [cm]
1	61	2
2	84	7
3.a	75	11
3.b	70	

Table of array performances

NEXT STEPS

- Improve the simplified turbine model predictions regarding the wake recuperation length of the actual turbine;
- Characterize the effective performances of other types of turbine such as the horizontal-axis turbine and the flapping foil turbine in order to extend the applicability of the simplified turbine model;
- Validate the performance and robustness of the ETM in perturbed flow conditions such as flows observed downstream of a turbine or a turbine row;
- Perform a thorough optimization study in order to establish turbine array configuration guidelines that can help project developers to increase their profitability.