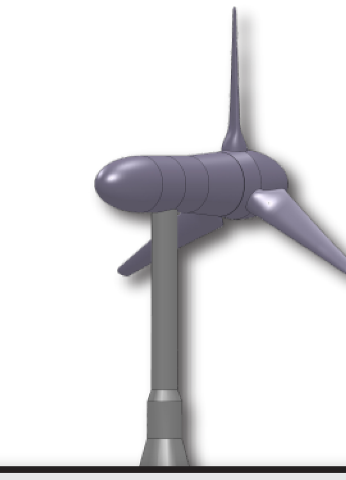
Turbulence effects of axial flow hydrokinetic turbines

OS53A-1763



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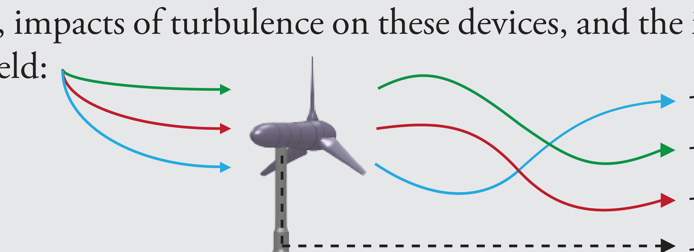
A. Introduction

Axial flow hydrokinetic turbines provide a method for extracting energy available in unidirectional (river), bidirectional (tidal) and marine currents; however, a deep understanding of the wake dynamics, momentum recovery, geomorphologic effects, and ecological interaction with these hydrokinetic turbines is required to guarantee their economical and environmental viability. The St. Anthony Falls Laboratory (SAFL) at the University of Minnesota (UMN) has performed physical modeling experiments using a 1:10 scale axial flow tidal turbine in the SAFL Main Channel, a 2.75m x 1.8m x 80m open channel test facility. A sophisticated control system allows synchronous measurements of turbine power along with high resolution 3D velocity measurements within the channel. Using acoustic Doppler velocimeters (ADVs), 3D velocity profile data were collected up to 15 turbine diameters downstream of the turbine location. These data provide valuable information on the wake characteristics (mean flow, turbulence, Reynolds stresses, etc.) resulting from a rotating axial flow hydrokinetic machine. Regions of high turbulence and shear zones that persist in the near wake regions are delineated along with the velocity deficit and momentum recovery within the wake downstream of the device. Synchronous ADV data shed light on the rotational characteristics of the wake and its potential impacts on the local geomorphology and hydrodynamic environment. This dataset on single hydrokinetic turbine flow characteristics is the basis for further work on the optimal arrangement and performance environment for arrays of similar hydrokinetic devices. Through this research, we seek to understand turbine wake recovery and the impacts it may have on the a) performance; b) stability and lifespan; and c) spacing requirements of nearby machines. Additionally, we begin fulfilling the need for high-resolution measurements to validate CFD models for further development.

There is growing interest by the U.S. Department of Energy (DoE) to accelerate the development of environmentally sustainable and renewable energy resources. Among those are hydrokinetic energy technologies. Aggressive studies are underway by DoE laboratories to quantify available resources from tides, rivers, and waves. An equally aggressive science-based approach is investigating technologies and their impact on the surrounding environment. For these technologies to develop into economically viable solutions to meet our Nation's energy demands by producing energy at competitive prices and scales (i.d. reducing levelized cost of energy (LCoE), research institutions, government labs, and industry are beginning to work together to understand hydrokinetic device performance, impacts of turbulence on these devices, and the impact the turbulent environments they produce has on near-field and far-field:



B. Experimental Setup

$Q_w = 1.265 m^3/sec$ h = 1.15m $\%_{blockage} = 6.2\%$
Re = 200,000 Fr = 0.12

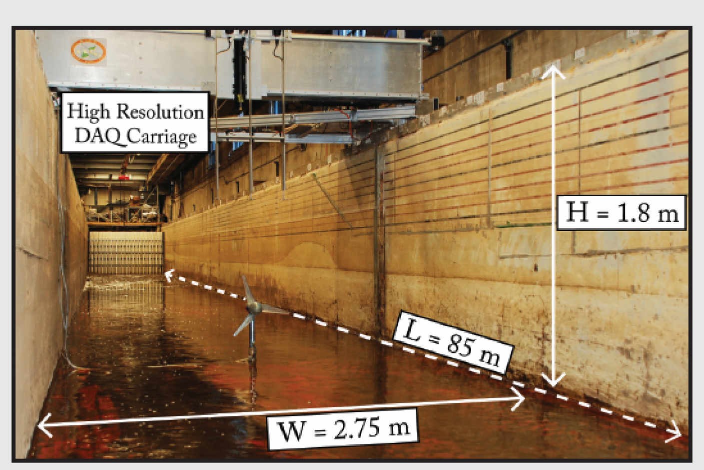


Figure B.1. SAFL Main Channel with automated Data Acquisition Carriage used to measure flow field, topography, and water surface elevation.

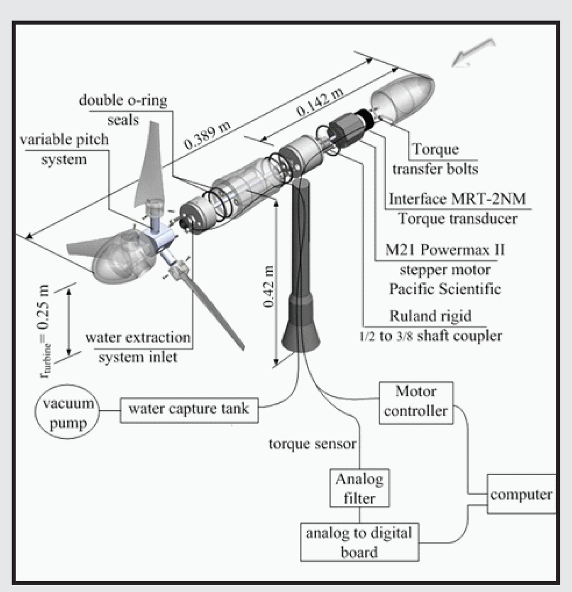


Figure B.2. Exploded view of the instrumented 1:10 scale model axial flow hydrokinetic turbine used for this study.

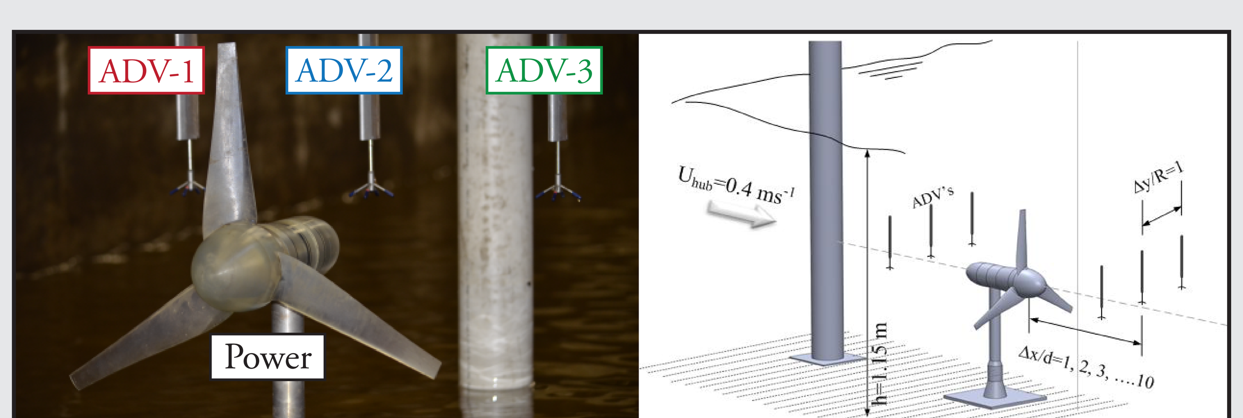


Figure B.3. Three acoustic Doppler velocimeters positioned at +/- 0.5d (ADV-1 and ADV-3) and hub center (ADV-2) synchronized with turbine power measurements allowing for correlation between flow field and turbine performance measurements.

C. Results

C.1. Turbine Performance

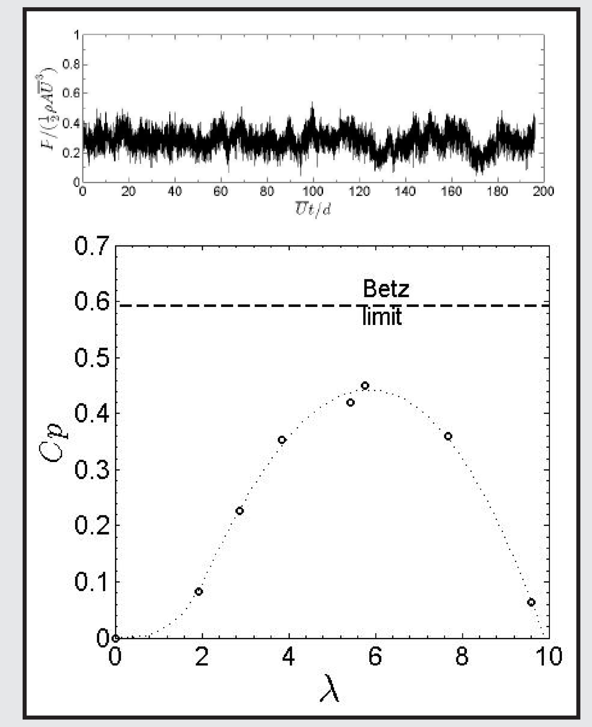


Figure C.1. Turbine power timeseries (top) and performance curve (bottom) (Chamorro et al.))

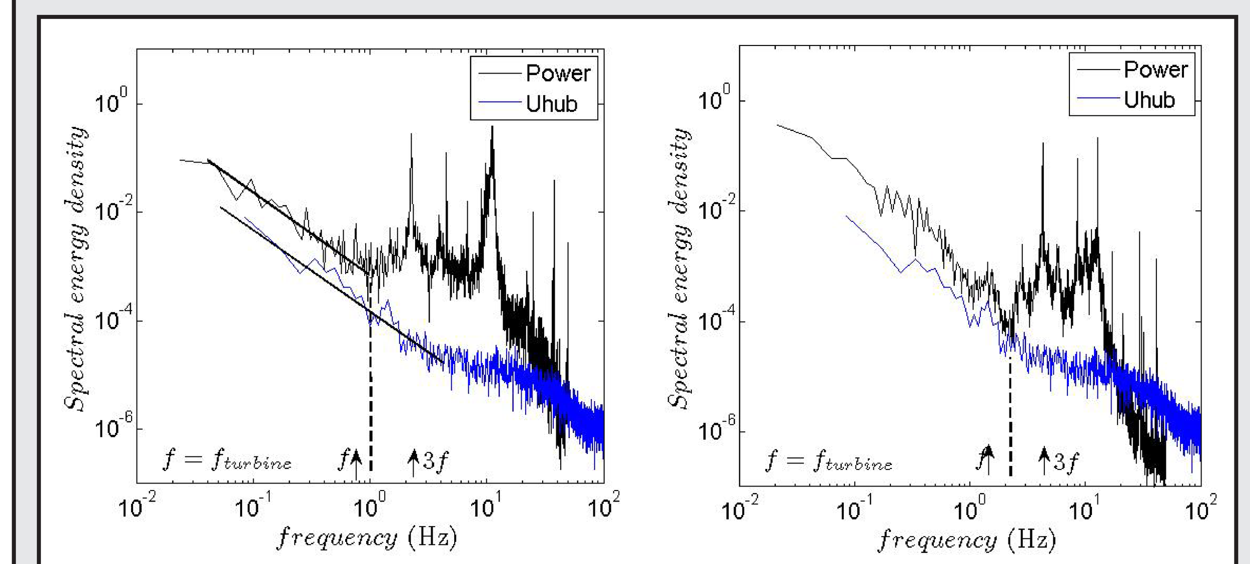


Figure C.2. Power spectral densities of approaching velocity (blue) and turbine power output (black) for two tip-speed ratios (TSR = 2.9 (left) and 5.6 (right)) highlighting critical frequencies for turbine response. (Chamorro et al.)

C.2. Flow Field

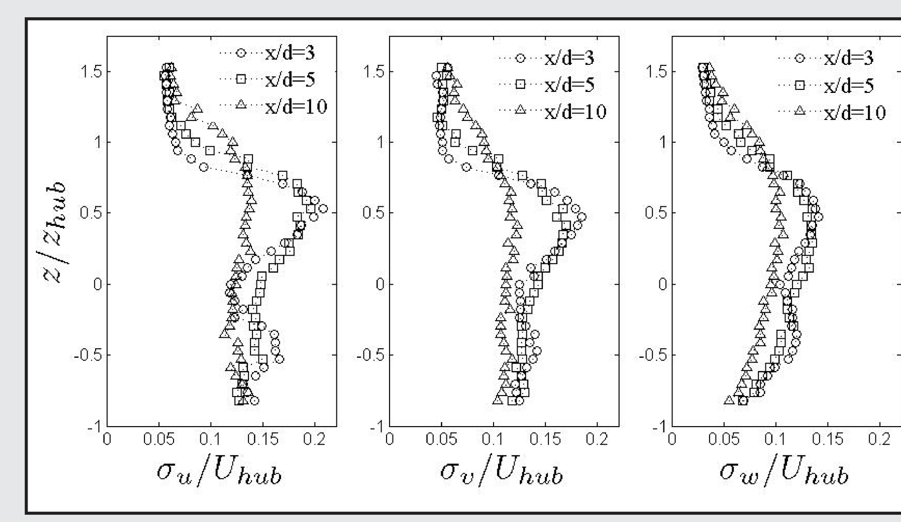


Figure C.3. Turbulence intensities (I_U, I_V, I_W) at 3, 5, and 10 rotor diameters downstream of the turbine. (Chamorro et al.)

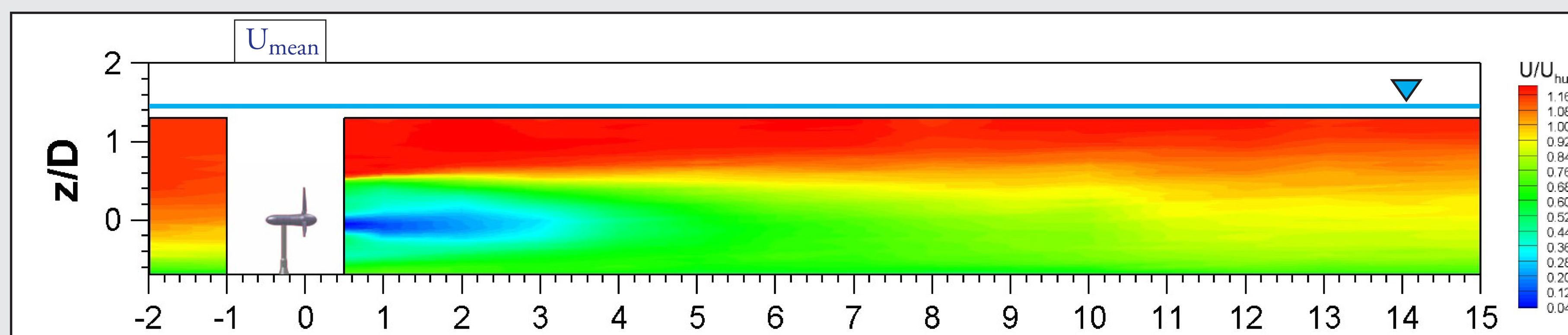


Figure C.4. Mean streamwise velocity from -2 to +15 rotor diameters along the centerplane of the turbine. (Chamorro et al.)

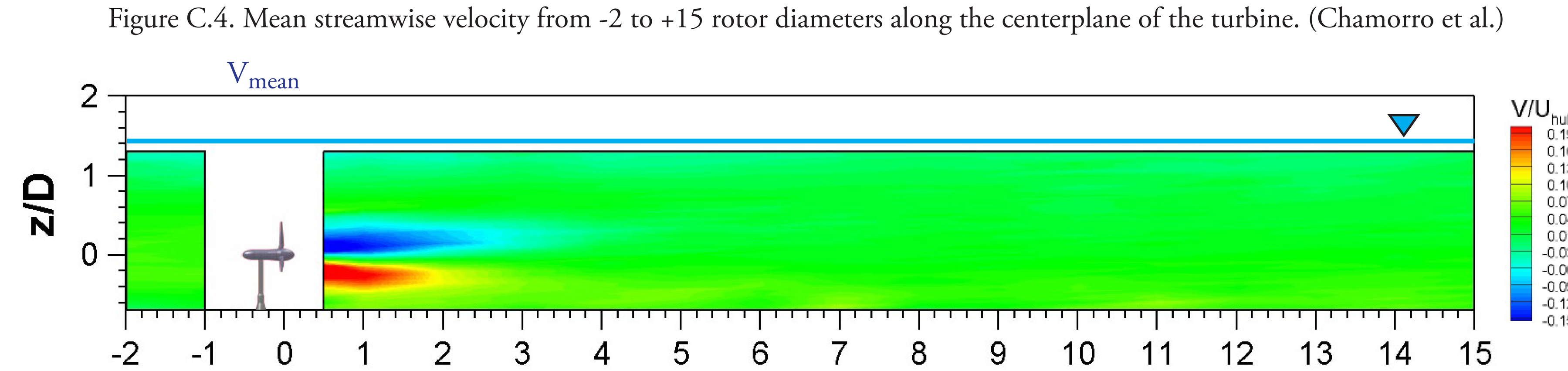


Figure C.5. Mean lateral velocity from -2 to +15 rotor diameters along the centerplane of the turbine. (Chamorro et al.)

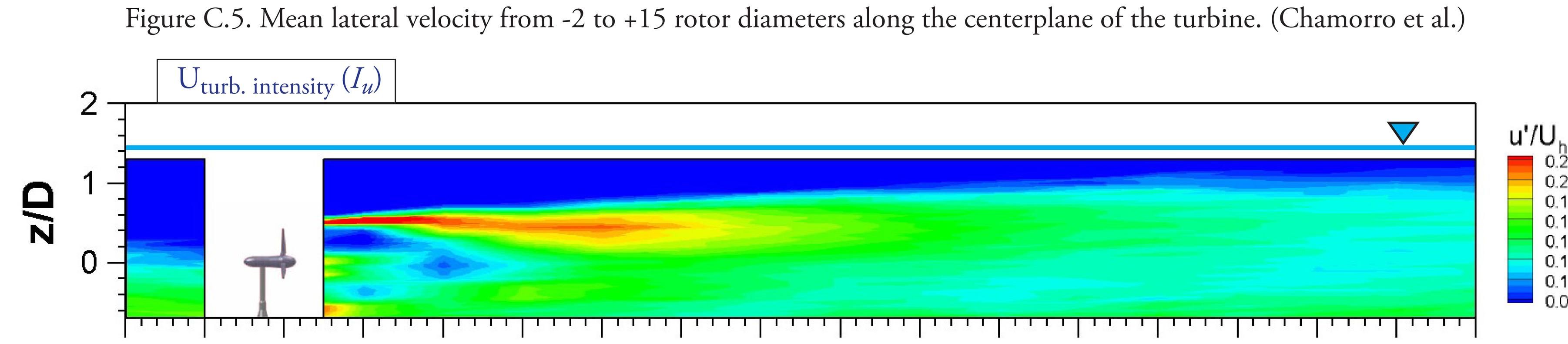


Figure C.6. Streamwise turbulent intensity from -2 to +15 rotor diameters along the centerplane of the turbine. (Chamorro et al.)

D. Discussion

D.1. Turbine Performance

- Figure C.2 illustrates how scales of turbulence that impact the turbine vary depending on turbine operating conditions (i.e. tip-speed ratio). For low frequencies, the turbine power slope is similar to the slope of the hub height flow velocity. At a critical frequency, the turbine no longer is impacted by higher turbulent frequencies.

- Figure E.1 illustrates the coherence between the turbine power and ADV-3. Without the presence of upstream obstacles (i.e. bridge piers, boulders, etc.), a strong signal is present between the turbine power and ADV-3. This disappears with turbulent approach flow conditions, likely a result of the increased capability of turbulent mixing and destruction of the tip vortices.

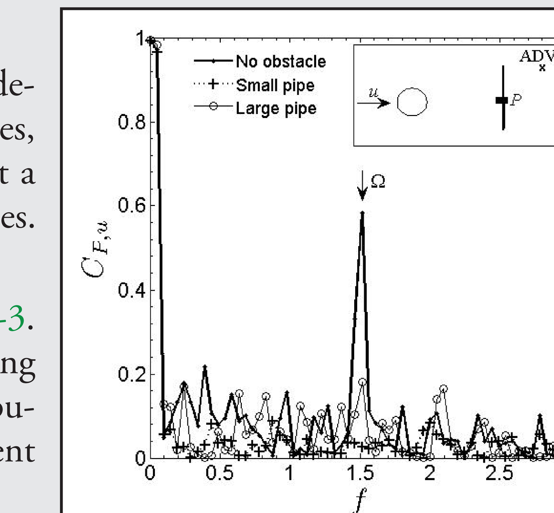


Figure D.1. Spectral coherence between turbine power and

D.2. Flow Field

- Figures C.3 to C.6 show the highly turbulent zones immediately downstream of the turbine. A zone of high shear aligned with the top tip elevation persists more than 5d downstream. The wake does not fully return to upstream conditions within the 10d, but results with turbulent inflow show that wake recovery occurs more rapidly in the near-field regions. This is likely a result of increased mixing. This only affects near-field regions, however, and the data show a remnant of the wake beyond 10d.

- The turbine rotated counter-clockwise during the experiments. The lateral velocity data (Fig. C.5) show clockwise rotation of the wake (reds = positive, into the page), however, these counter-rotating lateral wake velocities do not persist much beyond 3d downstream.

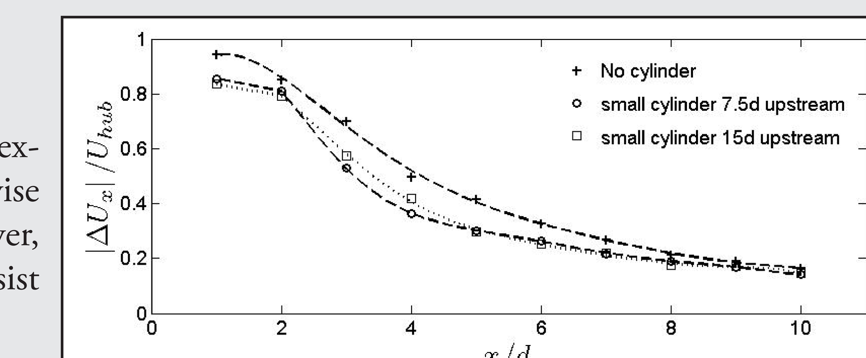


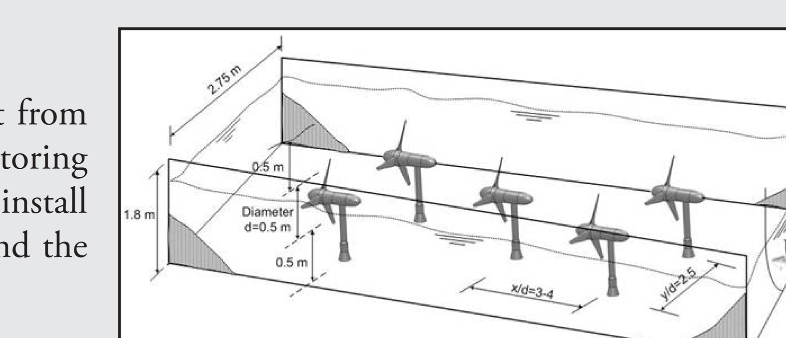
Figure D.2. Velocity deficit downstream of turbine with and without turbulence generating obstacles.

E. Summary

- Hydrokinetic technologies show promise of harvesting substantial energy to contribute towards the Nation's energy demands. This research provides insights on effects of near- and far-field environments, most notably showing:

  1. Highly turbulent zones exist in the downstream near-field environment;
  2. Turbine operating conditions respond to varying scales of turbulence;
  3. Wake recovery occurs more quickly with increased mixing from turbulent approach conditions; how ever, this may create structural instability for the turbine (further research needed).
  4. Turbulent regions downstream of the turbine could impact local geomorphology and aquatic ecosystems (or other nearby turbines).

- We continue to understand the surrounding environment from these experiments. Our immediate efforts are focusing on monitoring scour, if any, that occurs downstream. In the future, we plan to install arrays of turbines to understand turbulence effects of turbines and the interactions among devices in a water turbine farm.



F. Acknowledgements

This project was partially funded by Verdant Power and U.S. Department of Energy under Contract DE-AC05-00OR22725. We would like to also thank the contributions of the Engineering and Technical Staff at St. Anthony Falls Laboratory, and especially the assistance of SAFL Engineers Chris Ellis and Jim Mullin with design and instrumentation of the turbine power system and synchronized ADV measurement setup.

Chamorro, L.P., Morton, S., Hill, C., Ellis, C., Arndt, R.E.A., and Sotiropoulos, F. "Flow-structure interaction around a hydrokinetic turbine. Part I: Experiments." *In preparation.*