Numerical Investigation of Marine Hydrokinetic Turbines: Methodology development for single and small array simulation, and application to flume and full-scale cases.

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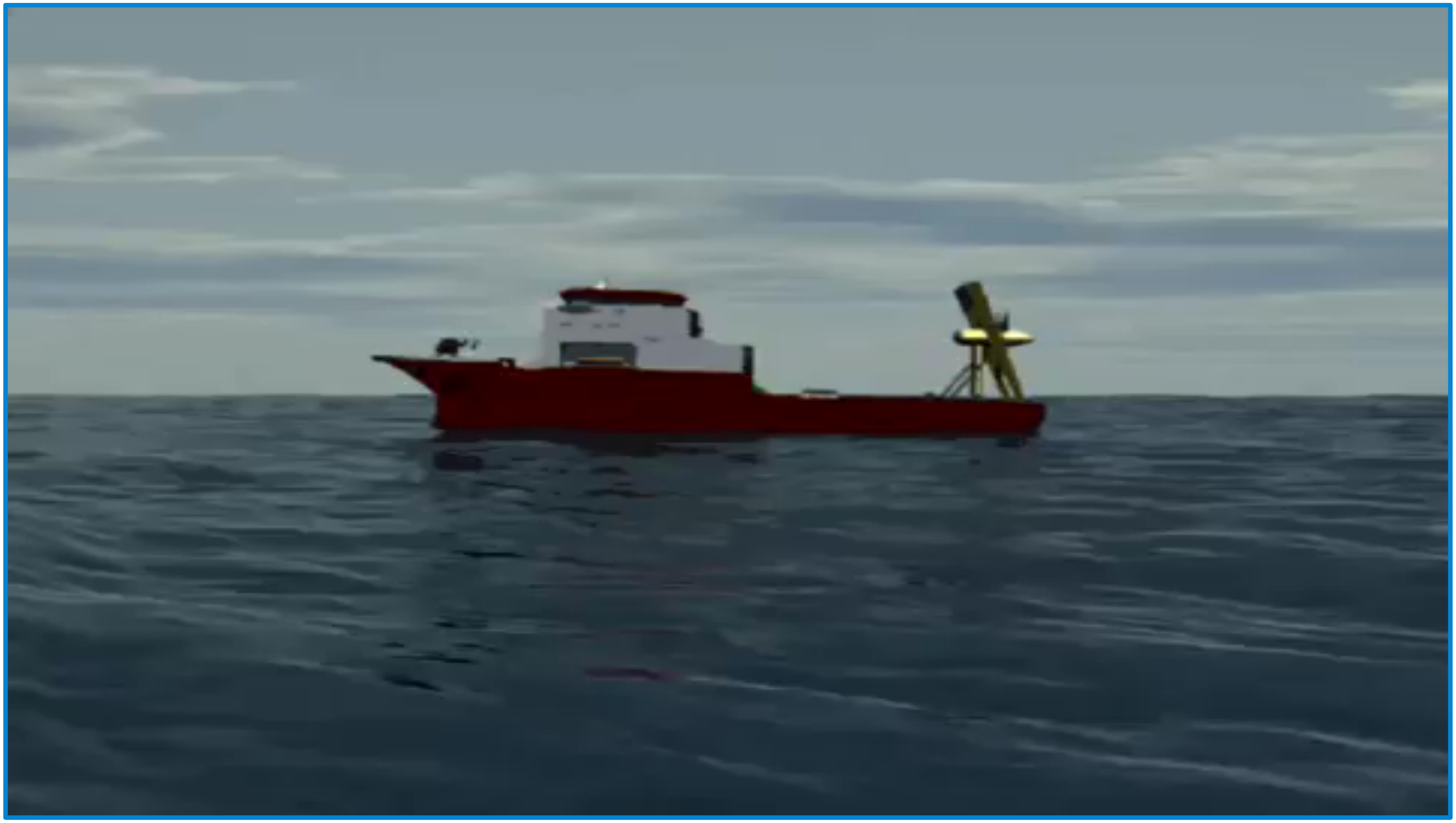
W OSU

Marine Hydrokinetic (Tidal) Energy - Source

Source:

Marine Hydrokinetic (Tidal) Energy - Harvest



Source:

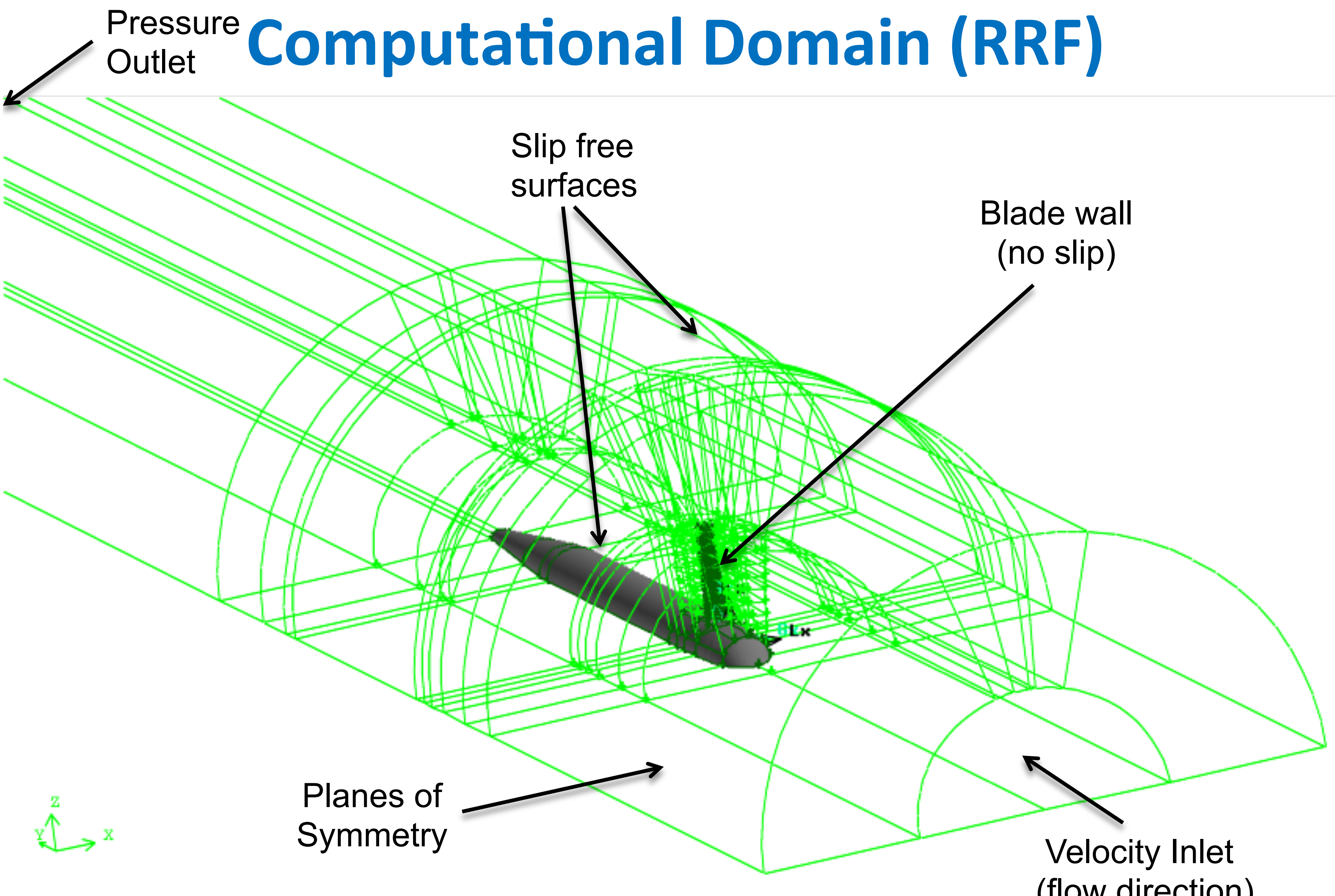
The Dissertation's Motivations and Goals

- **Investigate and address some of the open questions in MHK community.**
- **Numerical methodologies development (i.e. CFD tools) for MHK industry.**
- **Detail performance characterization and fluid dynamics simulation around and in the wake of a MHK turbine.**
- **Array optimization of MHK turbines.**
- **Physical environmental effects of the MHK turbines.**

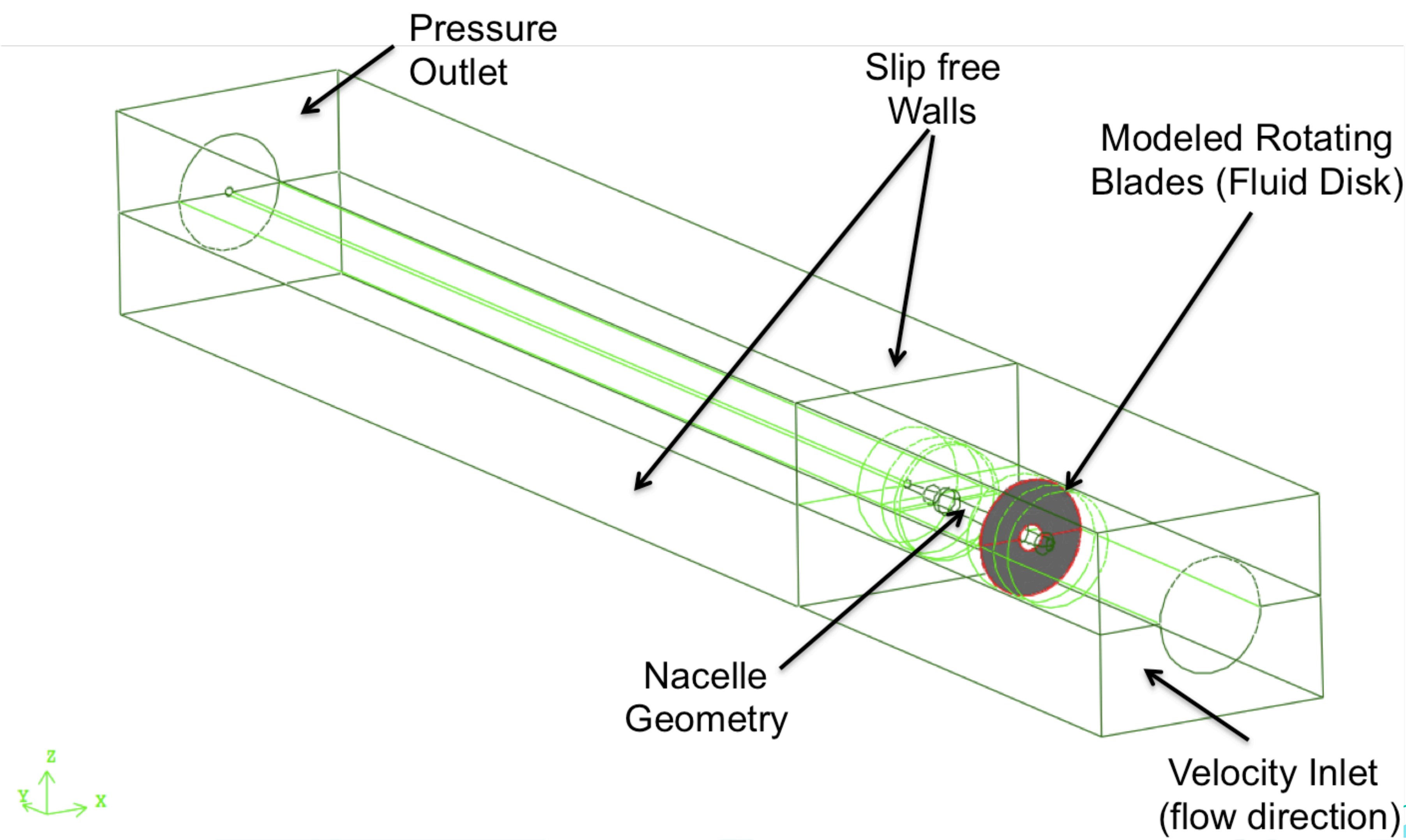
Numerical Methodology

1. Sliding Mesh Model
2. Rotating Reference Model (RRF)
3. Blade Element Model (BEM)
4. Actuator Disk Theory

Computational Domain (RRF)

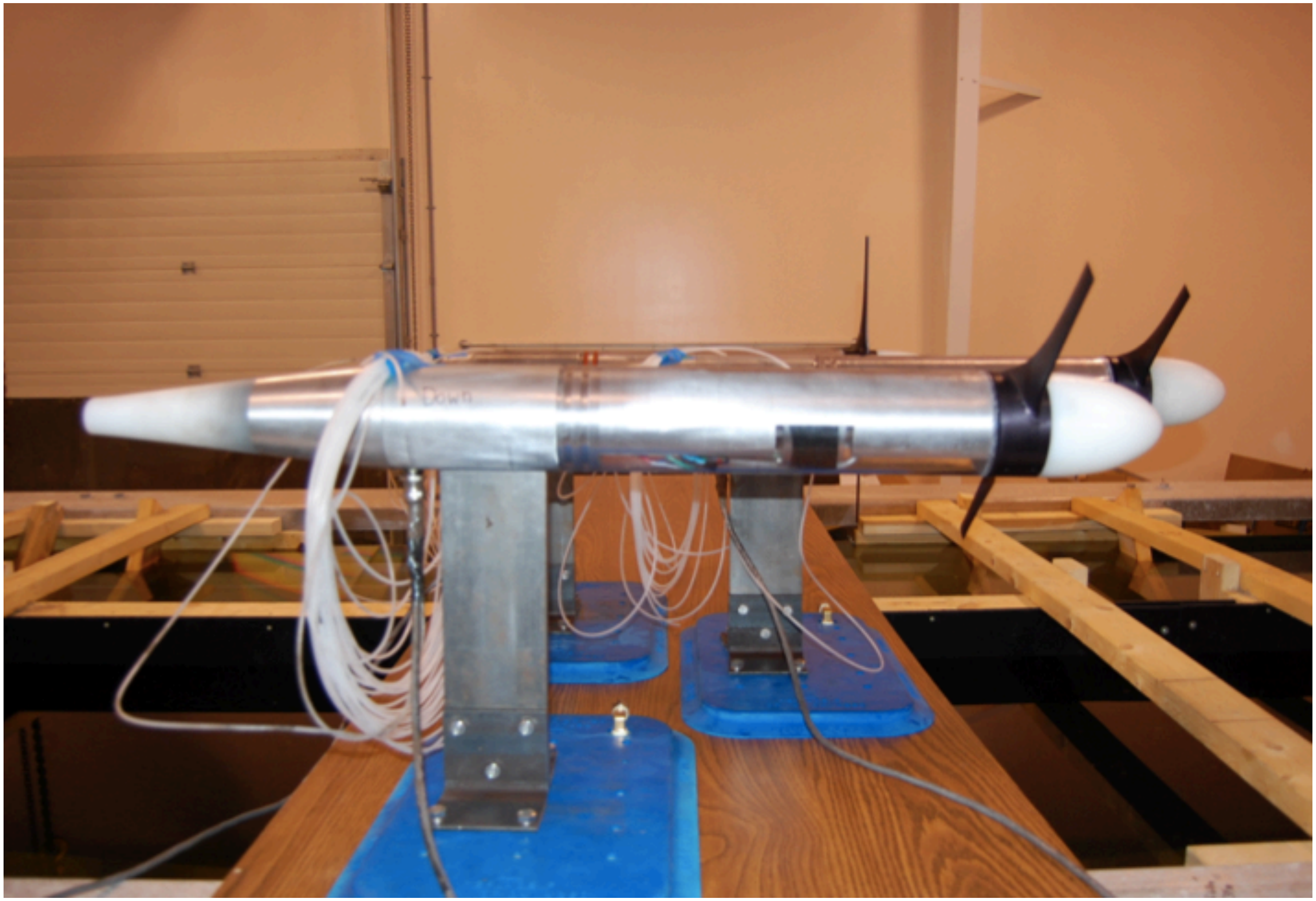


Computational Domain (BEM)



Single Turbine Performance & Wake Characterization

Laboratory Scale Turbine Model



Source: N. Stelzenmuller's MSME thesis

Essential Variables for Turbine Performance Characterization

$$Re = \frac{\rho V c}{\mu} \quad , \quad TSR = \frac{r\omega}{V}$$

$$C_p = \frac{P}{\frac{1}{2}\rho A V^3}$$

$$\rho = Fluid\ density$$

$$V = Free\ stream\ velocity$$

$$c = Blade\ chord\ length$$

$$\mu = Fluid\ viscosity$$

$$r = Rotor\ radius$$

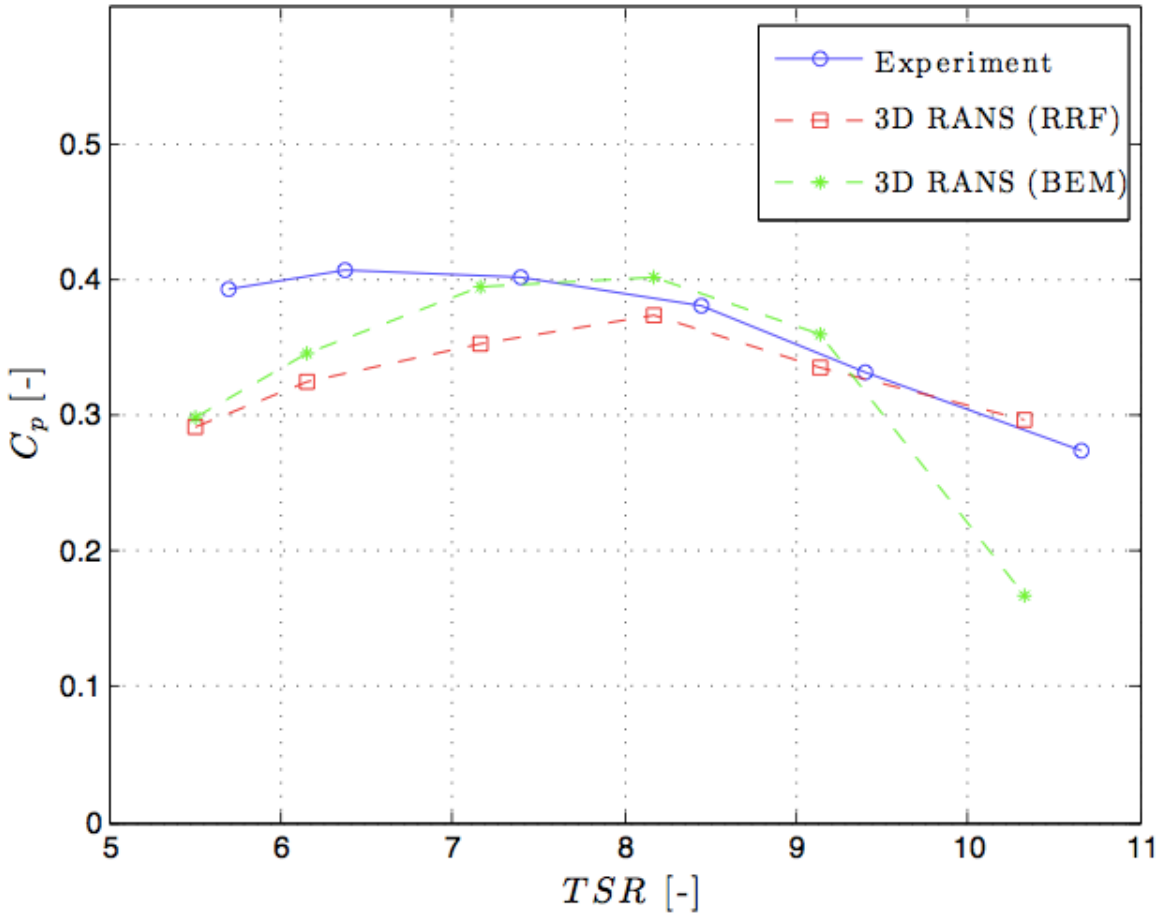
$$\omega = Rotational\ Speed$$

$$P = Power\ extracted\ by\ turbine$$

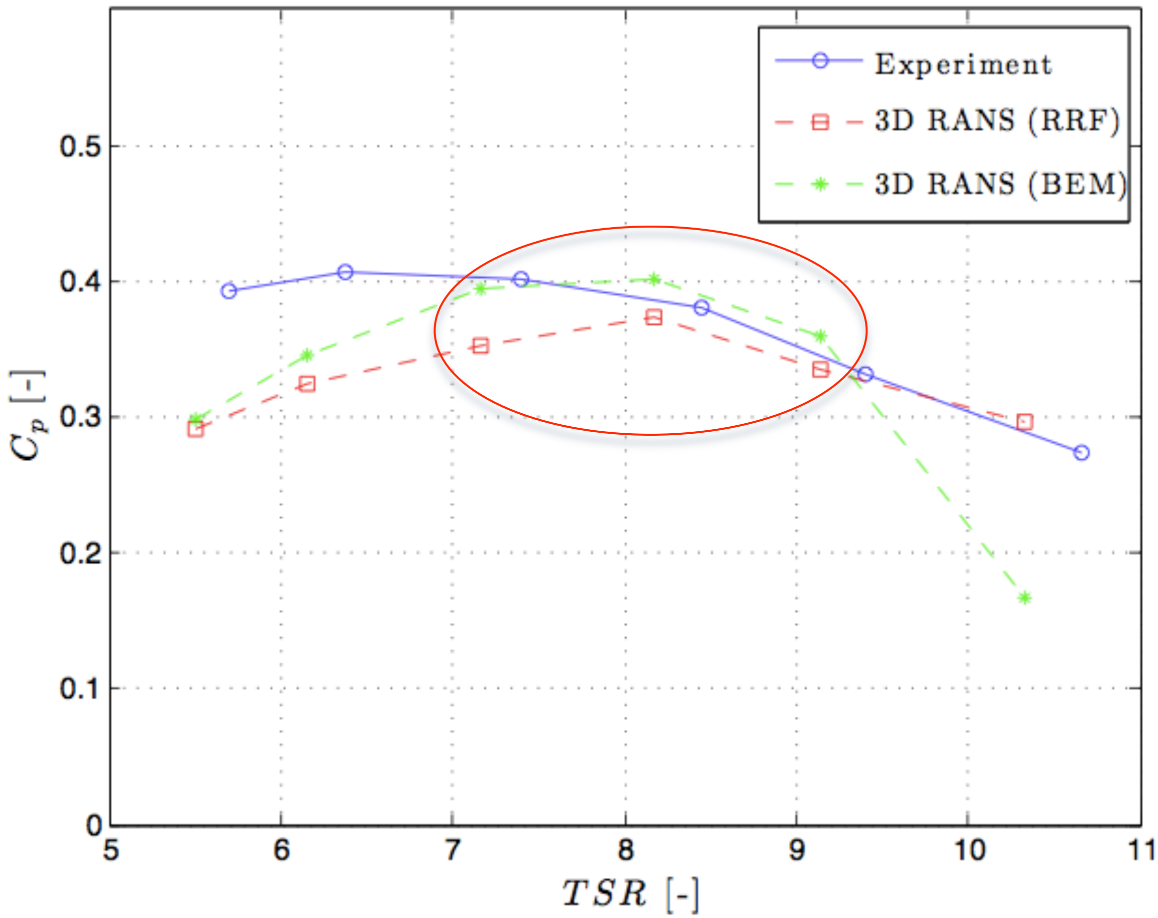
$$A = Rotor\ Area$$

$$C_p = Coefficient\ of\ performance, or\ efficiency$$

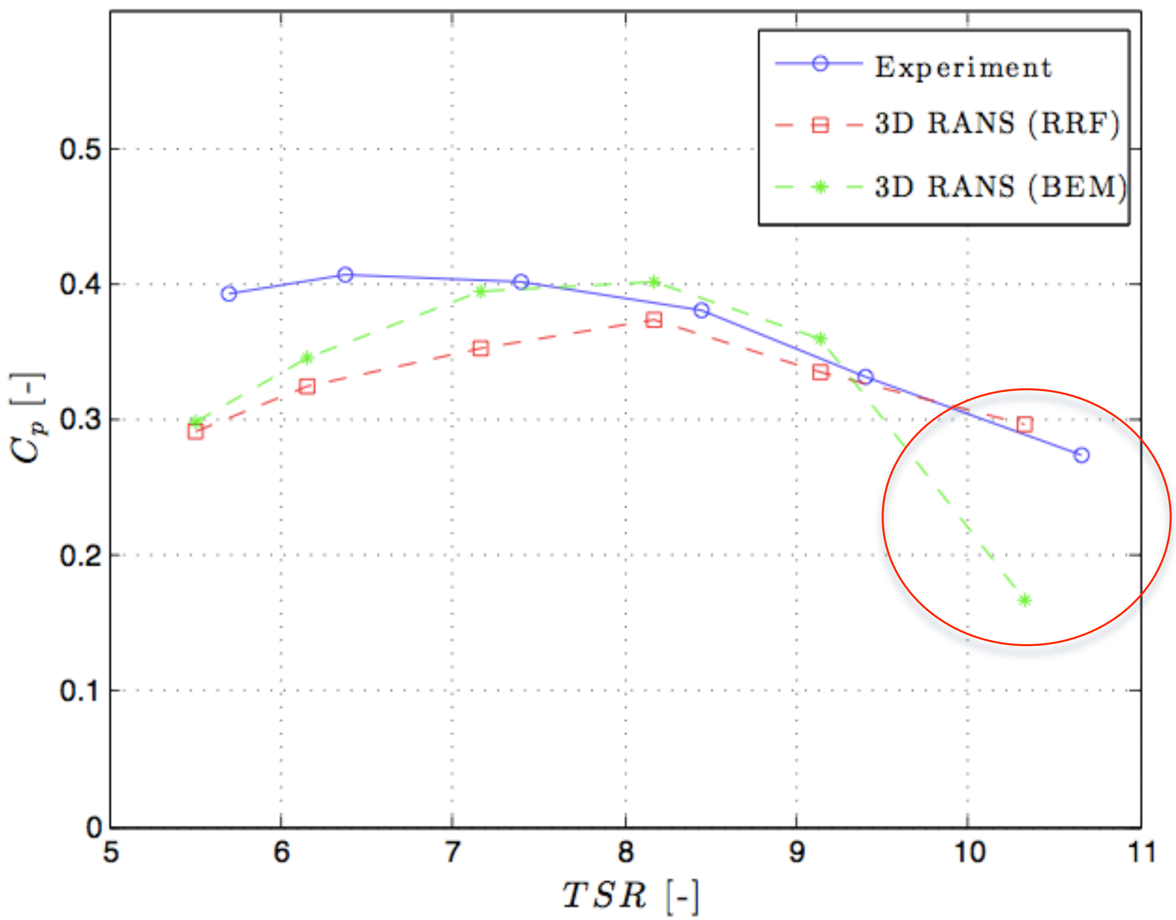
Numerical vs. Experimental Results
(C_p – TSR Curves)



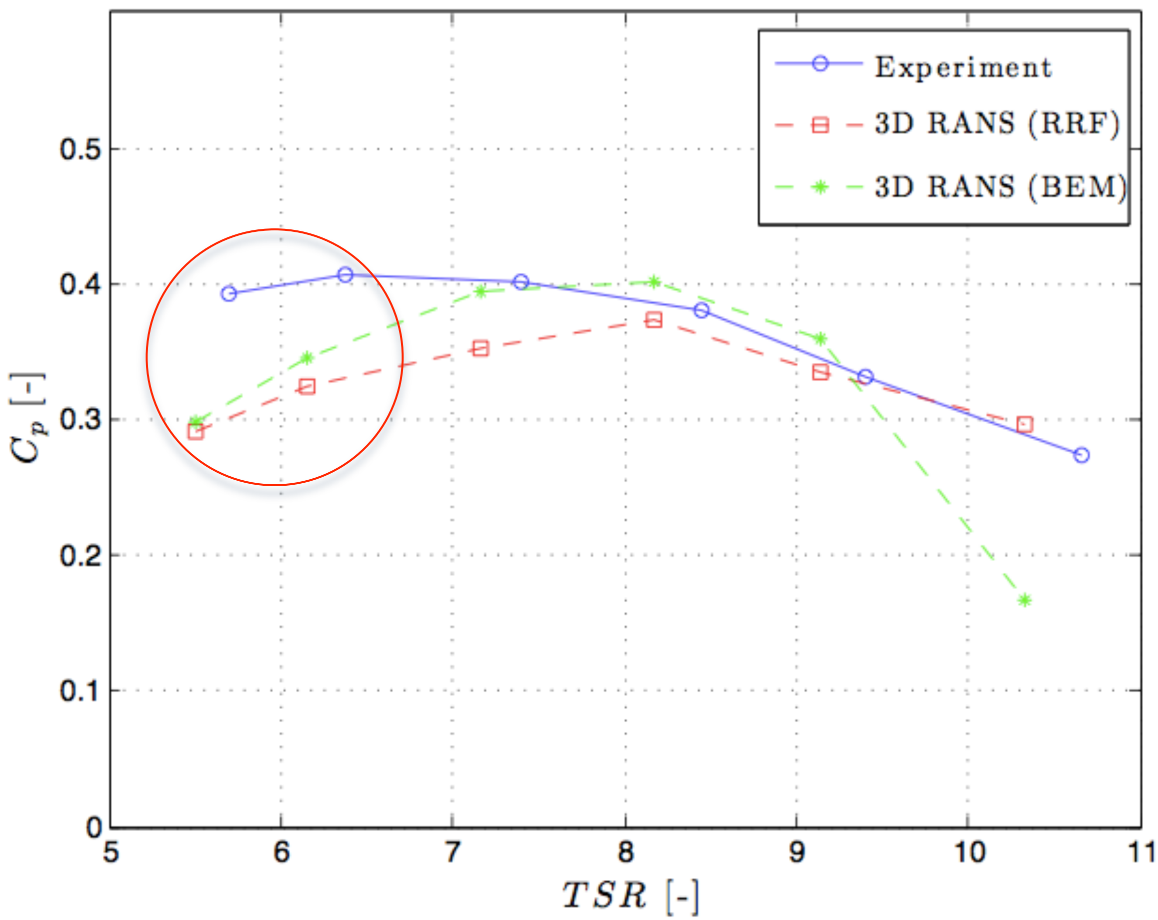
Numerical vs. Experimental Results
(C_p – TSR Curves)



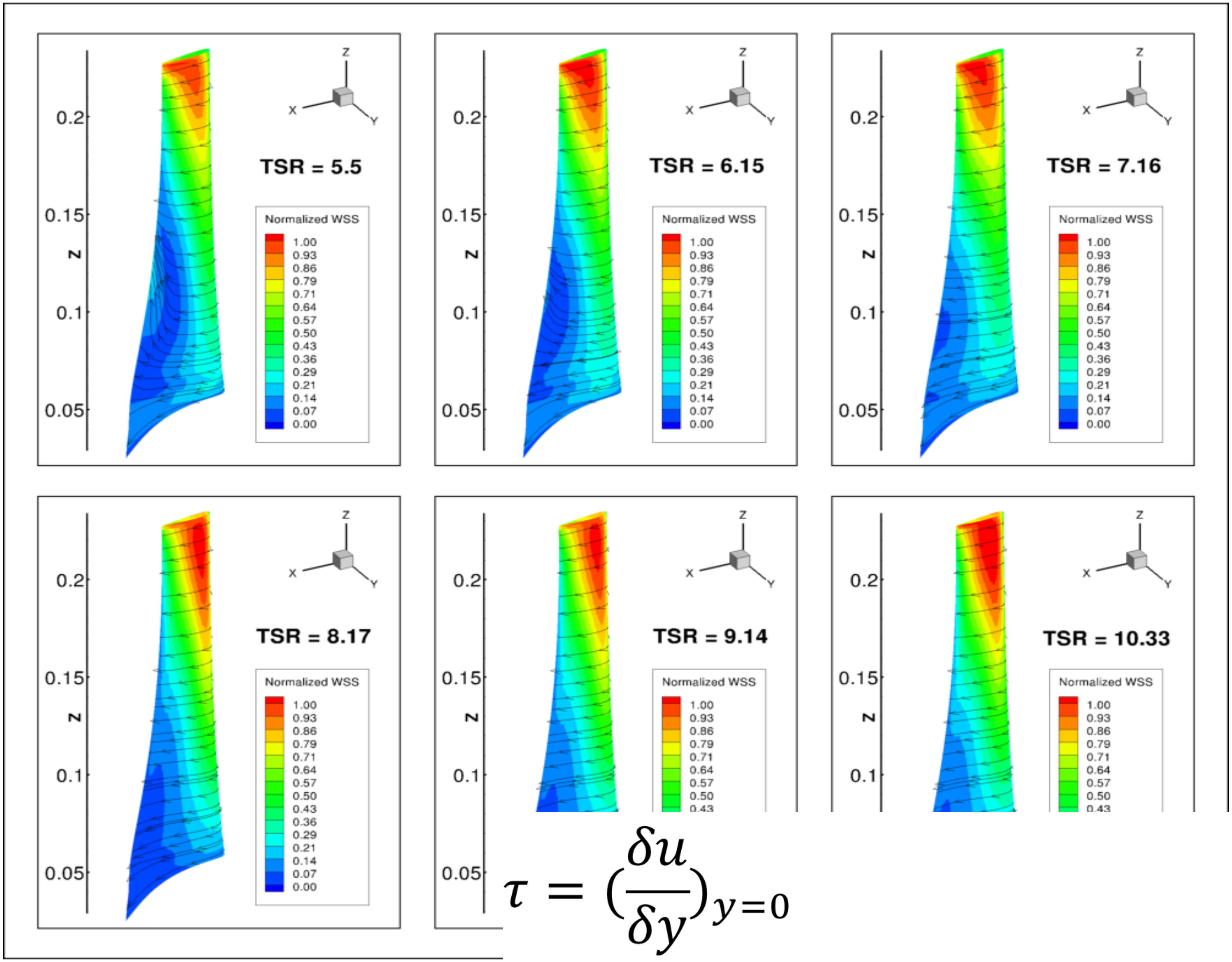
Numerical vs. Experimental Results
(C_p – TSR Curves)



Numerical vs. Experimental Results
(C_p – TSR Curves)

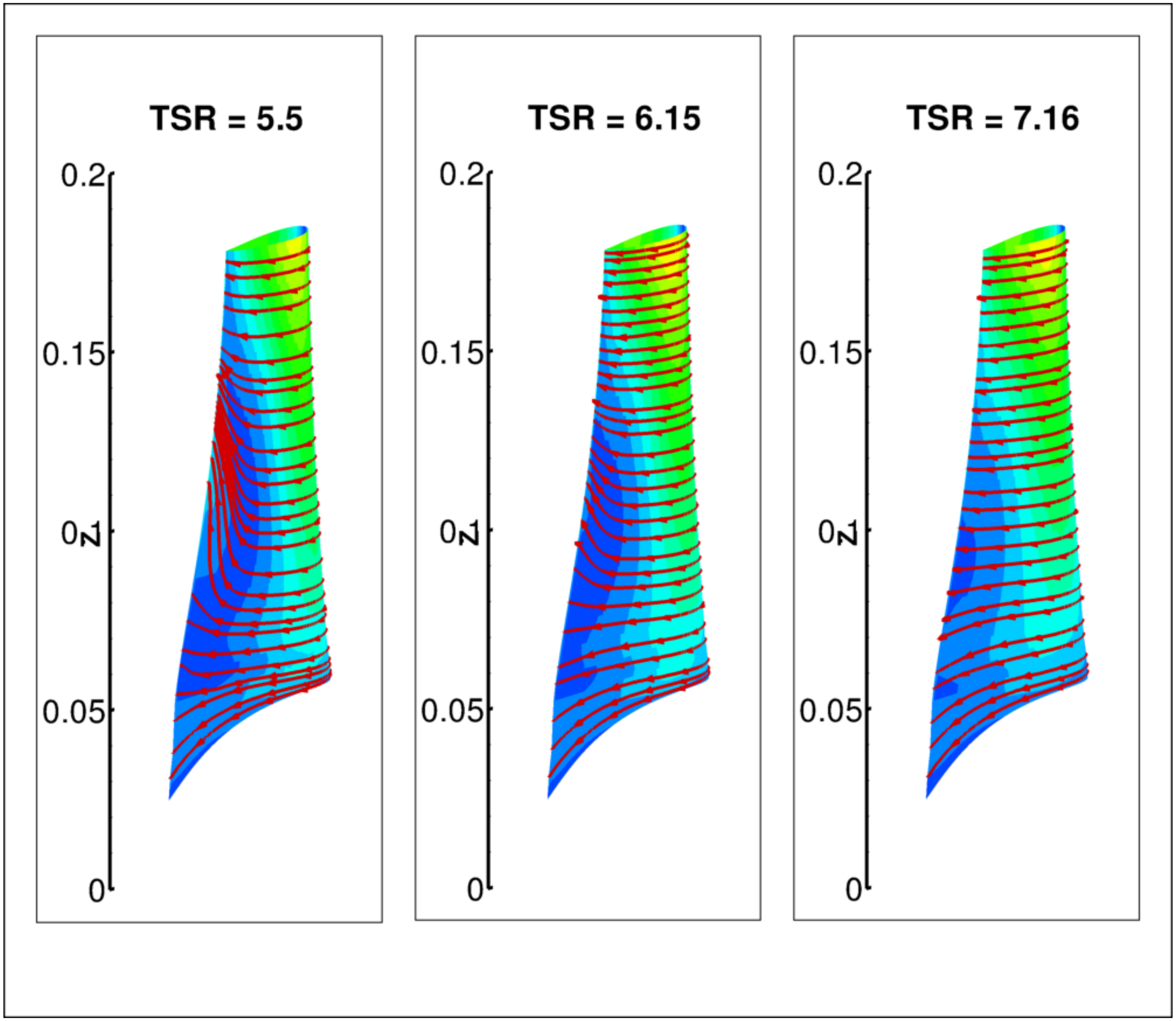


Wall Shear Stress along the Blade + Limited Streamlines

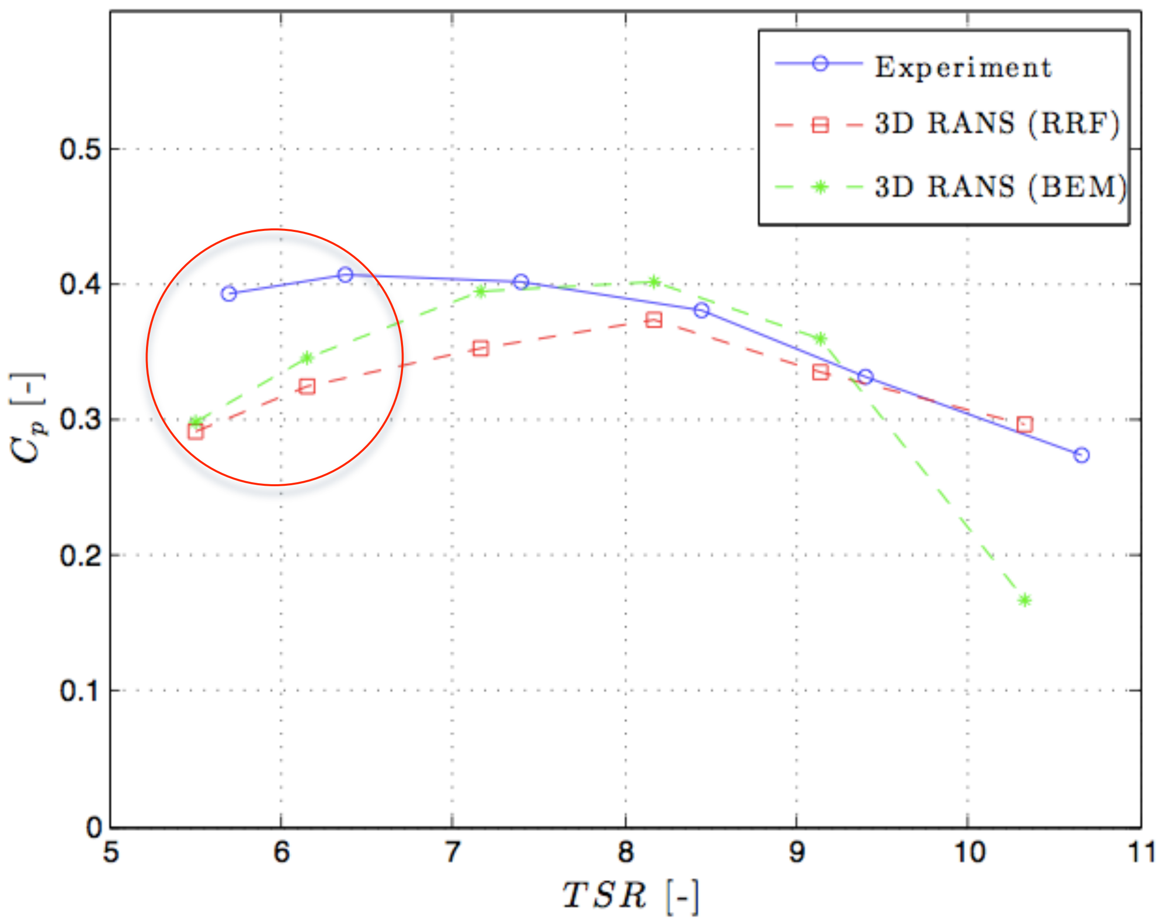


$$\tau = \left(\frac{\delta u}{\delta y}\right)_{y=0}$$

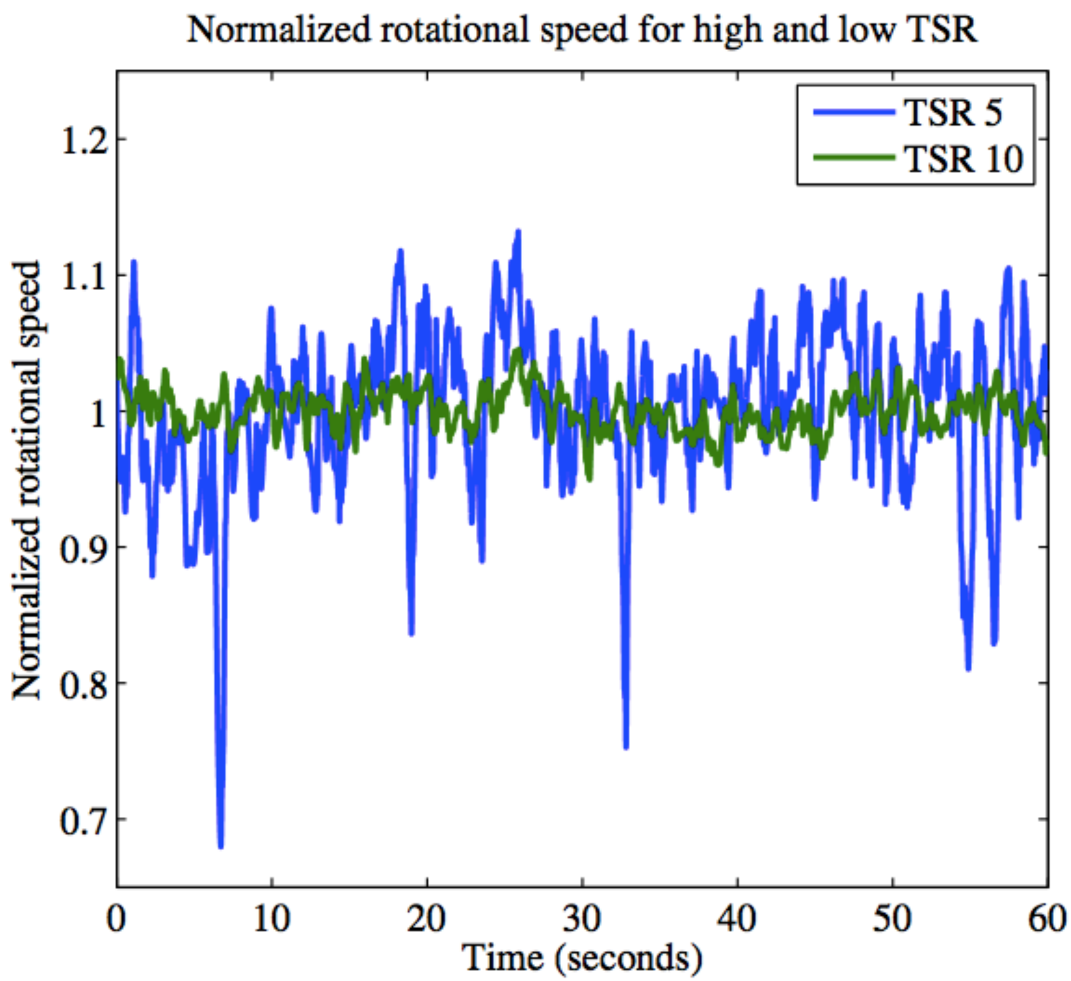
Wall Shear Stress along the Blade + Limited Streamlines



Numerical vs. Experimental Results
(C_p – TSR Curves)

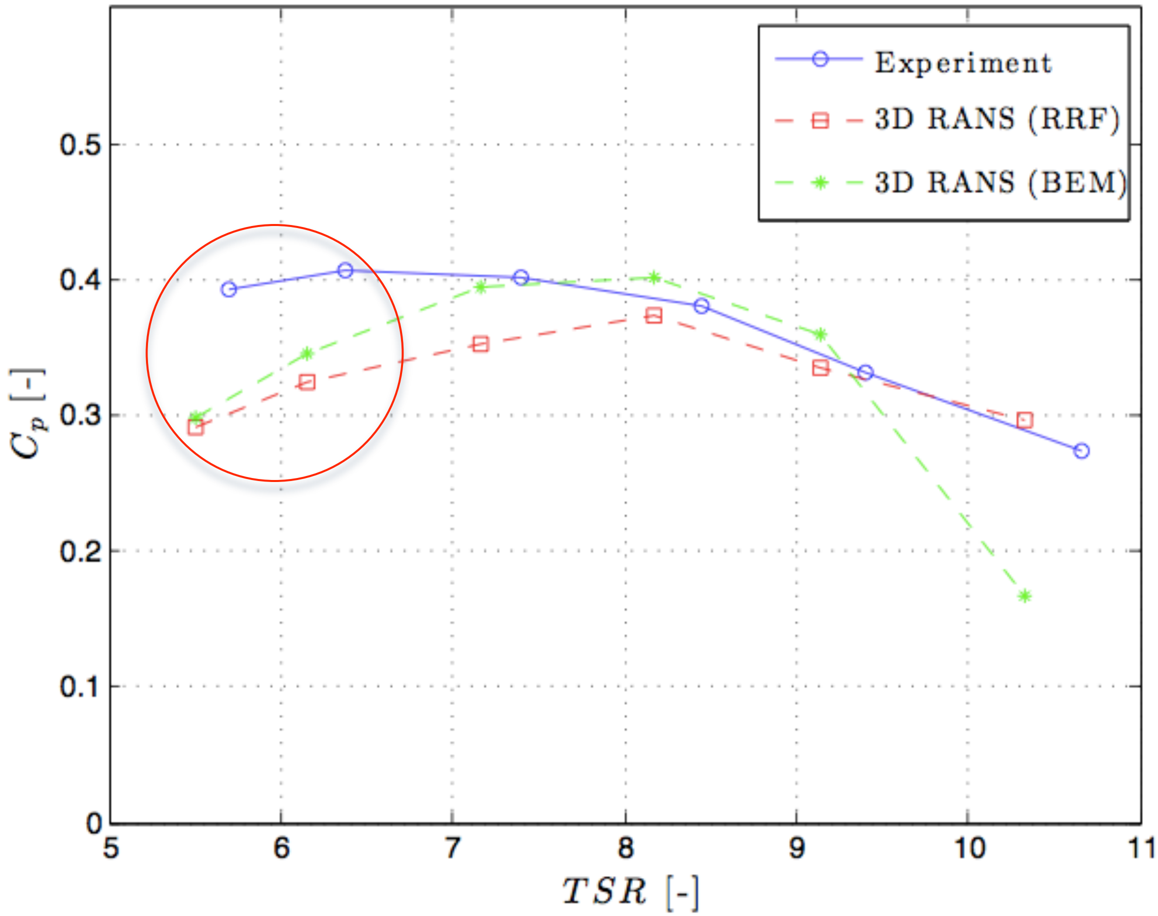


Dynamic Fluctuations in Experiment at Low TSRs

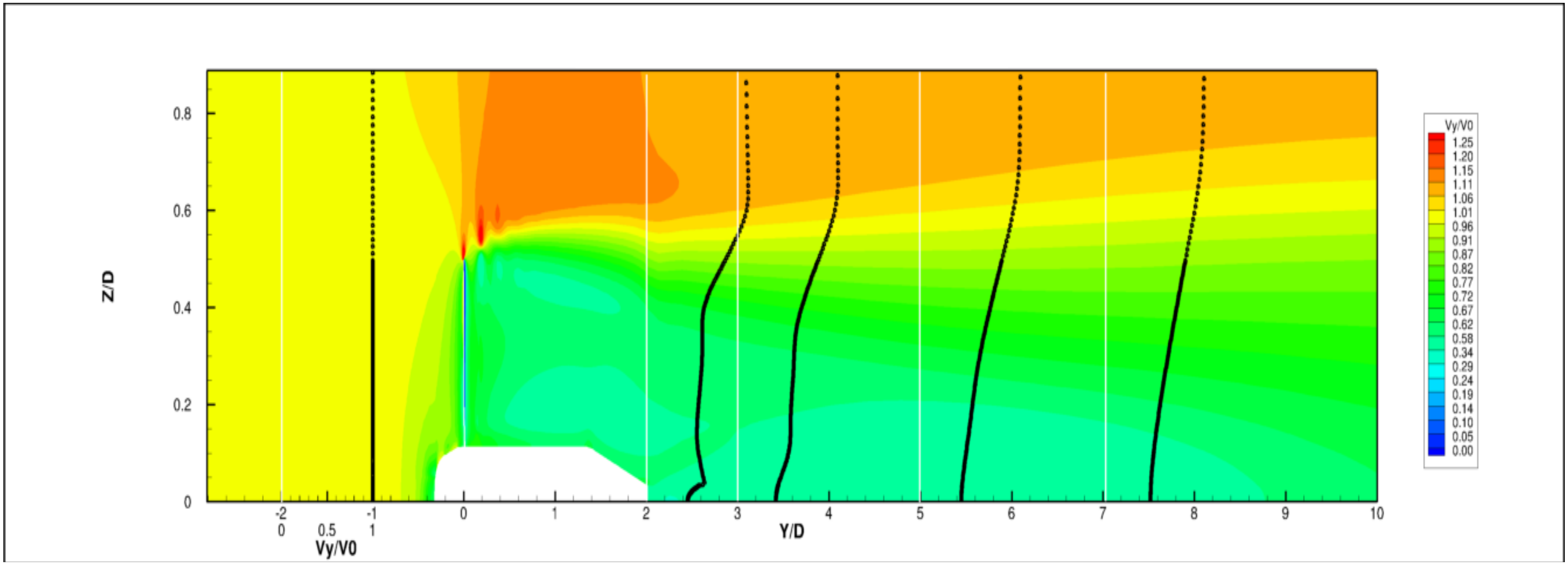


Source: N. Stelzenmuller's MSME thesis

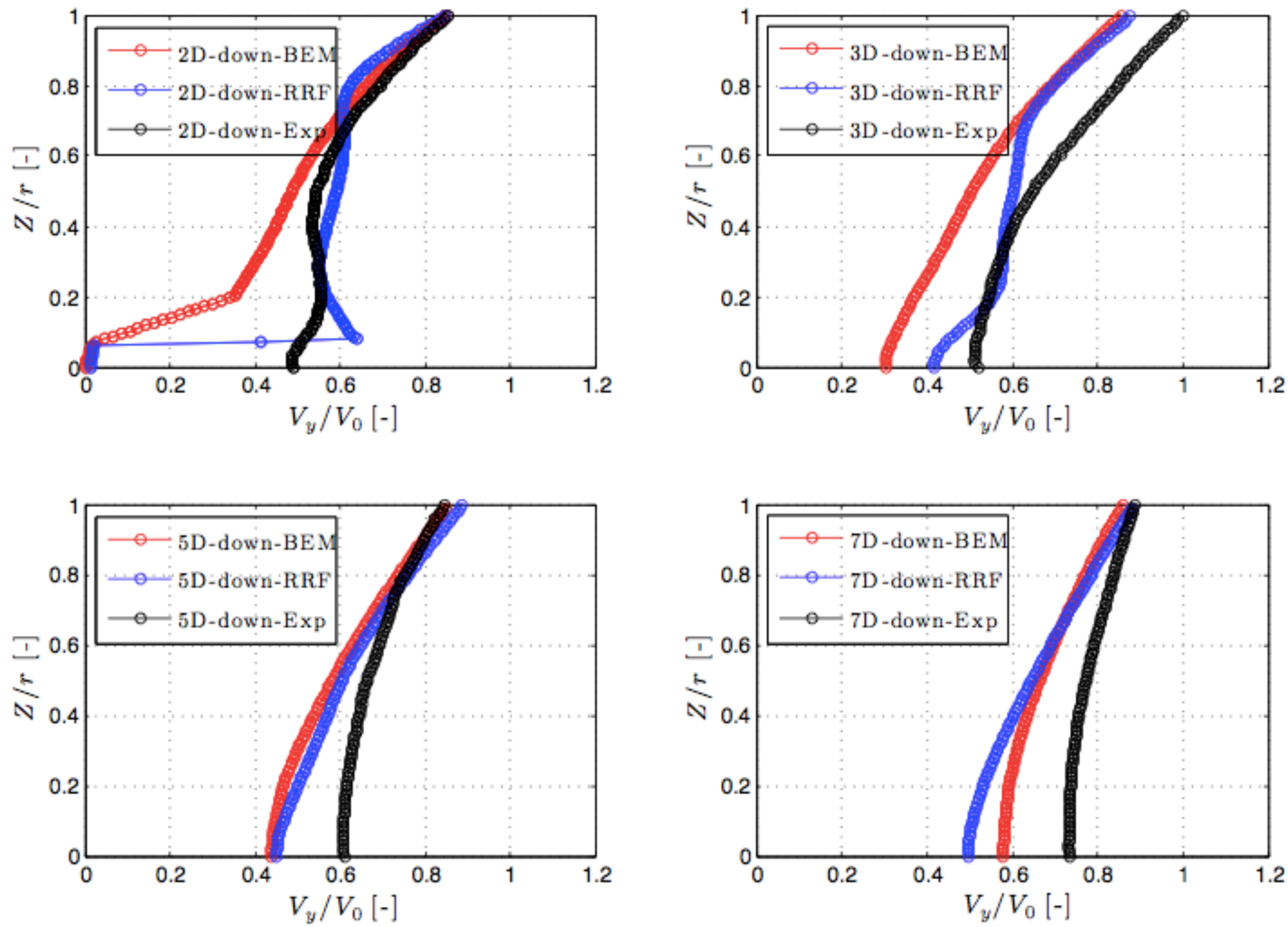
Numerical vs. Experimental Results
(C_p – TSR Curves)



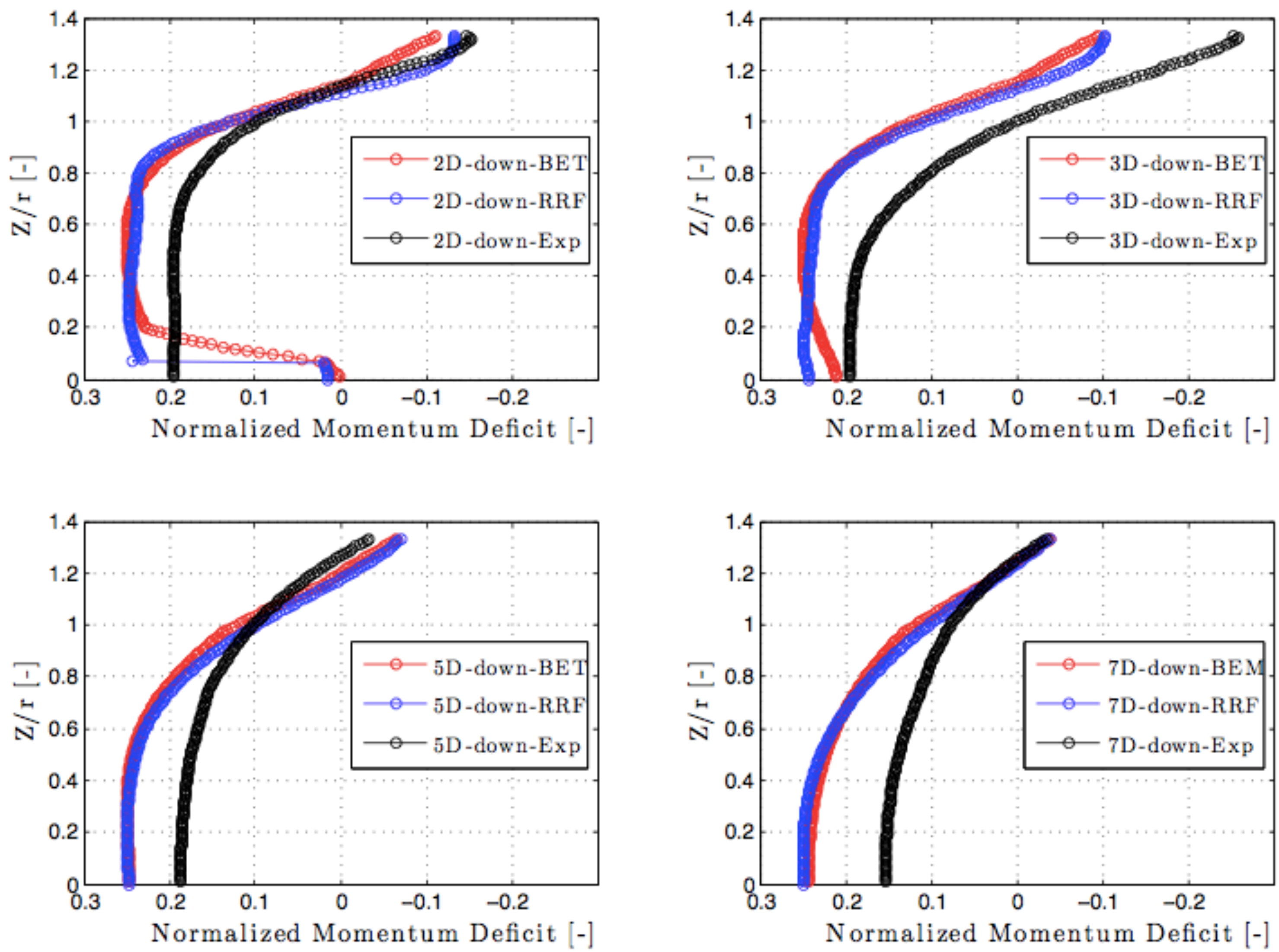
Numerical Results – TSR=7.16
(Flow Field Superimposed by Normalized Velocity Profiles)



Numerical vs. Experimental Results – TSR=7.16 (Normalized Velocity Deficit Profiles)



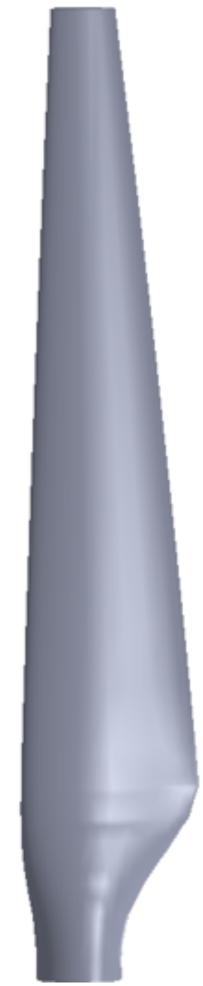
Numerical vs. Experimental Results – TSR=7.16 (Normalized Momentum Deficit Profiles)



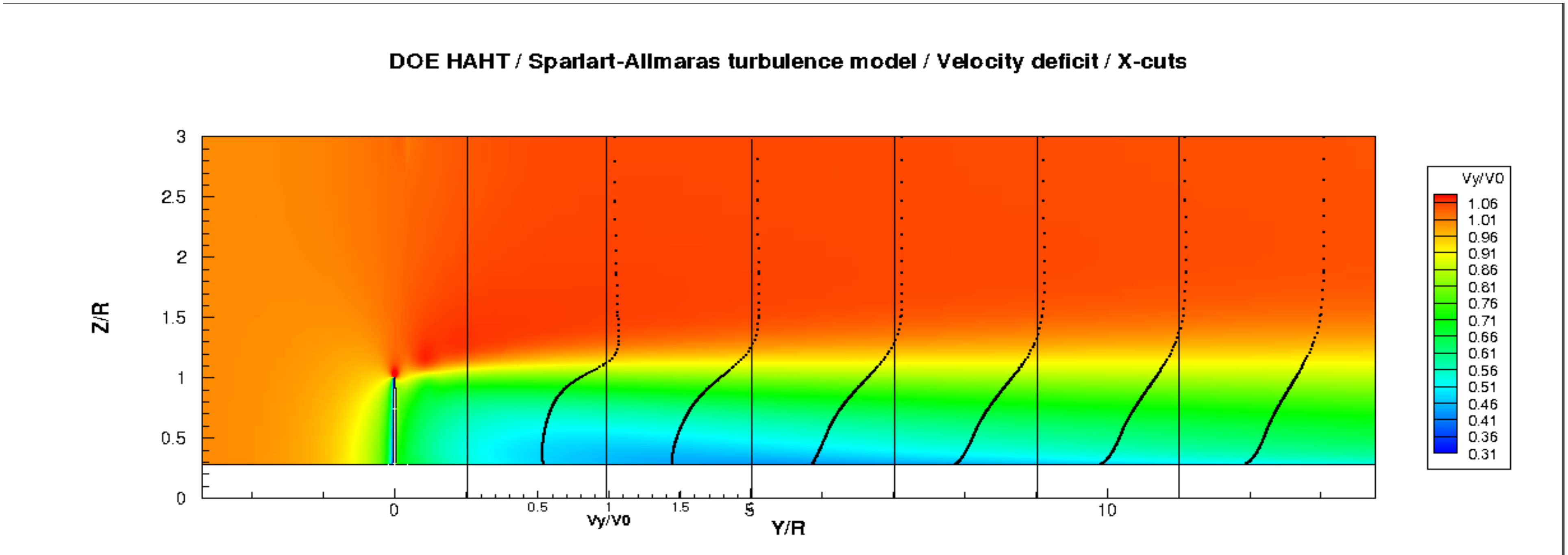
Application of the Validated Numerical Methodology to US Department of Energy Reference Model 1 (DOE RM1)

- **The US DOE with national labs put together an effort to design an open-source reference model for each MHK device type**

- **The DOE RM1 was published by Lawson et. al. at NREL as one of the reference models for horizontal axis MHK turbines.**



Numerical Results for the DOE RM1 (RRF Model)



Research Group	NREL	NNMREC
Numerical Solver	STAR CCM+	FLUENT 12.0
Mesh Structure	Unstructured	Structured
Element type	Polyhedral elements	Brick elements
Torque [N-m]	2.13×10^5	2.16×10^5
Relative Difference [%]	-	1.41

[Ref.] Lawson M., Li Y. and Sale D. *Proceedings of the 30th International Conference on Ocean, Offshore, and Arctic Engineering, 2011.*

Summary & Conclusions I

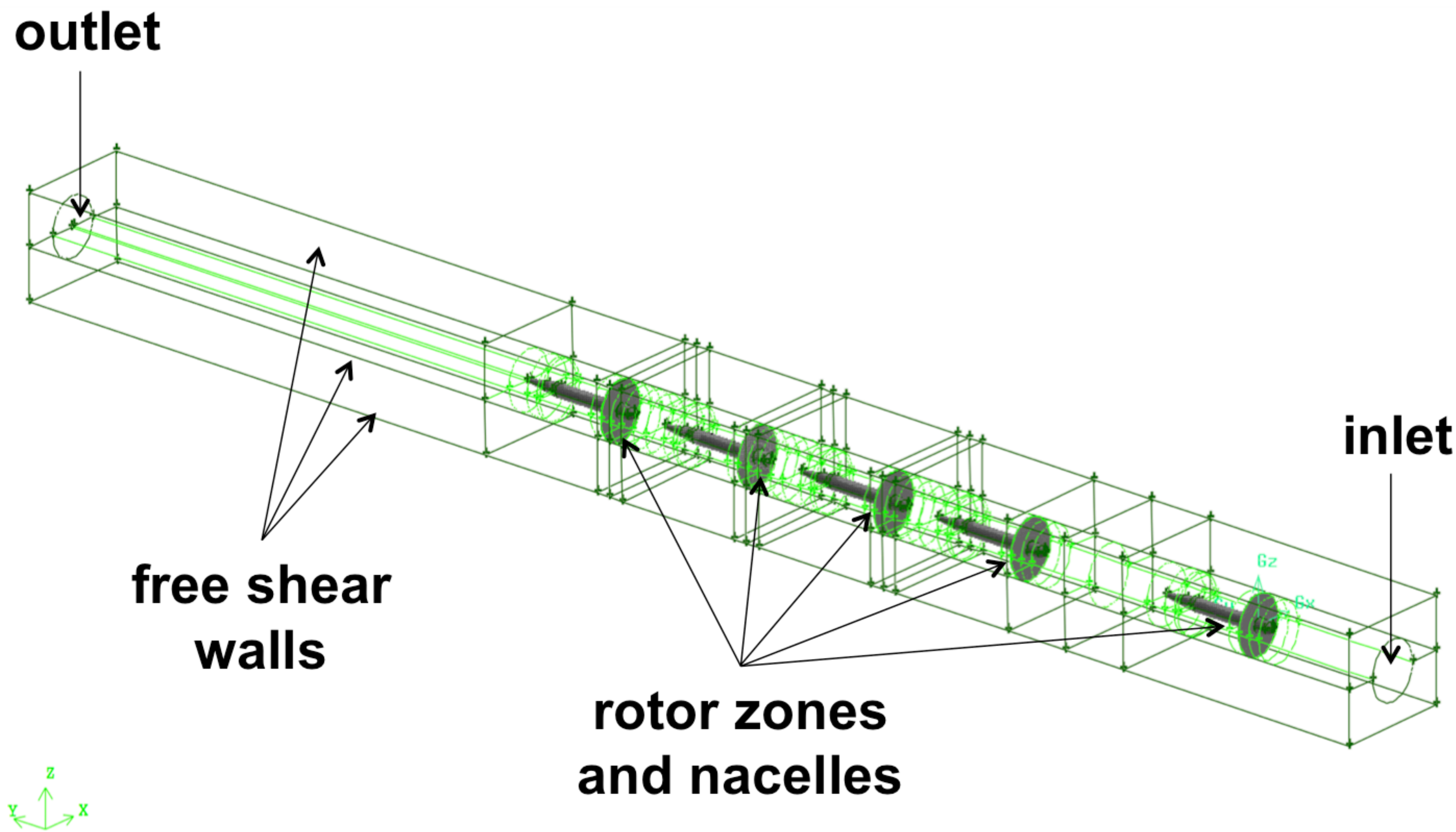
- 3D RANS methodologies are validated to characterize the performance and wake of horizontal axis MHK turbines.
- The error between the measured and predicted power values around optimum TSR was between 1% to 5%.
- Successful application of the validated numerical methodology to the DOE RM 1.
- Good agreement with Lawson et al. results with matched numerical models and operating conditions.

Turbine Array Performance Characterization and Optimization

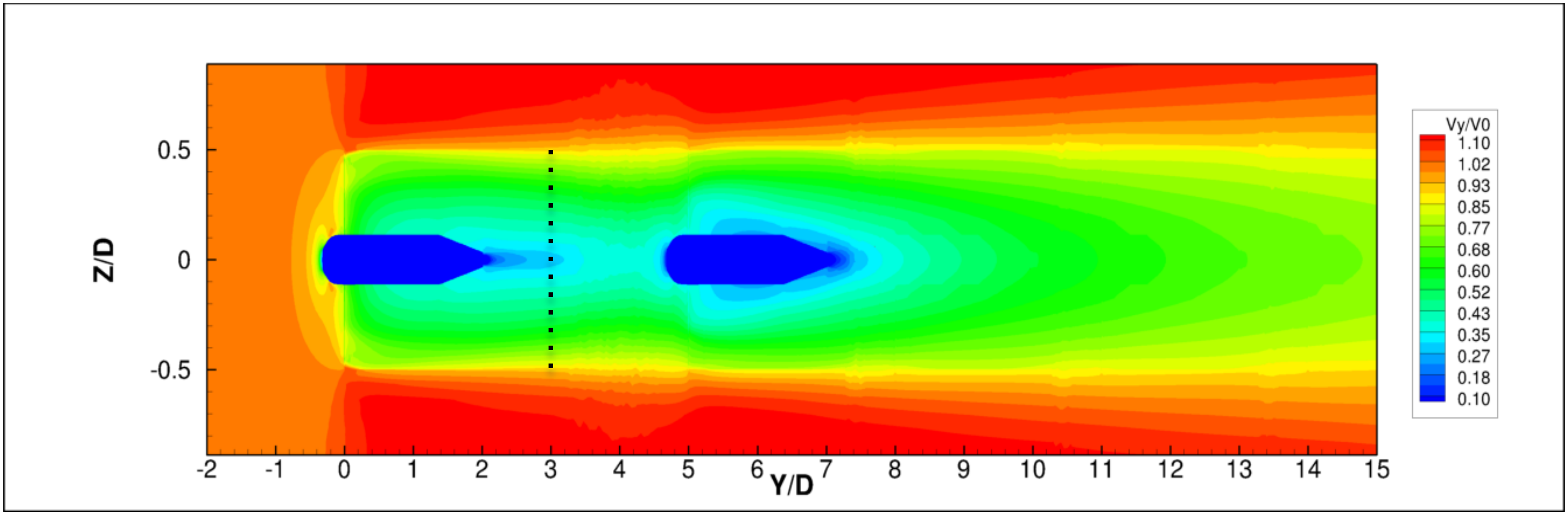
Background and Motivation

- Commercial Stage: Large turbine arrays.
- Due to confinement in MHK sites, the relative distances between turbines need to be optimized.
- The effect of variable relative distances on turbines performance in an array need to be investigated and optimized.
- Lack of methodological approach for the array optimization process in the previous studies.

Array of Two Coaxial Turbines



Methodology to Match the Experimental TSR Values in the Numerical Simulations



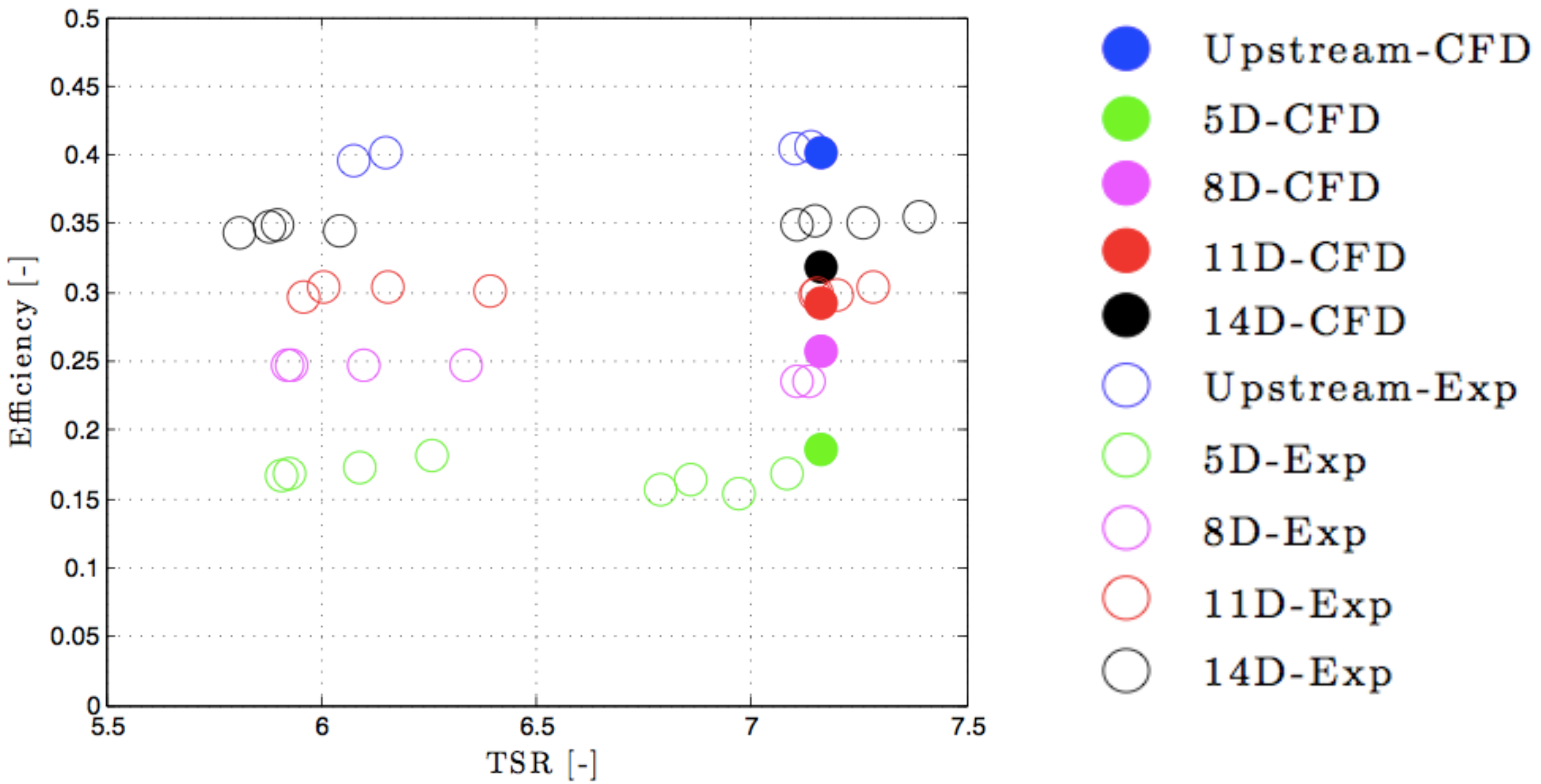
Experiments

Rotational velocity (**ω**): measured
Incident flow velocity (**V**): Free stream
TSR (**rω/V**): set

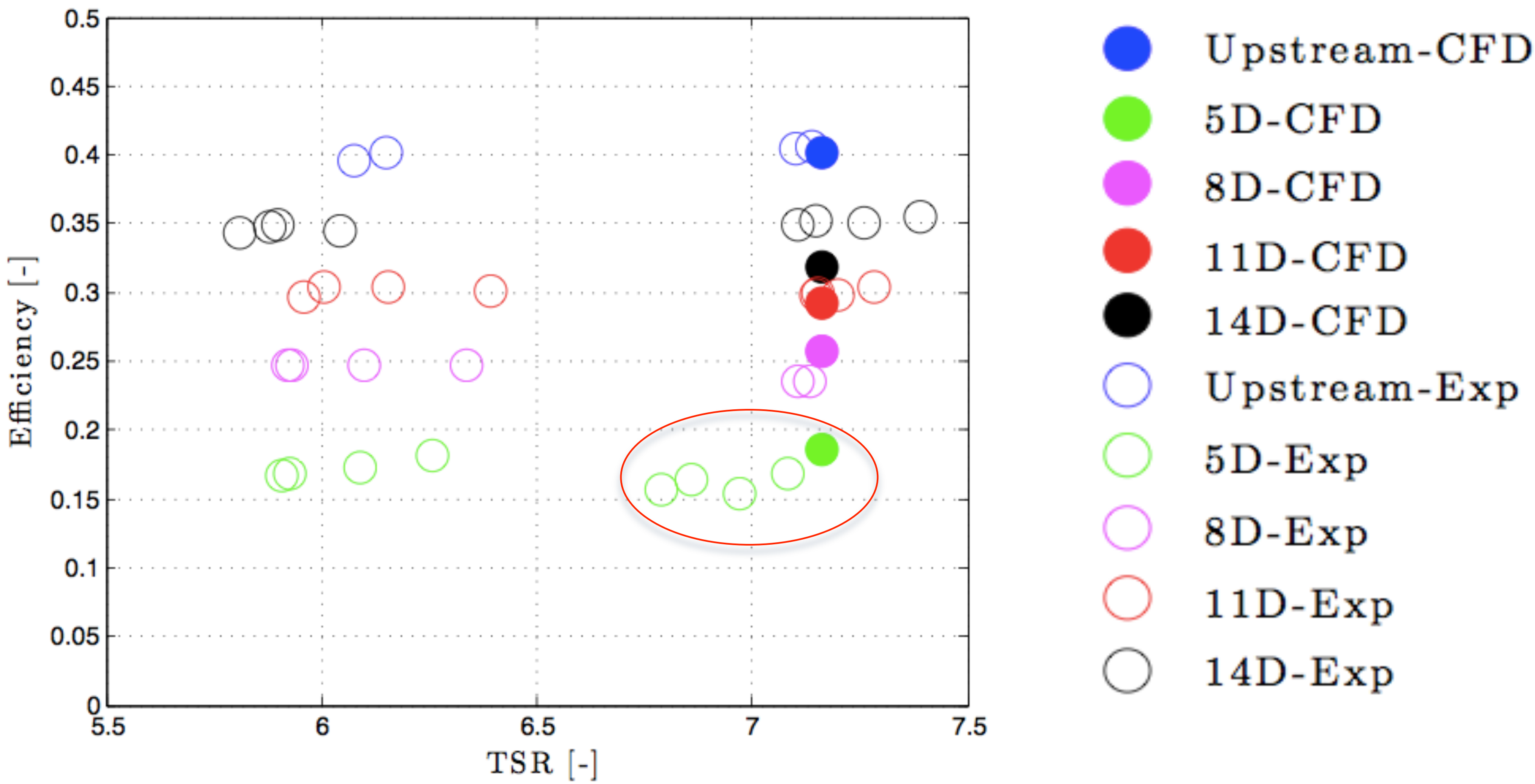
Simulations

TSR (**rω/V**): set from experiment
Incident flow velocity (**V**): averaged
Rotational velocity (**ω**): set

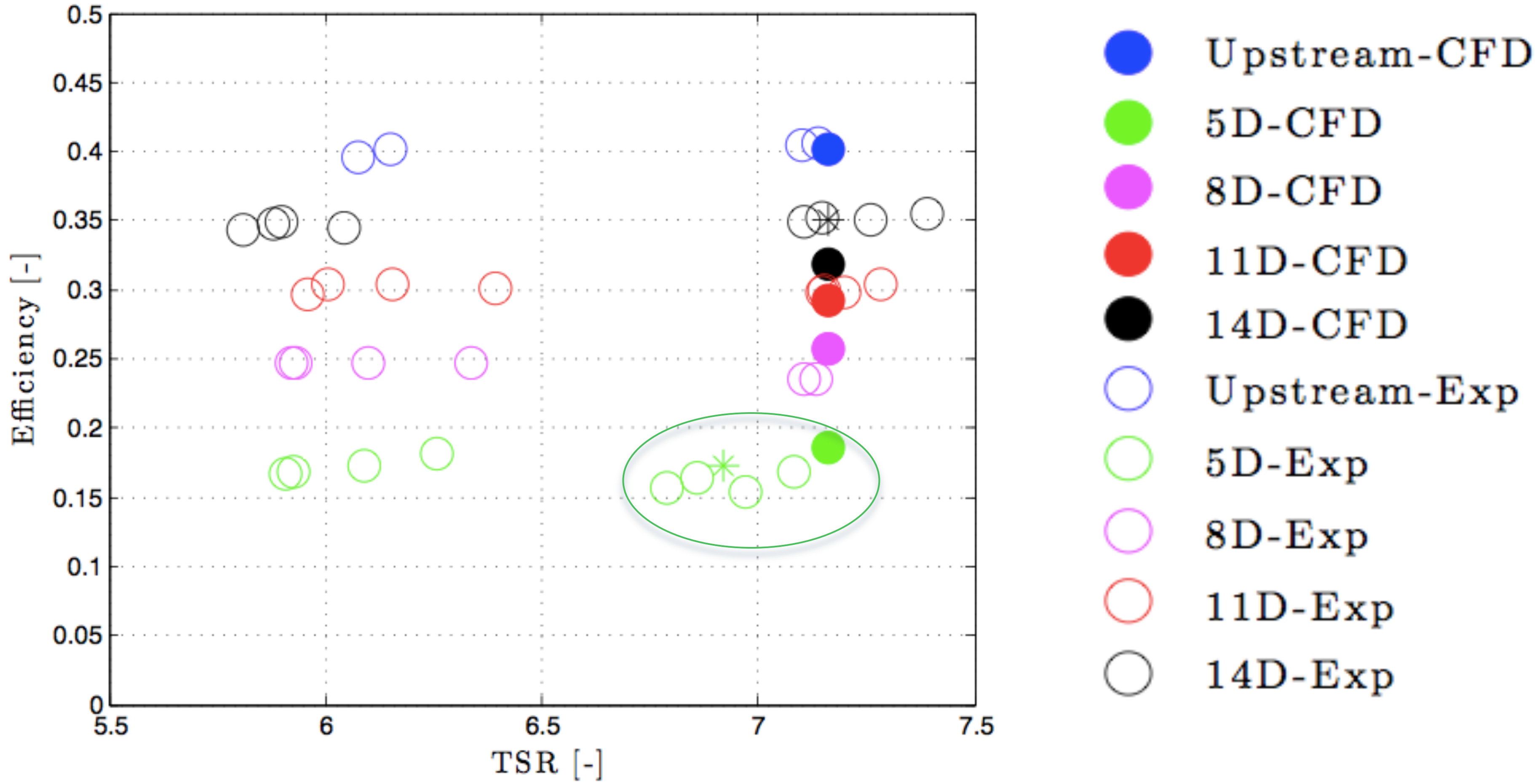
Numerical vs. Experimental Results (TSR=7.16)



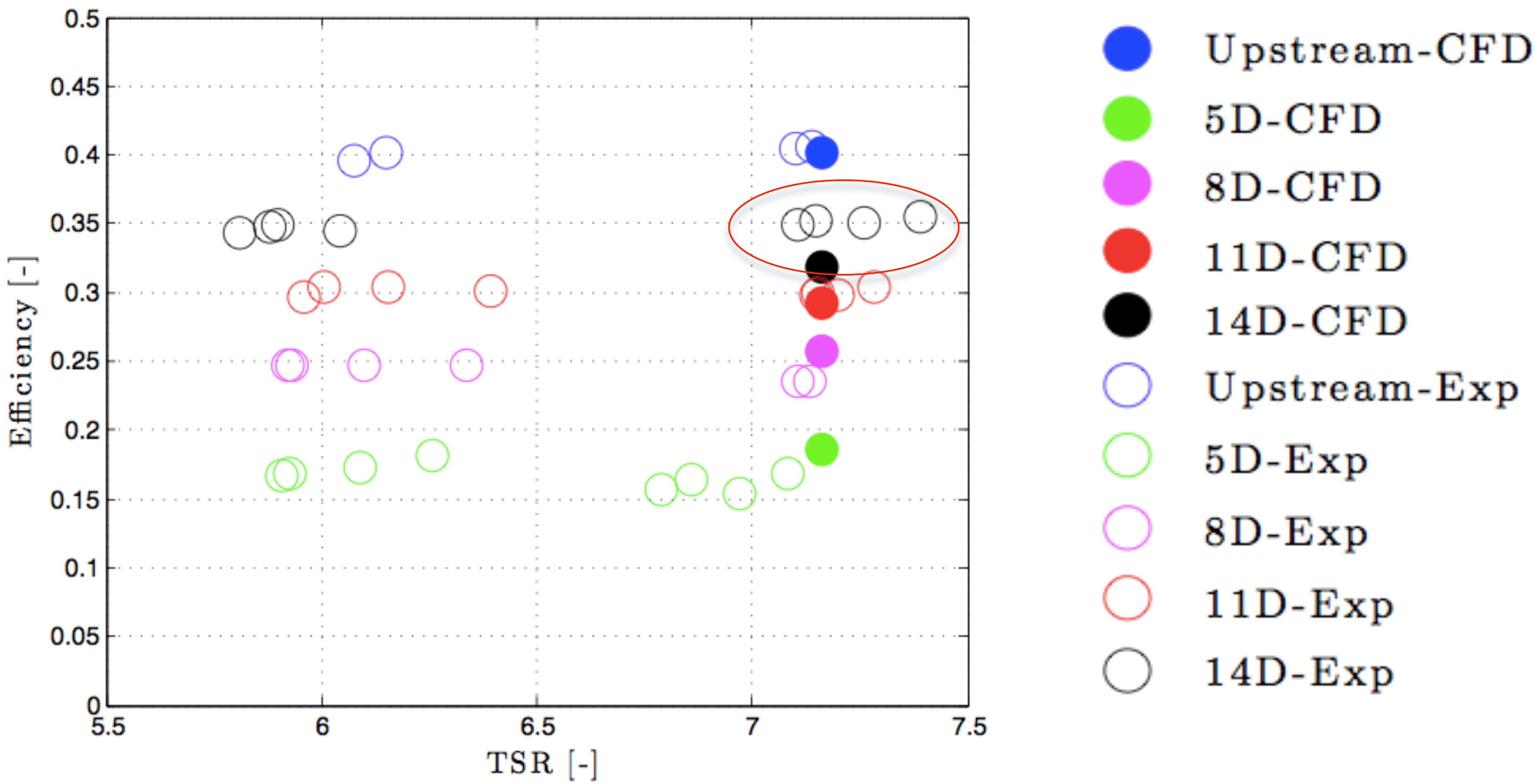
Numerical vs. Experimental Results (TSR=7.16)



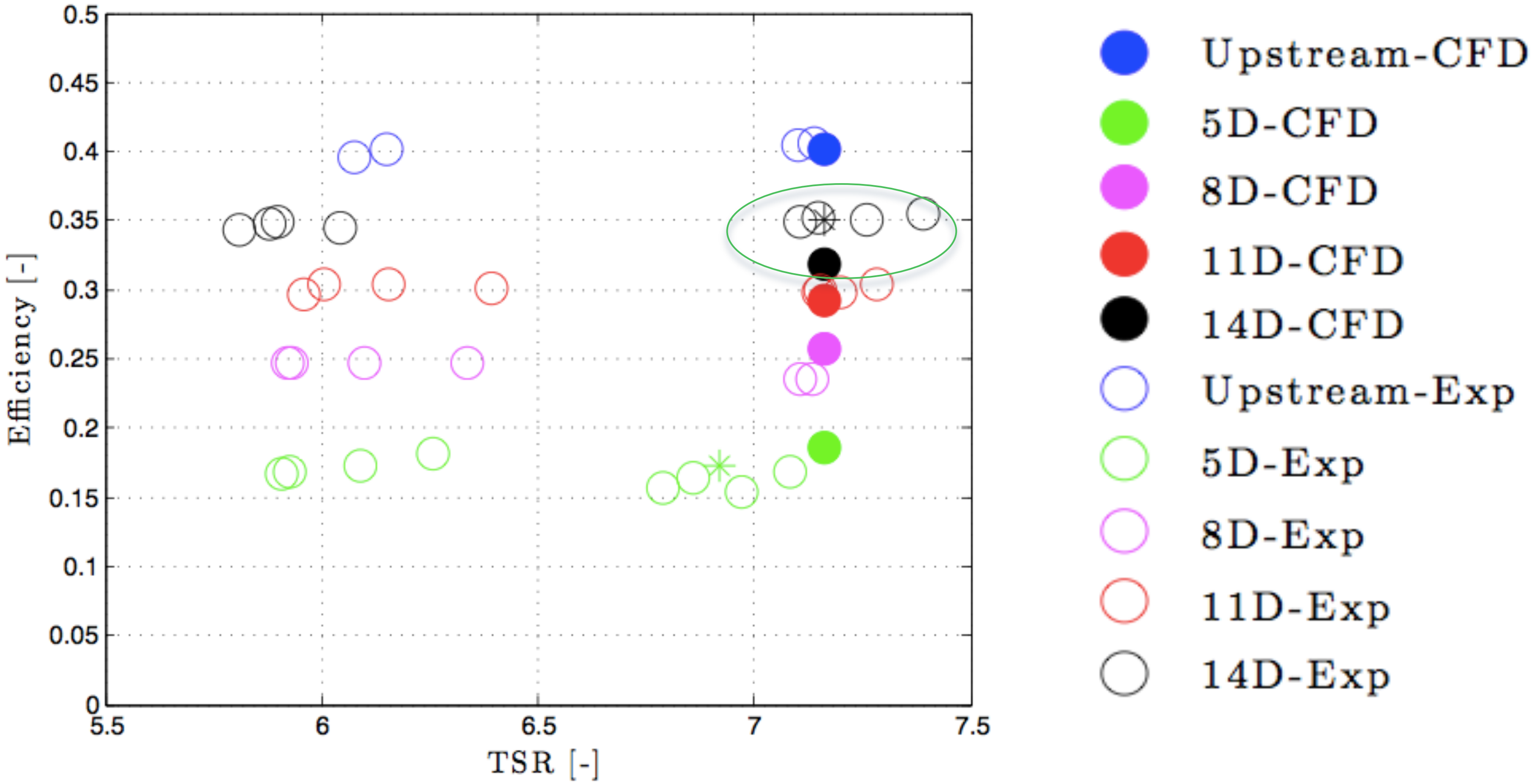
Numerical vs. Experimental Results (TSR=7.16)



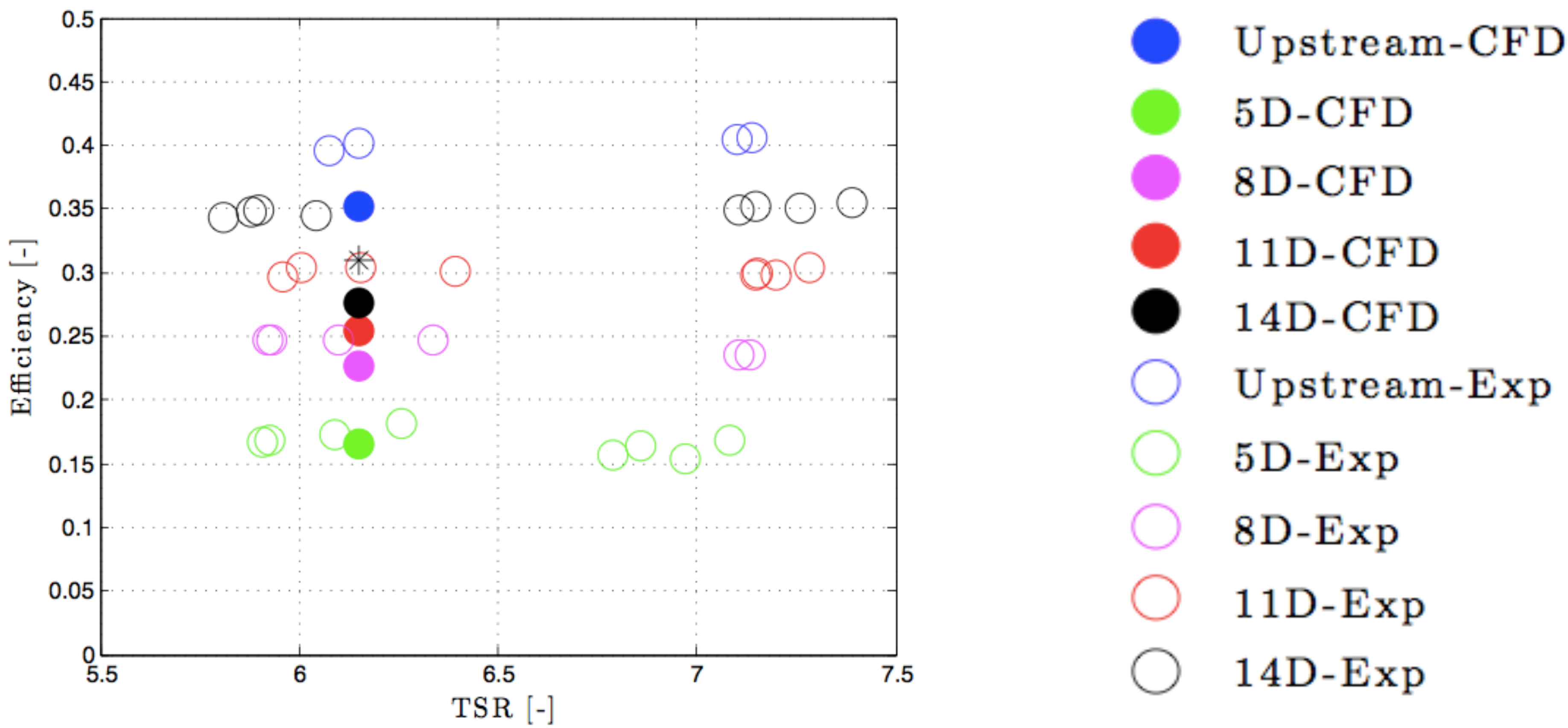
Numerical vs. Experimental Results (TSR=7.16)



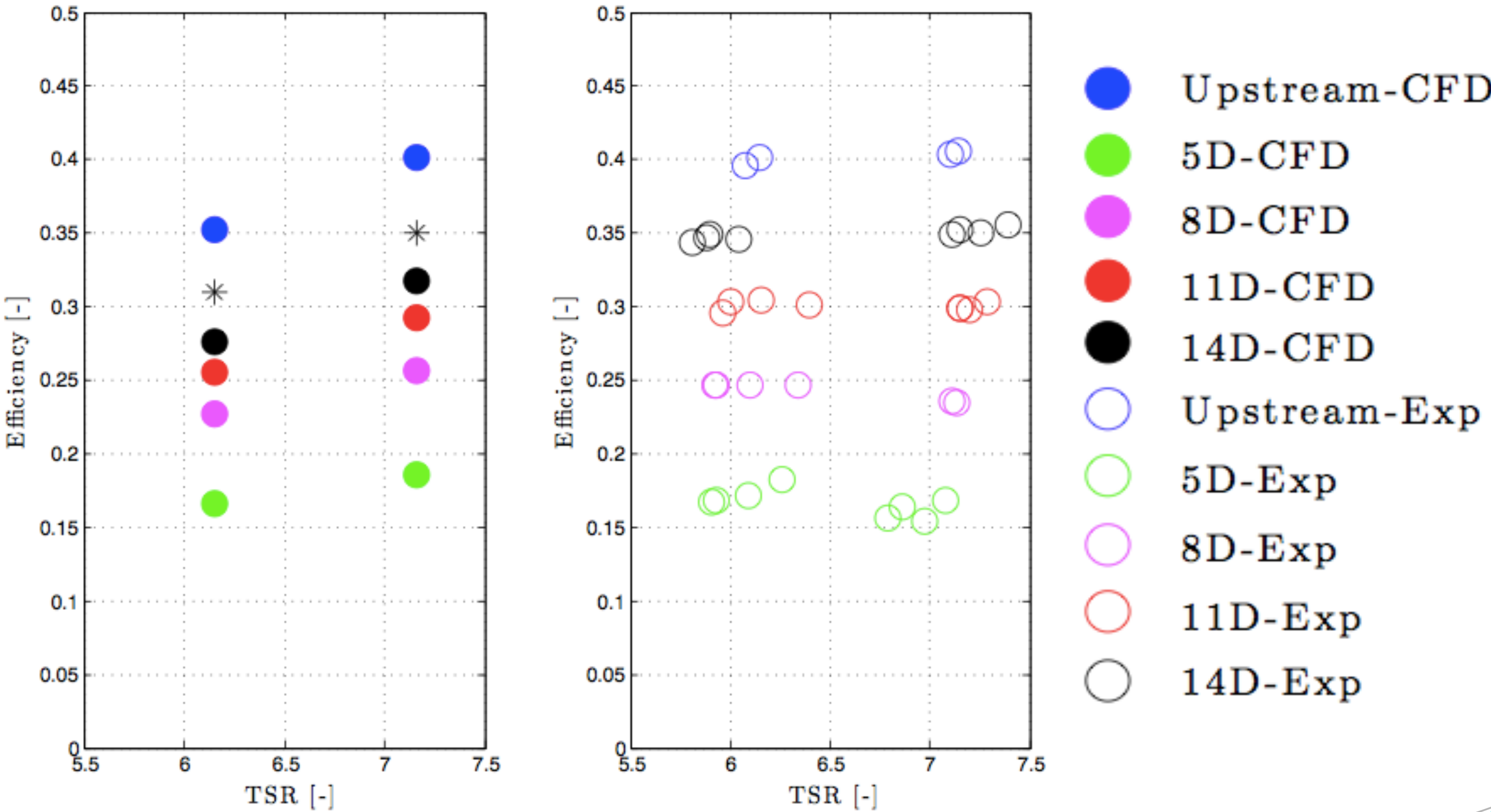
Numerical vs. Experimental Results (TSR=7.16)



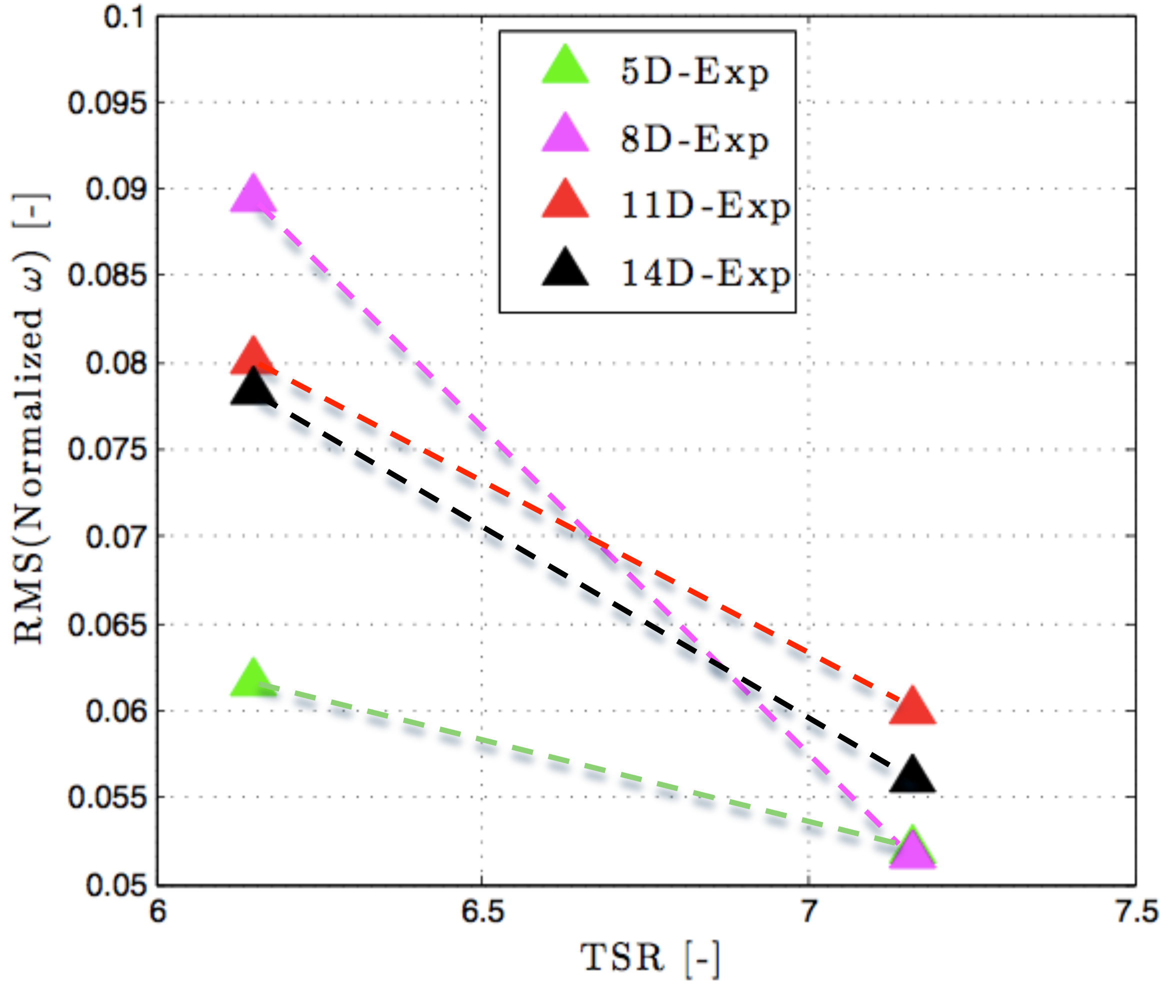
Numerical vs. Experimental Results (TSR=6.15)



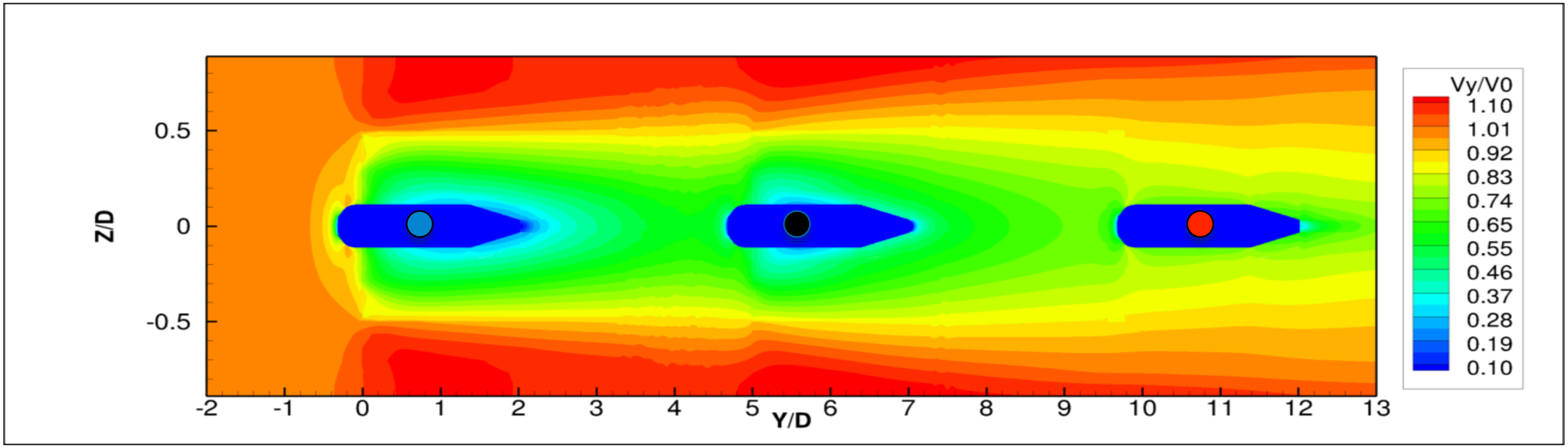
Numerical vs. Experimental Results (TSR=6.15, 7.16)

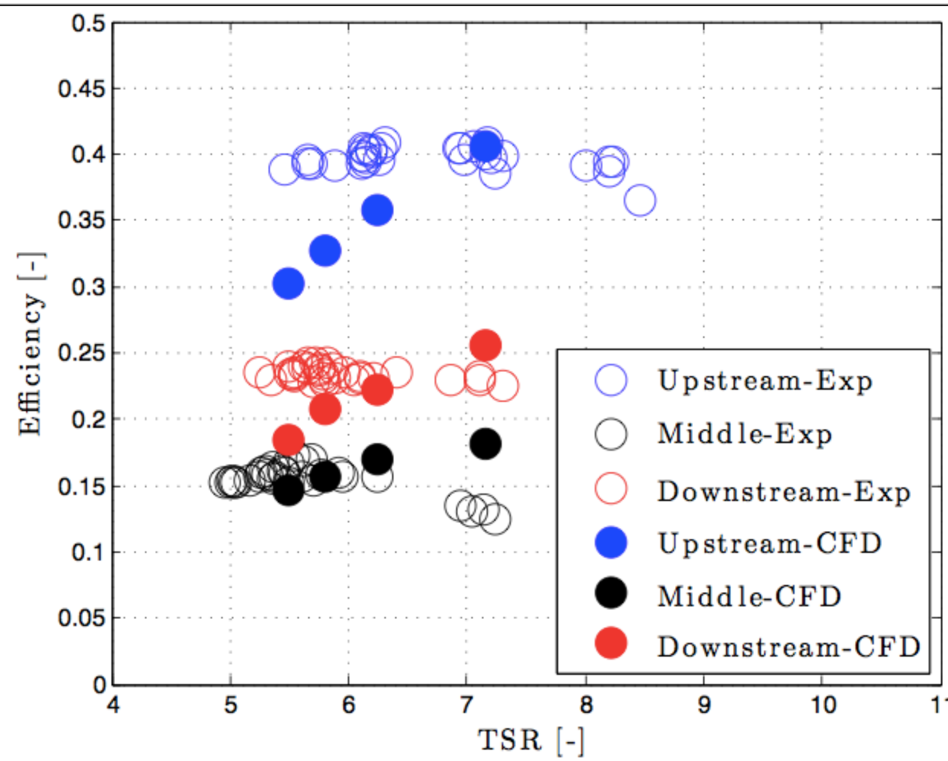


RMS of Normalized Rotational Velocity Temporal Evolution (TSR = 6.15, 7.16)



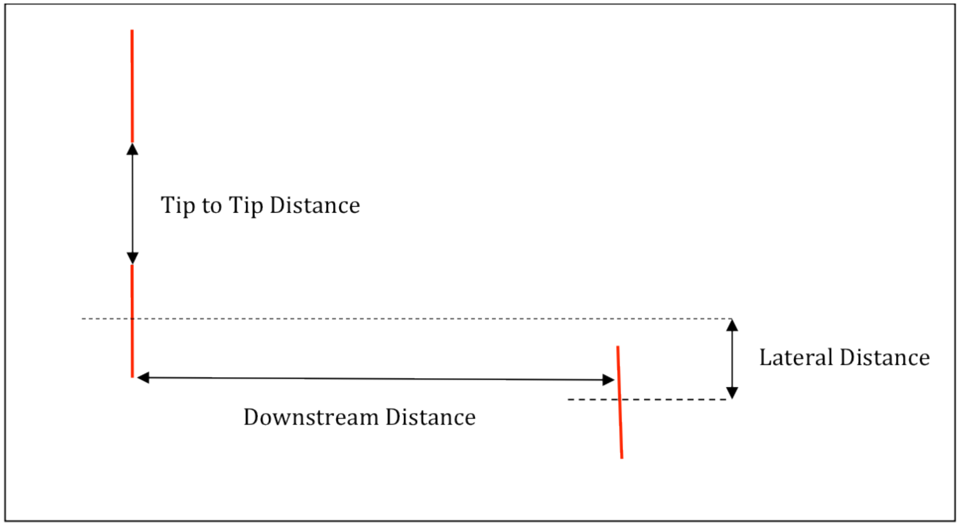
Numerical vs. Experimental Results (various TSRs)

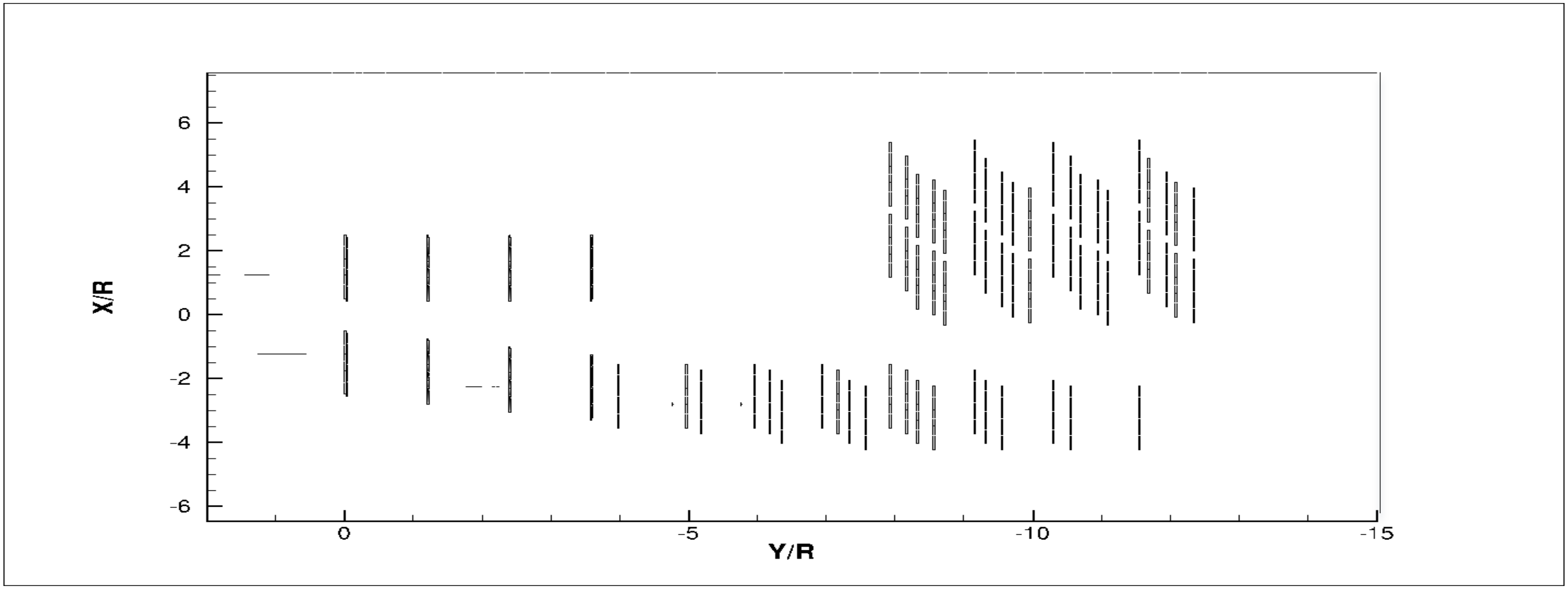




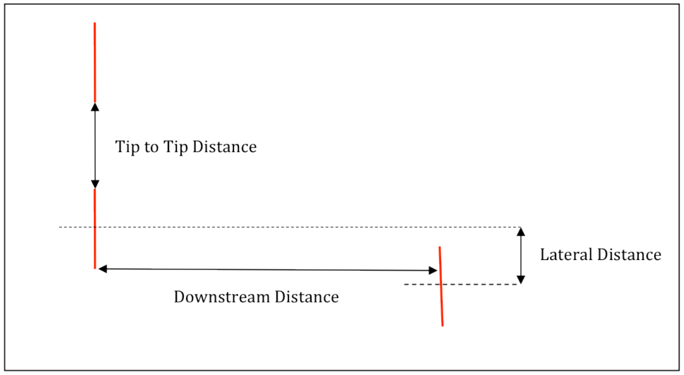
Dominant Spacing Variables in a Full-Scale Array

- Tip-to-Tip Distance
- Downstream Distance
- Lateral Distance

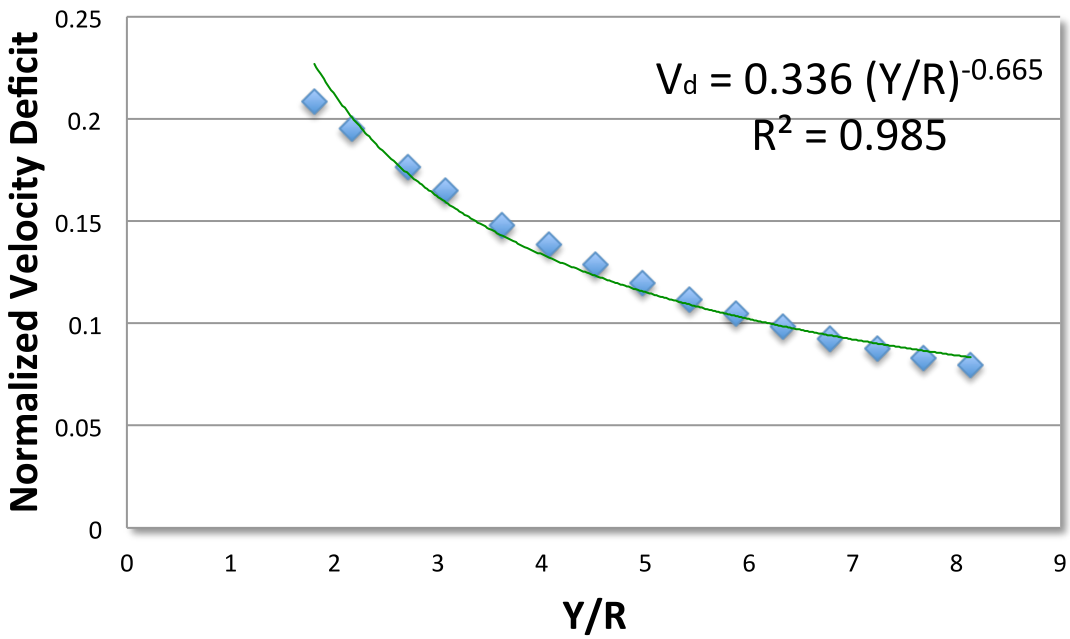




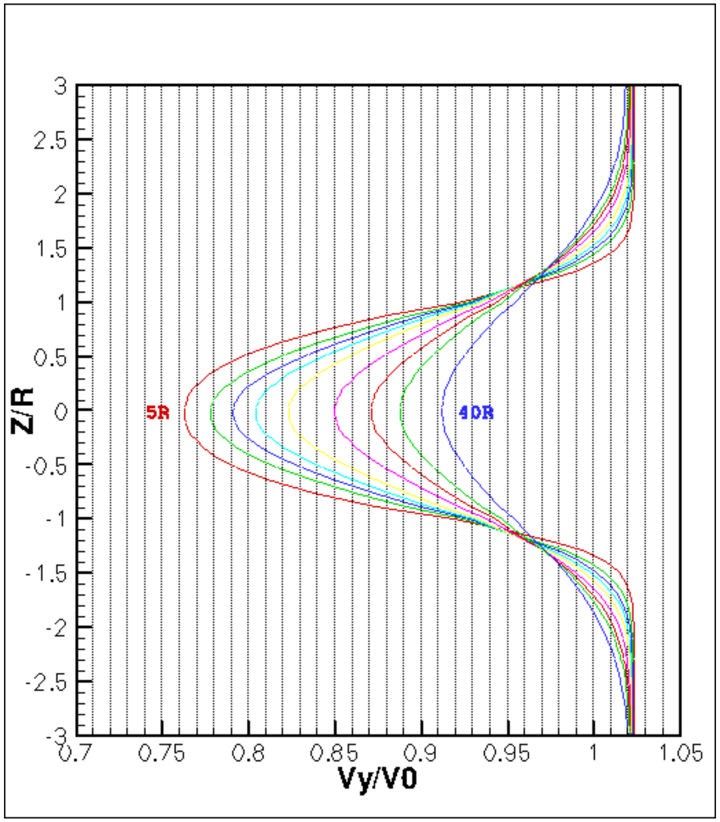
Downstream Distance



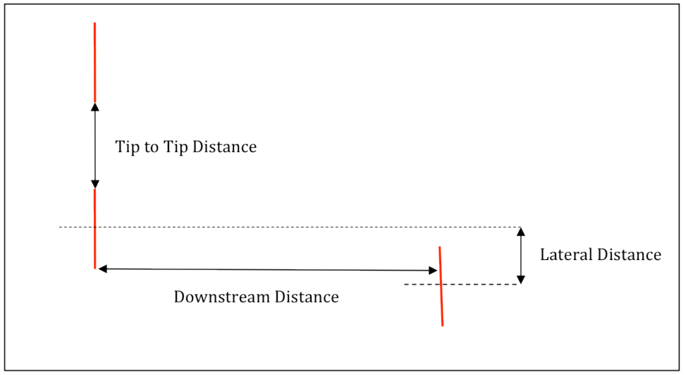
Normalized Centerline Velocity Deficit in the Simulated Turbulent Wake via the VBM

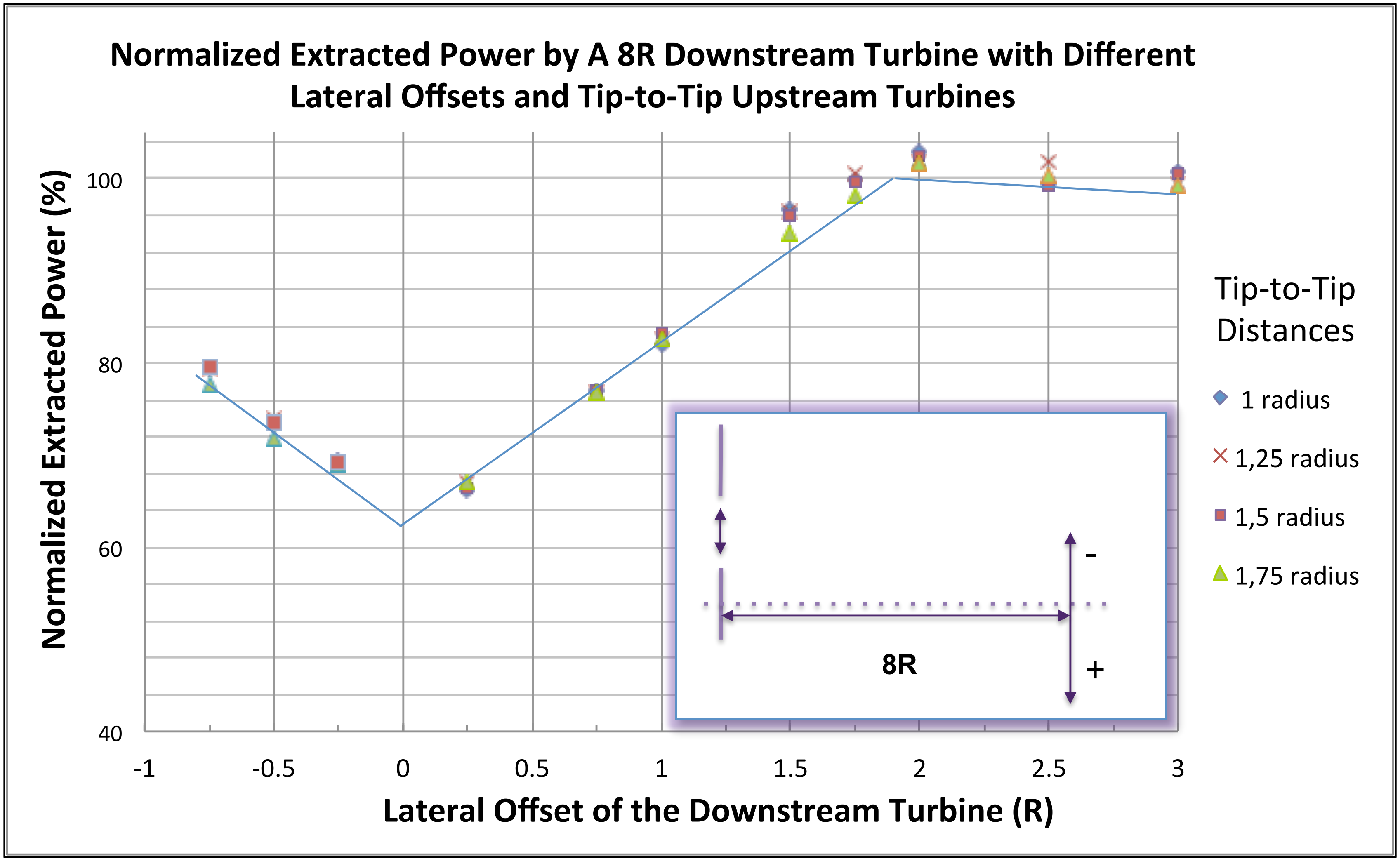


Simulated velocity deficit decay trend simulated by the BEM matched the self-similar solution for the axisymmetric wake.

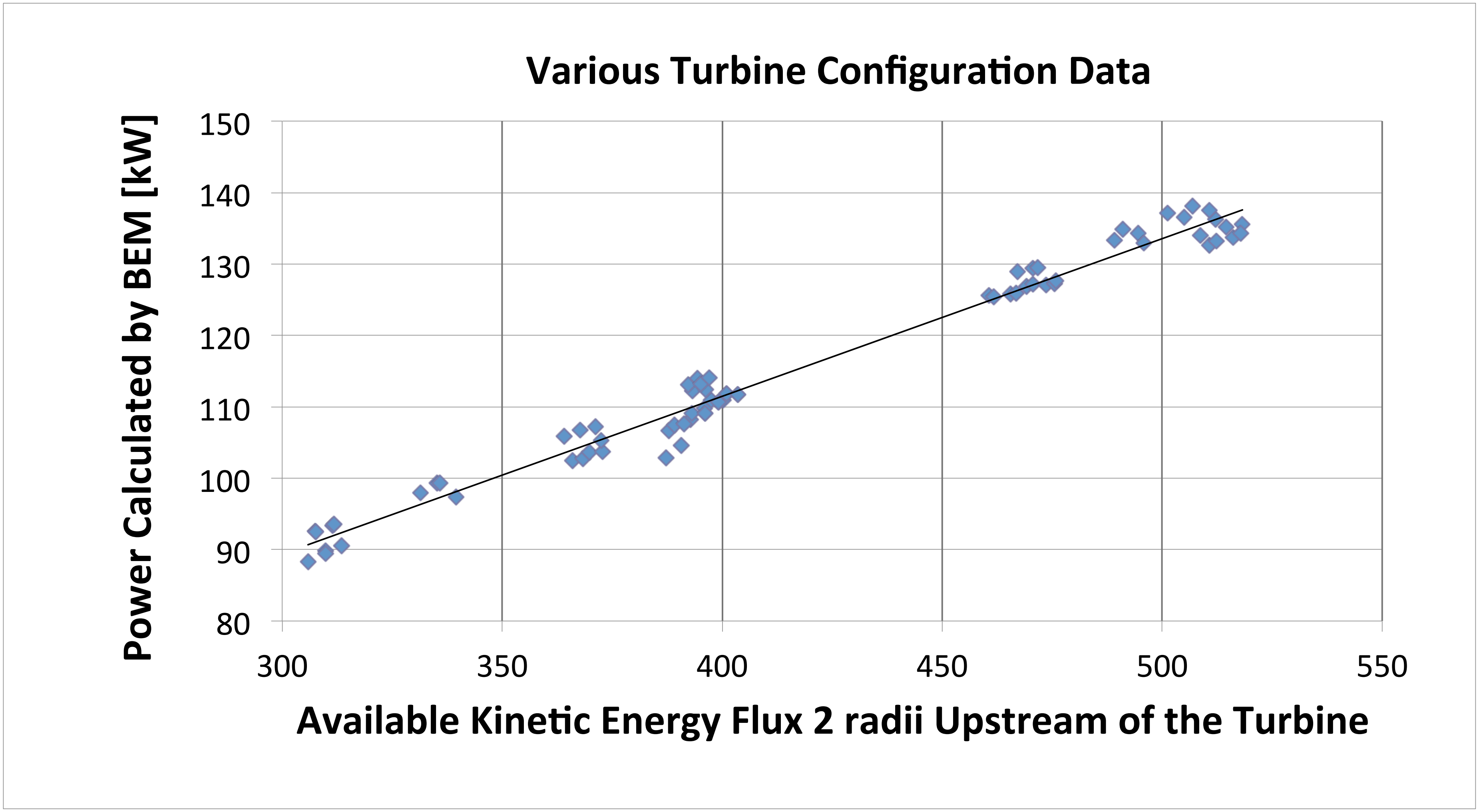


Lateral Distance

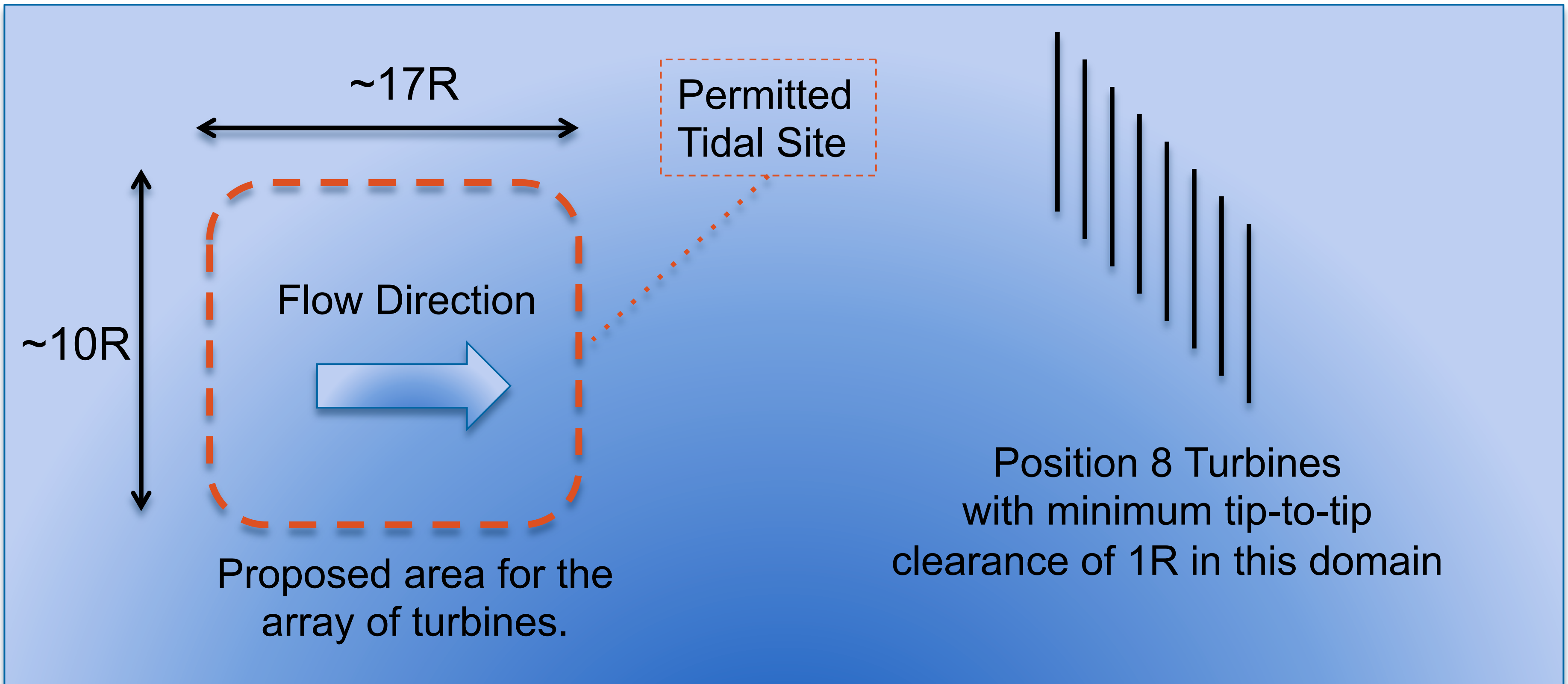




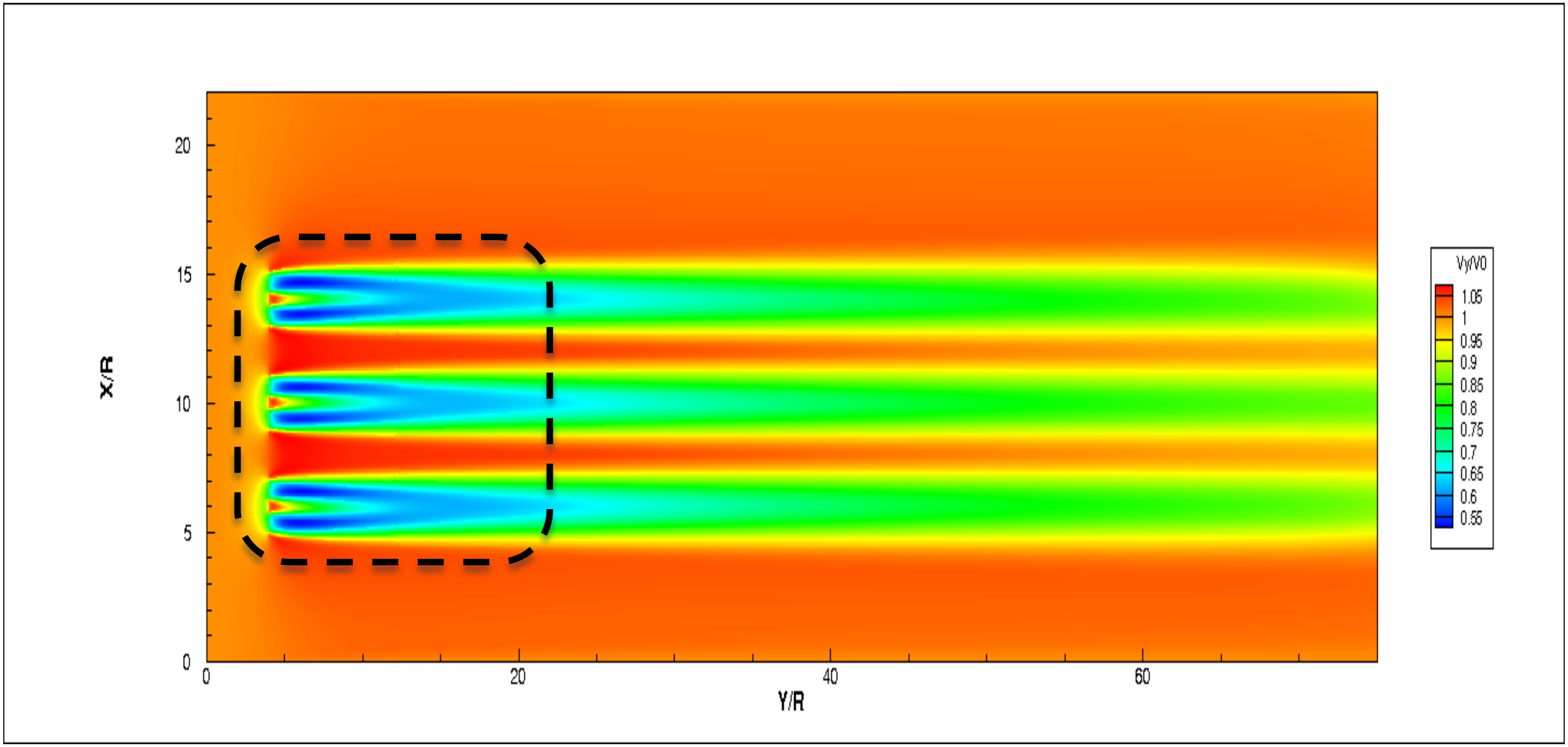
Constant Local Efficiency



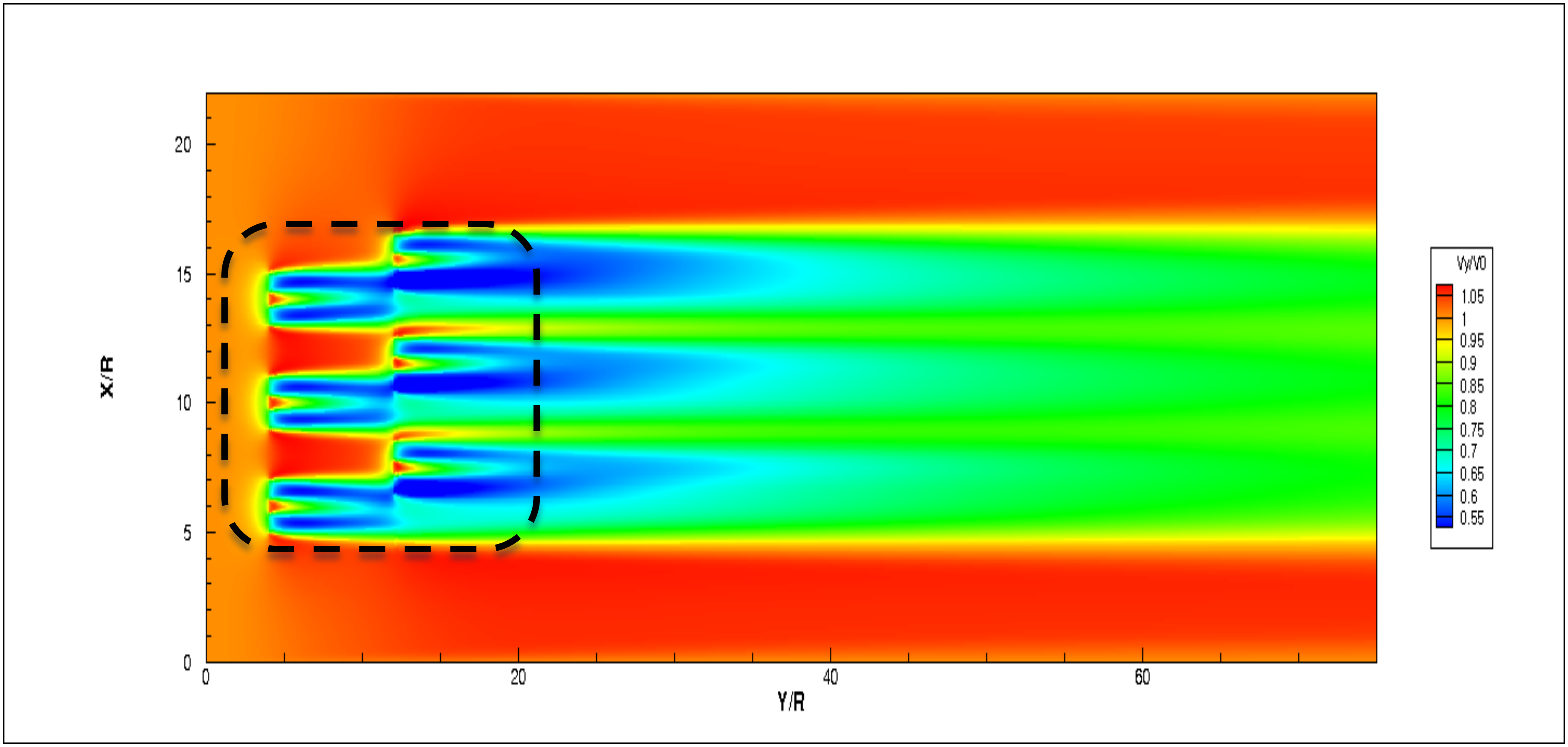
Methodology Development



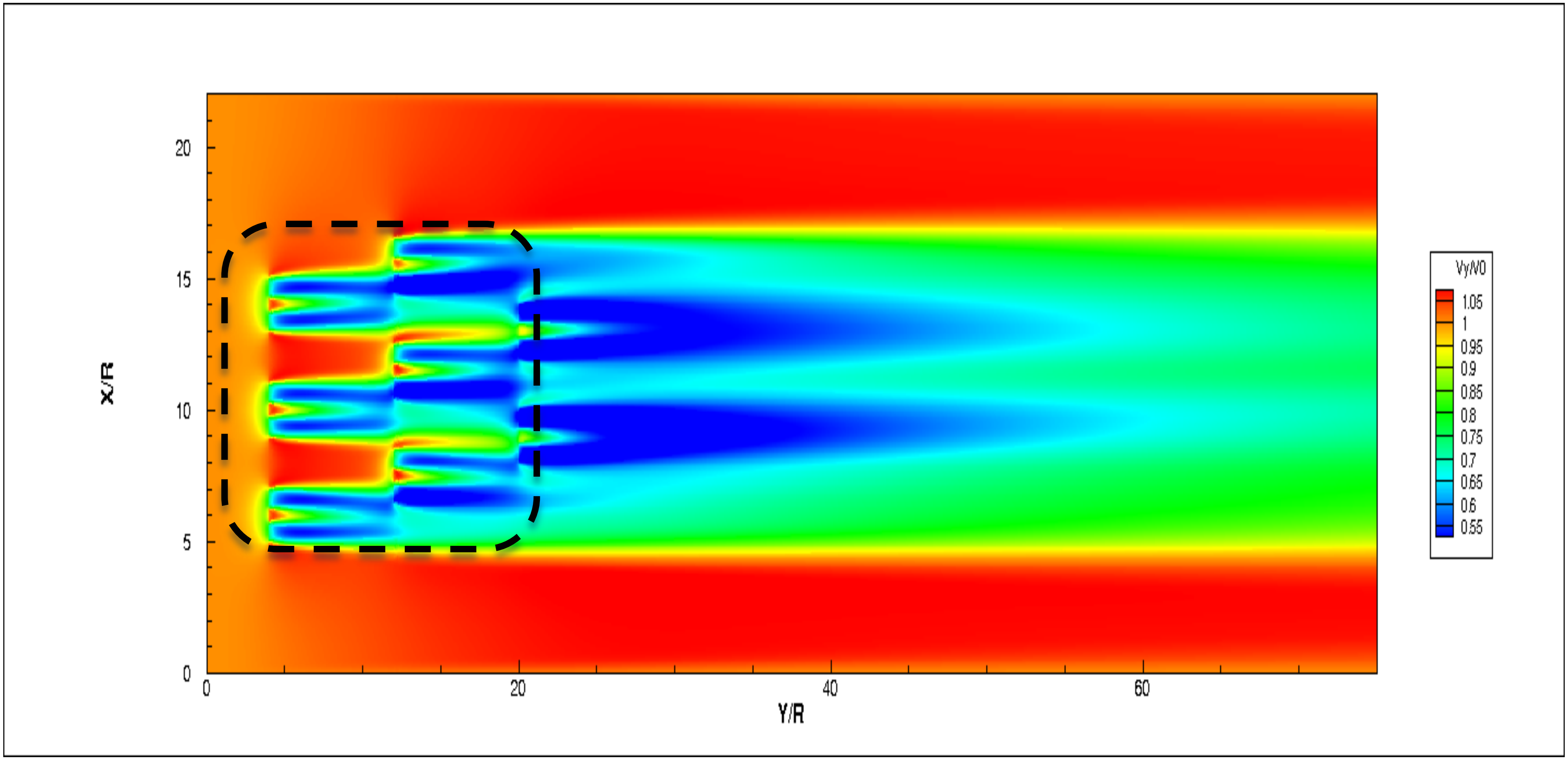
First Row of Turbines in the Array



Second Row of Turbines in the Array



Last Row of Turbines in the Array



Summary & Conclusions II

- Development and validation of a numerical methodology for performance characterization of a MHK turbine array.
- Investigation on the performance of various turbine array configurations (lab.- and full-scale).
- Development of a general numerical methodology for turbine array optimization.
- The numerical methodology helps to focus on limited numbers of possible optimized configurations from infinite possible choices.
- Using this methodology reduces the computational time and cost.

Potential Environmental Effects of MHK Turbines through the Flow Field Modification.

(Wake Effect on Sedimentation)

Numerical Methodology

- **Particle Dynamics:**

$$\frac{du_p}{dt} = F_D(u - u_p) + \frac{g_x(\rho_p - \rho)}{\rho_p} + F_x$$

- **The Blade Element Model (BEM)**

- **The Discrete Random Walk (DRW) Model:**

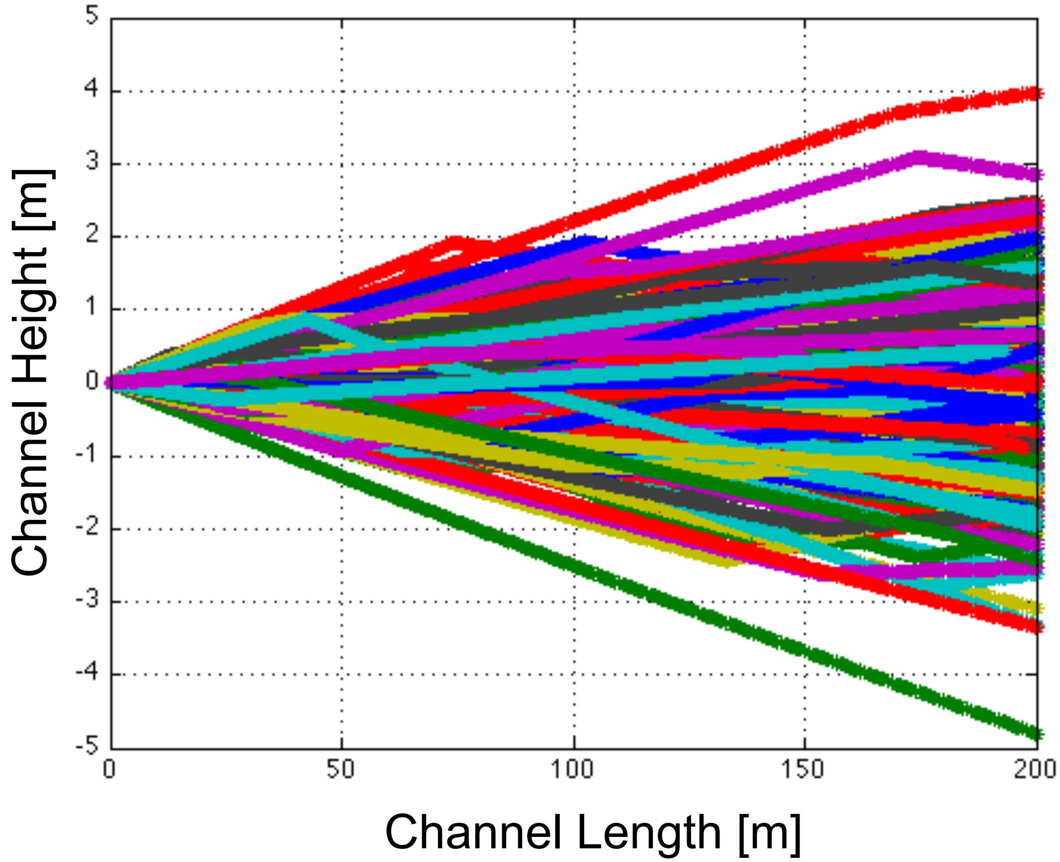
$$u = \bar{u} + u'(t) \text{ where } u' = \zeta\sqrt{\overline{u'^2}}$$

$$T_L \approx C_L \frac{k}{\epsilon}$$

$$t_{cross} = -\tau ln[1 - (\frac{L_e}{\tau|u-u_p|})]$$

$$T = min(T_L, t_{cross})$$

DRW Model Overestimates Particles Dispersion



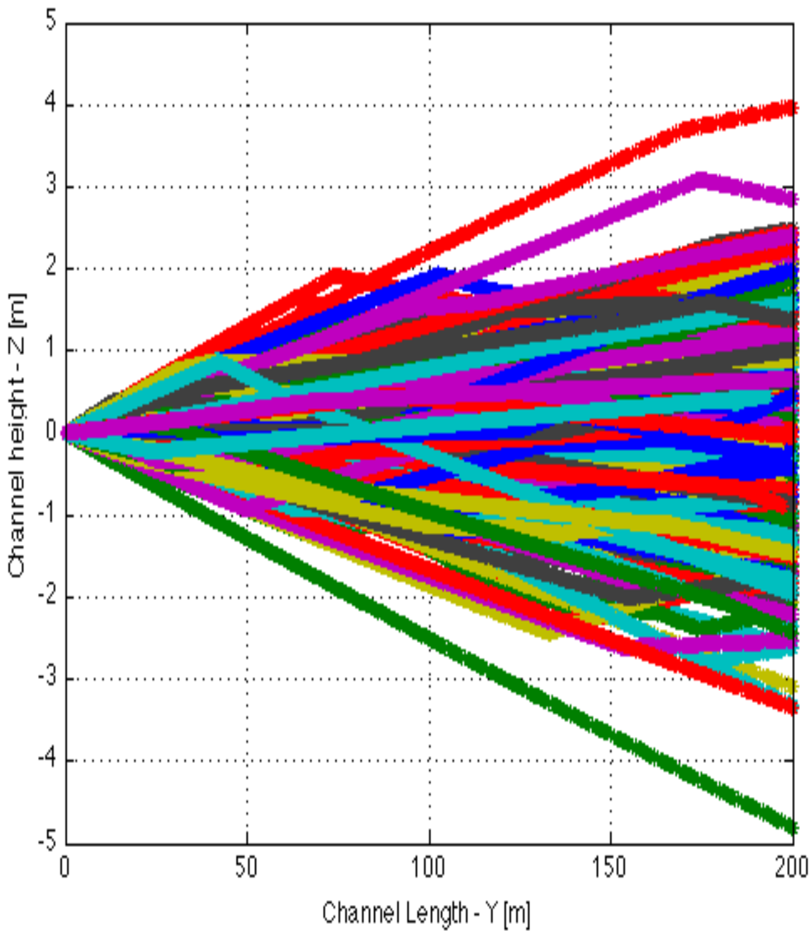
DRW Calibration via the G.I. Taylor Dispersion Theory

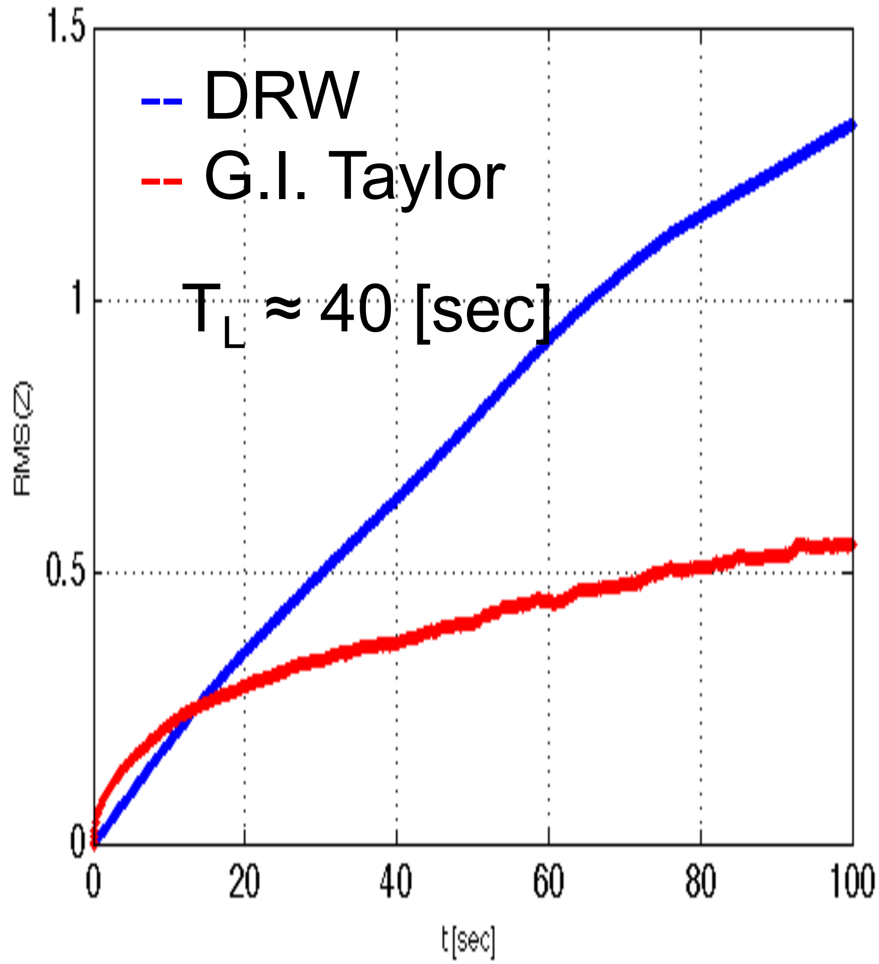
- **G.I. Taylor dispersion theory** predicts particle dispersion based on the characteristics of a homogeneous, isotropic turbulent flow:

$$\sqrt{[X^2]} = \sqrt{2\ I\ T\ [u^2]}$$

$\sqrt{[X^2]}$	RMS of particle position.
I	The time scale defined based on velocity correlation coefficient.
T	Particle residence time.
$\sqrt{[u^2]}$	RMS of particle velocity.

DRW Model Overestimates Particles Dispersion

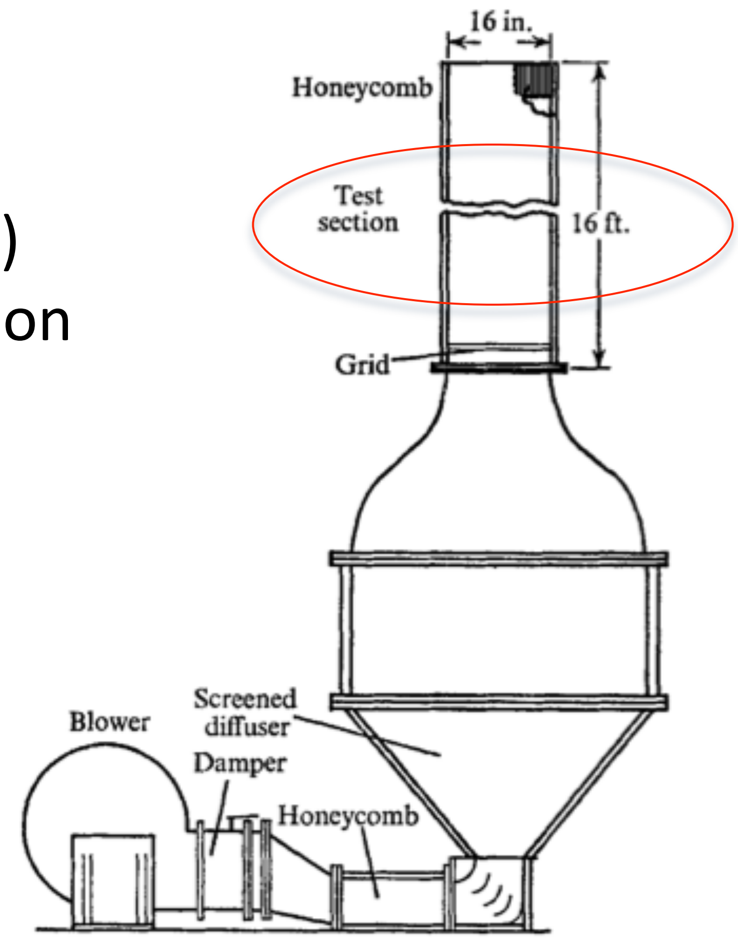




DRW Calibration Methodology - Experimental Validation

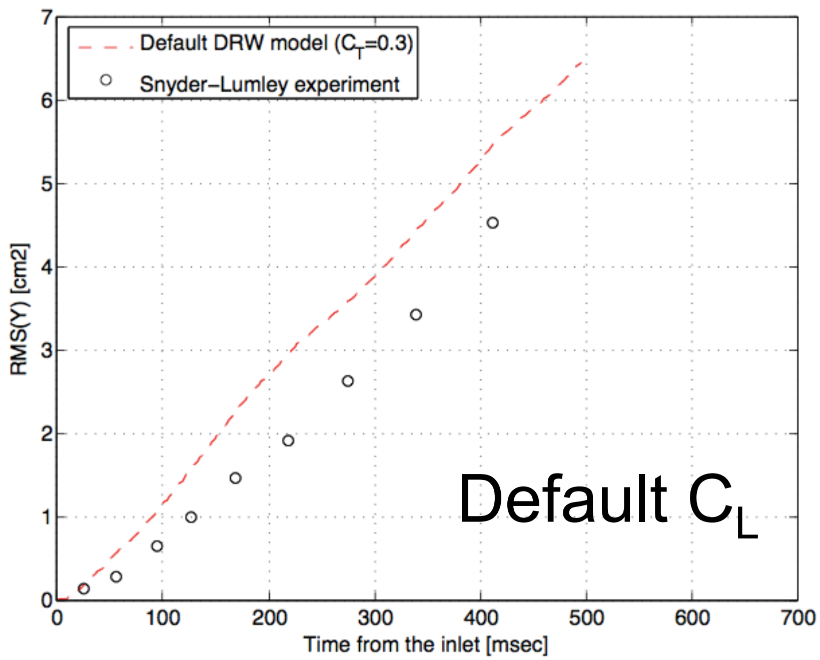
Investigation on particle dispersion from a wide spectrum of Stokes (St) number. Following particle dispersion was simulated:

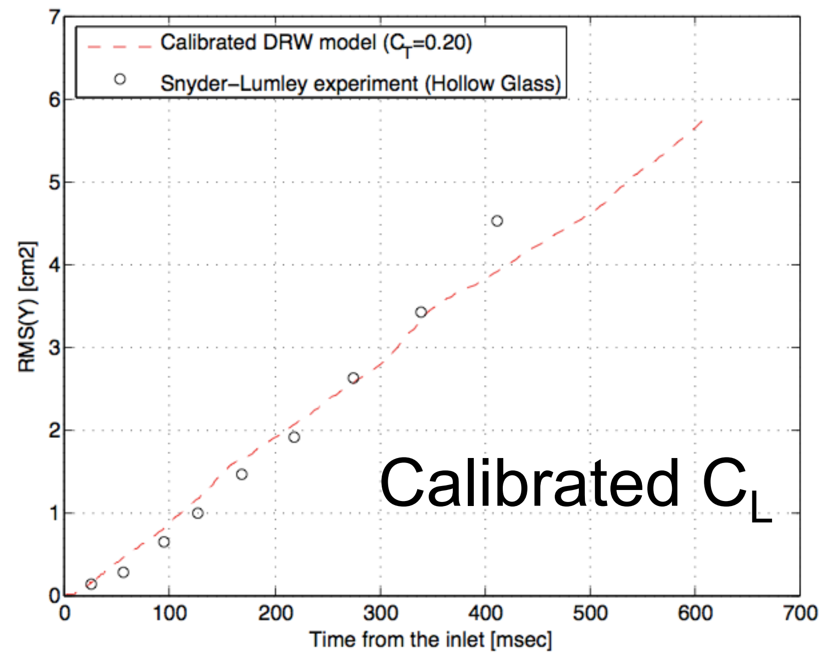
-Hollow Glass Particles (Low St)
-Copper Particles (High St)



Source: W. H. Snyder & J. L. Lumley, **Some measurements of particle velocity autocorrelation functions in a turbulent flow,** JFM - 1971

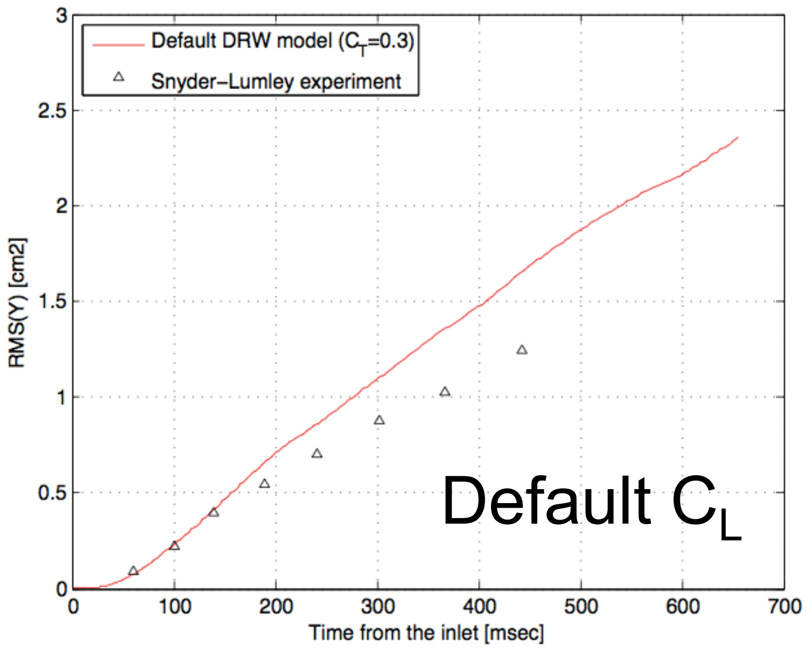
DRW Calibration Methodology
Experimental Validation

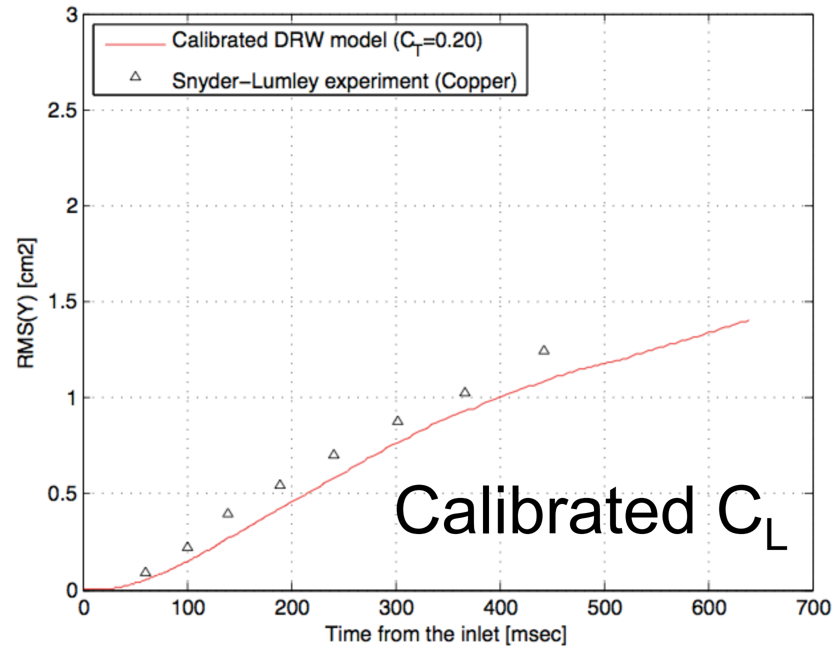




Averaged hollow glass particle dispersion
in RANS model (--) vs. Experiment (o)

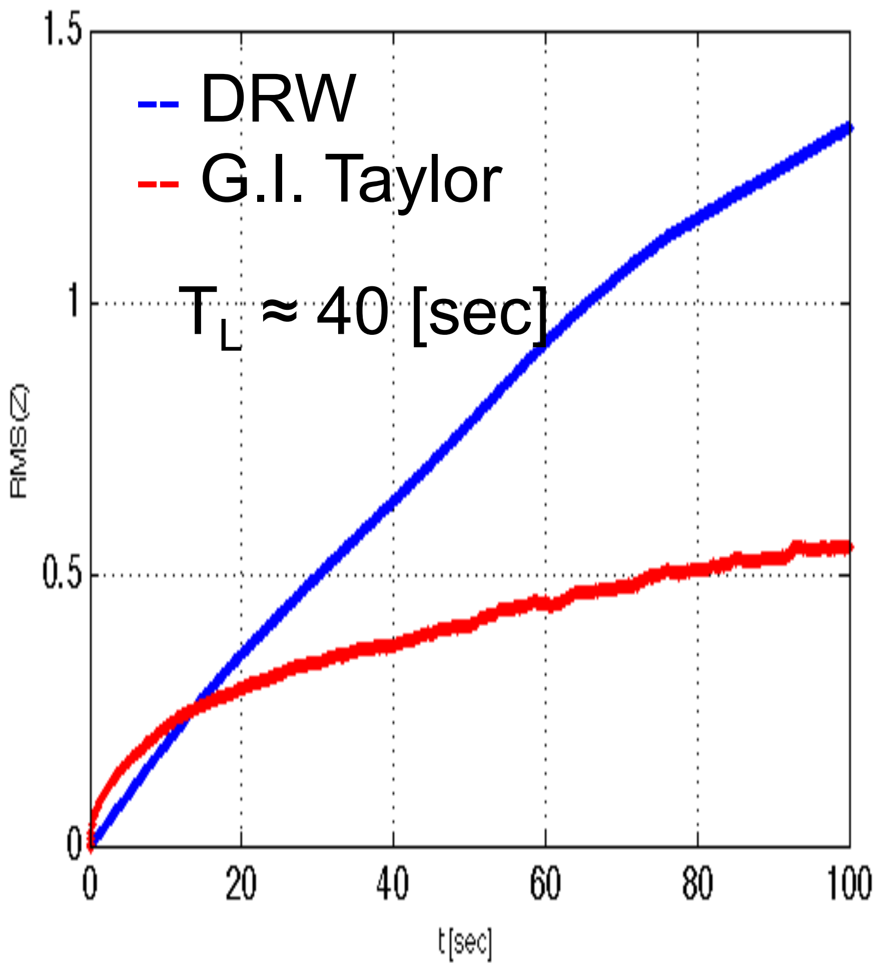
DRW Calibration Methodology Experimental Validation



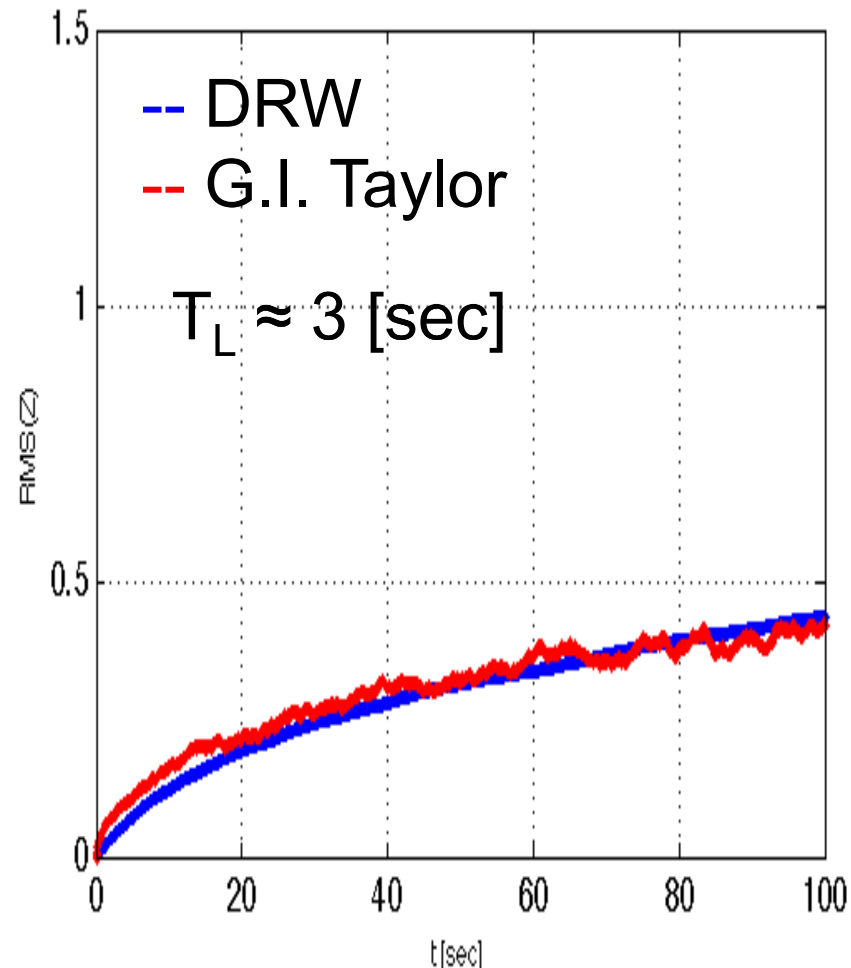


Averaged copper glass particle dispersion
in RANS model (--) vs. Experiment (o)

DRW Calibration for Particle Dispersion in a Tidal Channel



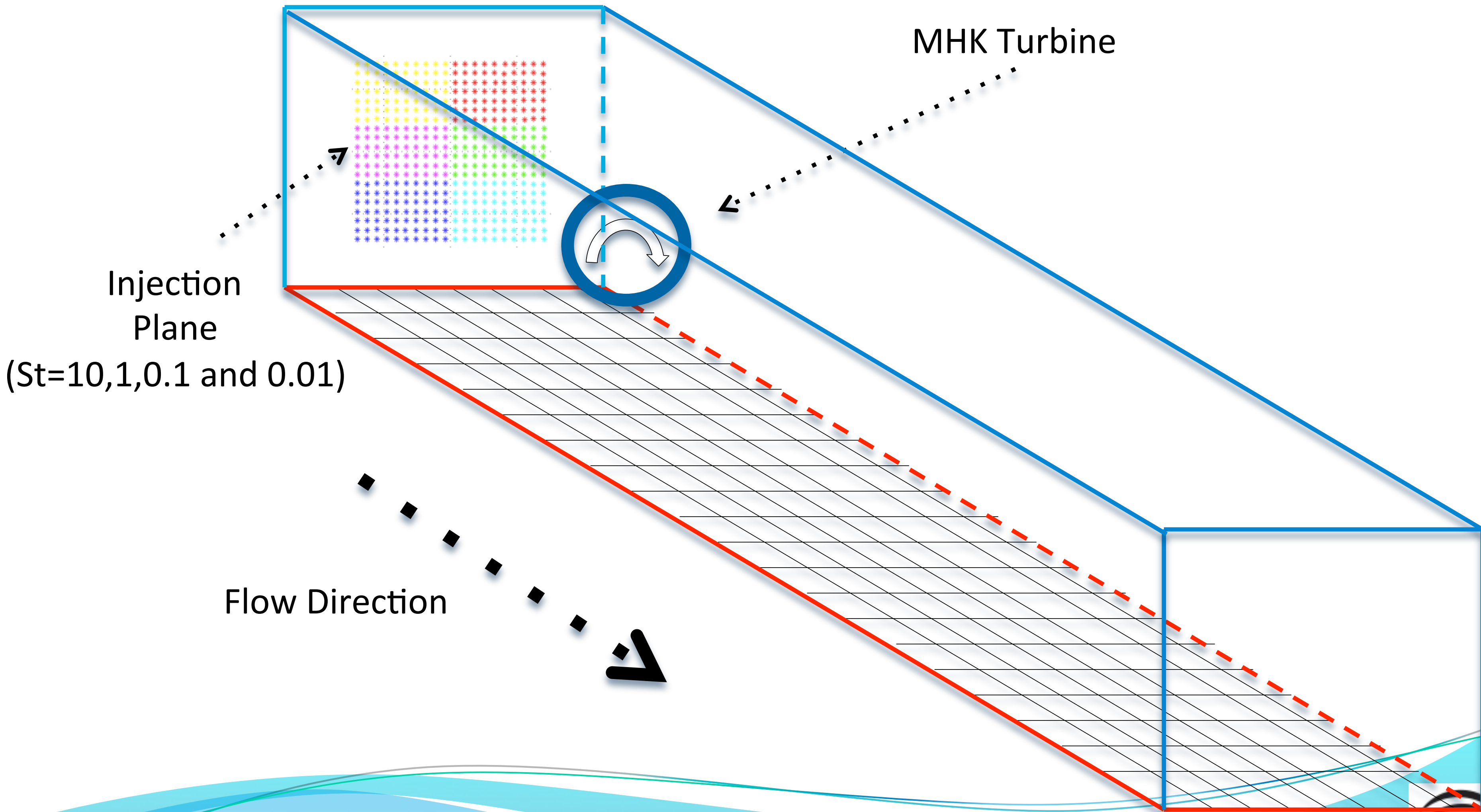
Default



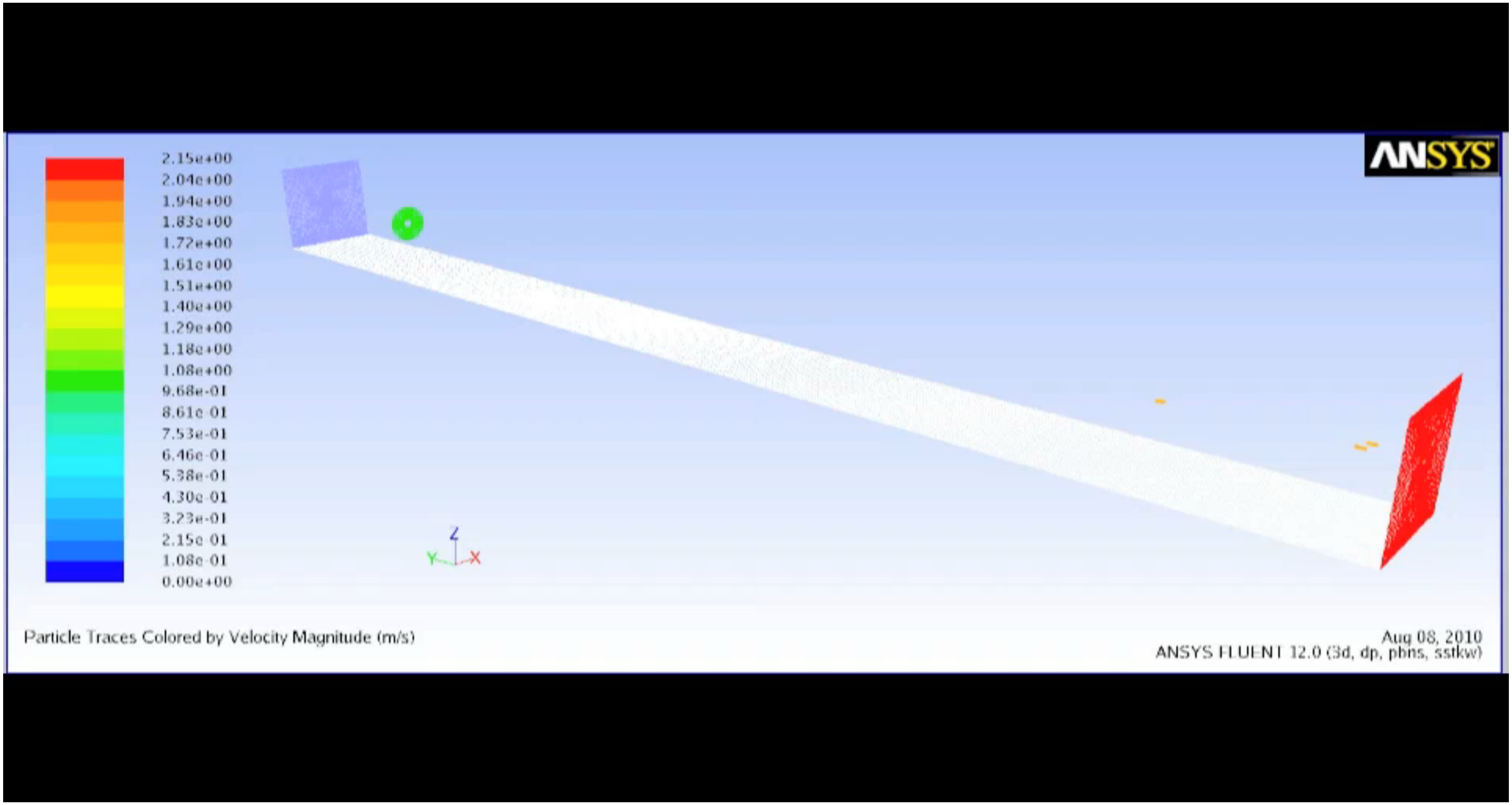
Calibrated

$$T_L \approx C_L \frac{k}{\epsilon}$$

Modeling the Particle Sedimentation in a Tidal Channel

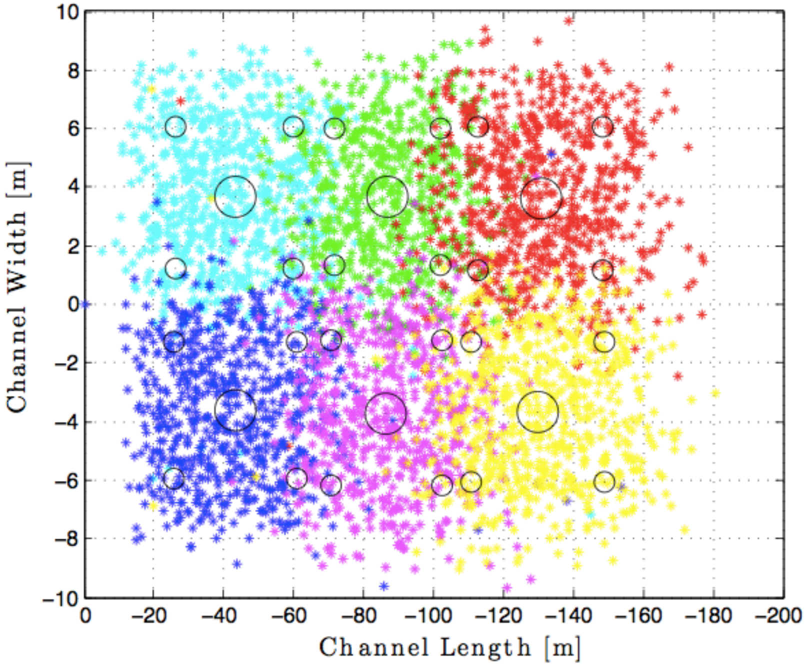


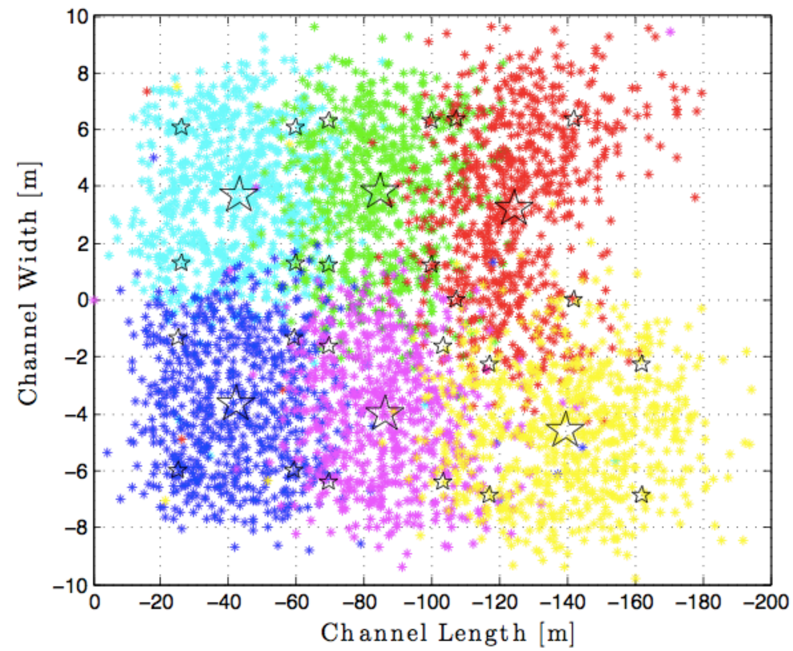
Simulation of the Physical Problem

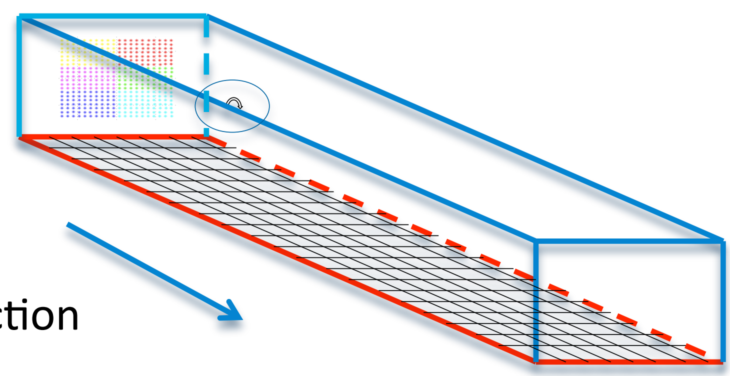


Sedimentation Process (St=1)

- **Channel without Turbine**
- **Channel with Turbine**



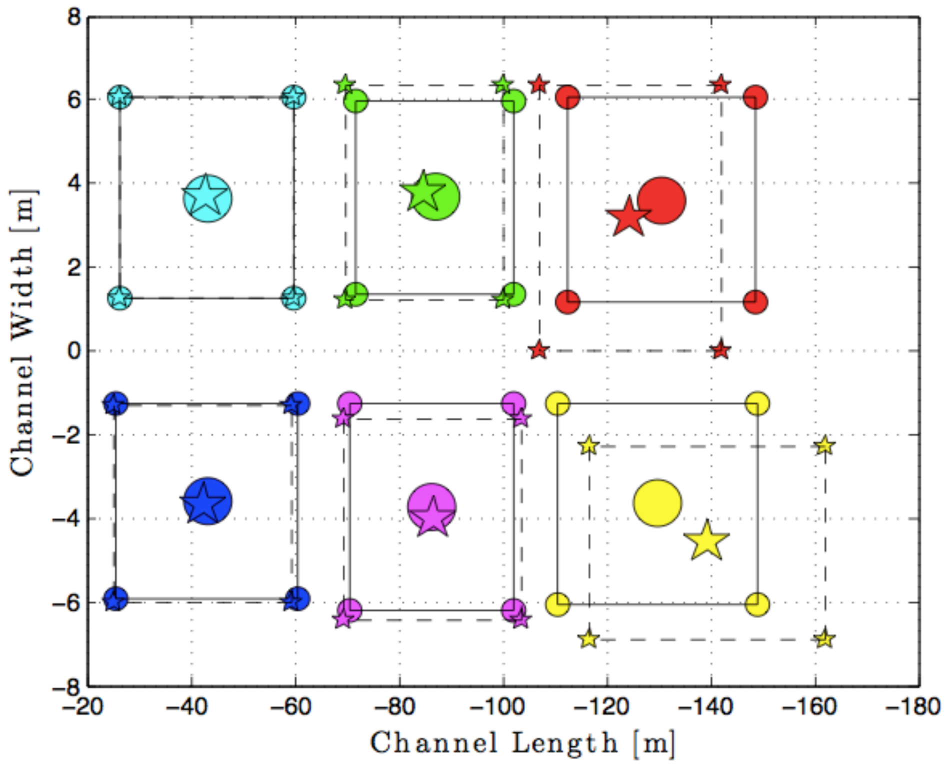




Flow Direction

Sedimentation Comparison (St=1)

- **Channel without Turbine: - and O**
  - **Channel with Turbine: -- and ★**



Summary & Conclusions III

- **Developed and validate numerical a methodology for investigation of turbine wake effect on sedimentation process of the suspended particles.**
- **Sedimentation of different Stokes number:**
  - St=10 : Sediment similar to ballistic trajectory.
  - St=1 : Signature of wake expansion and blades rotation.
  - St=0.1 : Stronger effect of turbine blade rotation.
  - St=0.01 : Enhanced sedimentation and strong mixing
- **Potential long term effect on the bottom of the tidal channel.**

Summary and Conclusions Final

- **Development of a general numerical methodology for the performance and wake characterization of the MHK turbines.**
- **Development of a general numerical methodology for the optimization of an array of the MHK turbines.**
- **Developed a methodology for investigation of MHK turbine wake effect on sedimentation of the suspended particles.**
- **Successful experimental validation of the numerical methodologies.**
- **Successful application of the numerical methodologies to the full-scale turbine design.**

In the Future

http://staff.washington.edu/teymourj/index.html

Thank you!

- Professor Aliseda
- Committee members:
  - Professor Dabiri
  - Professor Fabian
  - Professor Polagye
  - Professor Riley

Questions?