Experimental Measurements and Numerical Simulations in a 3-Turbine Array of 45:1 Scale DOE RM1 Turbines

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WHAT IS TIDAL ENERGY?

Background

Design

Experiment

Single Turbine Results

Array Results

LABORATORY-SCALE ROTOR GEOMETRY

I Maximize chord-based Reynolds number
I Choose foil to minimize Reynolds number effects
I Match performance and optimum tip speed ratio with blade-element momentum design code
I Attempt to match power extraction and wake characteristics at scale, not geometry

0.2 0.4 0.6 0.8 1

0.4 0.6 0.8 1

2 x 10^5

r/R Normalized spanwise coordinate

Chord-based Reynolds number

Solid lines represent DOE RM 1
Dotted lines represent lab-scale rotor

DOE RM 1 Turbine Scaling down process
Geometrically-scaled DOE RM 1 Turbine Performance

- Maximize chord-based Reynolds number
- Choose foil to minimize Reynolds number effects
- Match performance and optimum tip speed ratio with blade-element momentum design code
- Attempt to match power extraction and wake characteristics at scale, not geometry

Graph showing efficiency vs. TSR (Tip Speed Ratio) for full-scale and lab-scale DOE RM 1 turbines.
Performance-scaled DOE RM 1 Turbine

- Maximize chord-based Reynolds number
- Choose foil to minimize Reynolds number effects
- Match performance and optimum tip speed ratio with blade-element momentum design code
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Graph showing:
- Full-scale DOE RM 1 efficiency (predicted from BEMT)
- Lab-scale DOE RM 1 experimental efficiency

Graph axes:
- $C_p$ [-]
- $TSR$ [1]$^{SR}$
DOE RM1 @ 45:1 scale
Similarity based on performance curves

**Background**

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**Laboratory-Scale Turbine**

- 45 cm diameter rotor

**Diagram**

- Main Body of Nacelle (Aluminum)
- Tailcone (Aluminum)
- Cable Gland
- Data Cable
- 3/8"x4" Flat Bar (Steel)
- 4" O.D. Clear Tube (Polycarbonate)
- 0-rings
- Newly Designed Rotor
- Nosecone (Plastic)
- Vacuum Pad
Experimental Conditions

\[ \text{Re}_\text{chord} \sim 10^5 \quad \text{Tip Speed Ratio (TSR)} = 4.5-8 \]
\[ \text{Blockage Ratio} = 20\% \]
Three Different Array Configurations

1. Array of two coaxial turbines.

2. Array of three coaxial turbines.

3. Array of three turbines with lateral offset.
Measurement Locations:
Two Turbines Coaxially Mounted

- 5D
- 8D
- 11D
- 14D
Performance for Two Coaxial Turbines: Experimental Measurements

Performance curves for two coaxially arranged turbines at various separation distances:
- Upstream turbine
- 5D downstream turbine
- 8D downstream turbine
- 11D downstream turbine
- 14D downstream turbine
Performance of Two Coaxial Turbines: Comparison of Experiments and Simulations
Measurement Locations:
Three Turbines Mounted Coaxially

Diagram showing three turbines mounted coaxially, with dimensions labeled.

- 5 D
- 12.3 m
- 0.8 m
- 0.4 m
3-Turbine Coaxial Array Performance Comparison of Experiments and Simulations

Downstream separation 5D
Evolution of the available Kinetic Energy Flux a 3-Turbine Coaxial Array

\[ \text{Normalized Avail. KE Flux} = \frac{\int \frac{1}{2} \rho \left< V_{2D}^3 \right> \, dA}{\int \frac{1}{2} \rho V_{\infty}^3 \, dA} \]

Downstream separation 5D
Evolution of TKE contours in a 3-Turbine Coaxial Array

Downstream separation 5D
3-Turbine Offset Array Performance
Comparison of Experiments and Simulations

3 Turbines, streamwise spacing = 5D, offset spacing = 0.25 D

- Large-Eddy-Simulation
- 1D-Momentum
- Blade-Element-Momentum

power coefficient, \( C_p \)
tip speed ratio, \( \text{TSR} \)
3-Turbine Offset Array Performance
LES Simulations
Investigation of the Flume Blockage Effect

- Increase in blockage leads into increase in efficiency (vertical shift of $C_p$ curve).
- Increase in blockage shifts the peak of efficiency toward higher TSR values (horizontal shift of $C_p$ curve).

$\varepsilon = 20\%$
$\varepsilon = 10\%$
$\varepsilon = 5\%$

$\text{TSR} [-]$
Summary and Conclusions

• Three Turbines Array present non-monotonic performance: third turbine has higher efficiency than middle turbine
• Confinement plays a increasingly important role for higher number of turbines and lateral offset in the Array.
• Agreement between experimental and numerical results is best for single turbine and optimum TSR.
• Angular velocity fluctuations in the experiments, and enhanced wake recovery, not captured by simulations, leads to numerical/experimental divergence with lower TSRs, larger arrays and higher confinement.
RMS of Normalized Rotational Velocity Temporal Evolution (TSR = 6.15, 7.16)
Array of Three Turbines with Lateral Offset

- Observation of similar physics compared to results from array of two & three coaxial turbines.
- Downstream turbines’ efficiency increase monotonically with the TSR value.
3-Turbine 1/4D Lateral Offset Array Performance
Reynolds-number Dependent Performance

Efficiency

TSR

0.52 m/s flowspeed
0.61 m/s flowspeed
0.65 m/s flowspeed
0.71 m/s flowspeed
0.75 m/s flowspeed
0.90 m/s flowspeed
Turbine Comparison for Performance

![Graph showing Efficiency vs TSR for Turbine 1, Turbine 2, and Turbine 3.]

- Turbine 1
- Turbine 2
- Turbine 3
PIV Velocity Profiles in the Wake

Streamwise velocity profiles for TSR 7

- Free surface
- Rotor tip

Normalized vertical distance from centerline vs. Normalized streamwise velocity for various downwind positions:
- 2D up
- 2D down
- 3D down
- 5D down
- 7D down
Results of BEM study (3/3)

Effect of blockage on efficiency

- Blockage increases the efficiency.
- Blockage shifts the peak of efficiency to the right.
- Blockage delays the peak of efficiency of the two downstream turbines.

\[ \alpha(r) = \arctan \left( \frac{V_{inc}(r)}{r \omega} \right) + \beta(r) \]

Source: S. J. Miley's catalog of airfoils
3-Turbine 1/4D Lateral Offset Array Performance

Downstream separation 5D