U.S. DEPARTMENT OF ENERGY REFERENCE MODEL 1 & 2: EXPERIMENTAL RESULTS ON PERFORMANCE & WAKE CHARACTERISTICS

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INTRODUCTION

The Reference Model Project, sponsored by the U.S. Department of Energy's Wind and Water Power Technologies Program, aims at expediting industry growth and efficiency by providing non-proprietary point designs of marine hydrokinetic (MHK) technologies as Reference Models (RM) for open-source research and development [1]. As part of this program, two reference MHK turbine models were tested at the University of Minnesota's St. Anthony Falls Laboratory (UMN-SAFL) (Fig. 1). This high resolution laboratory investigation provides additional knowledge on the power performance and wake dynamics of two MHK turbine subclasses, axial flow and cross flow turbines. It also provides a robust dataset enabling the evaluation of various computational fluid dynamics models. Recent advancements in computational resources and modeling efforts have proven that when combined with state-of-the-art experimental capabilities for validation, turbine performance characterization and interactions between MHK devices and the surrounding environment can now be addressed by modeling full-scale deployment scenarios [2].

RM1 is a 1:40 scale dual-rotor axial flow device with a rotor diameter d_T = 0.5 m. It was designed for a tidal current energy reference site modeled after the Tacoma Narrows in Puget Sound, WA [3]. RM2 is a 1:15 scale dual-rotor cross flow vertical axis device with a rotor diameter d_T = 0.43 m and rotor height h_T = 0.32 m. It was designed for a river current energy site modeled after a reach in the lower Mississippi River near Baton Rouge, LA [4]. Results highlight performance characteristics for each rotor spanning a range of tip-speed ratios. Vertical velocity profiles collected in the wake of each device from 1-10d_T are used to characterize the turbulent wake environment.

EXPERIMENTAL SETUP

Experiments for the RM1 and RM2 were completed in the Main Channel facility at the UMN-SAFL. This channel is 2.75 m wide by 1.8 m deep by 85 m long and continuously supplied with Mississippi River water. Detailed descriptions, schematics, photos and blade characteristics of the experimental setup for RM1 and RM2 are provided in Hill et al. [5,6]. Details of the experimental testing plan for RM1 and RM2 are discussed in Neary et al. [7].

FIG. 1: 1:40 SCALE AXIAL-FLOW RM1 AND 1:15 SCALE CROSS-FLOW VERTICAL AXIS RM2 TURBINES INSTALLED AT THE UMN-SAFL FACILITY.

RESULTS

Reference Model 1: Dual-Rotor Axial Flow Turbine

Optimal performance occurred at approximately λ = 5.1 with a corresponding C_P = 0.48 (right rotor) and C_P = 0.43 (left rotor). The blade chord length Reynolds number was $Re_c \approx 3.0\times10^5$. For comparison, Lust et al. [8] observed optimal performance at approximately λ = 6.5 with a corresponding C_P = 0.41 for a single scaled model RM1 rotor in a large towing tank facility at the United States Naval Academy (USNA). The turbine model for the USNA test consisted of a 0.8 m diameter rotor with a NACA 63-618 blade cross section. Similar performance has been reported for a single rotor 3-bladed model turbine, d_T = 0.5 m, with optimal performance occurring at λ = 5.8 with $C_P \approx 0.45$ [9]. The complexity of flow in the UMN-SAFL open channel facility and slight asymmetry in the approach flow may have been a factor in the observed difference between the left and right RM1 rotor performance. Because turbine performance is a function of velocity cubed, $C_P \sim f(U^3)$, a difference of 0.03-0.05 ms^{-1} ($\approx$ 3-5% in the RM1 experiments) from one side of the channel to the other could result in C_P values varying by approximately 9-15%.

Turbine wake velocity profiles indicate the largest velocity deficit occurs in the near wake region at the center between the two rotors, immediately downstream of the center cylindrical vertical and horizontal support arms. Elevated levels of turbulent kinetic energy (TKE) are present in the wake, particularly in the region aligned with the center tower extending to approximately $2d_T$. The tip vortices shed from the blades also create elevated regions of TKE. Near wake ($\approx 1d_T$) velocity deficit in the wake of each rotor is approximately 30% and increases up to about 40-50% around 3-$4d_T$ downstream of the turbine location, at which point it begins to gradually recover. Hub height velocity measurements were collected up to $24d_T$, at which point the velocity deficit had recovered to only about 5% in the wake of each rotor, while the center of the wake was still nearly 15% deficient. Far wake ($5 \le x/d_T \le 10$) velocity deficit is similar between values reported from a single rotor turbine measured in experiments [9,10] and the dual-rotor RM1 turbine (≈10%-20%).

Reference Model 2: Dual-Rotor Cross Flow Turbine

Optimal performance occurred at approximately $\lambda \approx 2.2$ with a corresponding $C_P \approx 0.08$, well below the predicted efficiency, occurring at $\lambda \approx 3$ with a corresponding $C_P \approx 0.45$ [4]. This large discrepancy was caused by the low chord Reynolds number, $Re_c \sim 10^4$, which is below the threshold value needed to properly scale stall (and lift) characteristics. For a 3-bladed cross-flow turbine of similar geometry, Bachant and Wosnik [11] reported that $Re_c \equiv \lambda U_\infty c/\nu \approx 2.1 \times 10^5$ was required to achieve Reynolds number independence. The range of angles of attack for the RM2 turbine caused the blades to operate under dynamic stall, a Reynolds number dependent phenomenon. The performance of the cross flow turbine in [11] had a maximum performance of C_P = 0.26 at λ = 1.9.

Turbine wake velocity profiles were collected downstream of the RM2 rotor locations from 1-$10d_T$ at $1d_T$ spacing. The largest velocity deficit (≈35%) occurs up to approximately $4d_T$ and decays to approximately 20% near x = $10d_T$. Bachant and Wosnik [11] report little to no significant Reynolds number effects on wake measurements, primarily in the mean streamwise velocity, turbulence intensity, and Reynolds stress values, a reassuring finding for the detailed RM2 wake measurements collected during the UMN-SAFL experiments.

CONCLUSIONS

The RM1 and RM2 hydrokinetic turbines, designed by the U.S. DOE as reference models to benchmark technical performance, were tested in the SAFL Main Channel facility at the UMN. Detailed performance and velocity measurements were collected to assess the interaction of RM1 and RM2 with the surrounding environment. The RM1 chord Reynolds number was sufficiently high to obtain a Reynolds independent result. The performance measured at the best efficiency point was close to that reported for a similar performance test and similar to the performance measurements for single rotor devices reported by others. Detailed wake velocity measurements provide detailed descriptions of flow recovery in the wake of a dual-rotor device and show a reduced velocity deficit compared to similar measurements for a single rotor device in the near wake and similar far wake velocity deficit values up to $24d_T$. The measured RM2 performance results were found to be significantly lower than that predicted [6] due to the low chord Reynolds numbers achieved during the experiments. As a result, these measurements cannot be used for validating mid-fidelity models, e.g., CACTUS [4], but may still be of value for validating high fidelity CFD models that can capture the lift and drag characteristics at low Reynolds numbers. Detailed RM2 wake measurements could be useful for model validation and comparison to single device cross flow studies, given that previous reports show little to no Reynolds number dependence on the turbulent wake characteristics. These measurements can provide insight into the interactions between cross flow devices and the hydrodynamic environment and inform multiple device layouts during array design.

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