PAPER

Experimental Evaluation of a Mixer-Ejector Marine Hydrokinetic Turbine at Two Open-Water Tidal Energy Test Sites in NH and MA

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ABSTRACT

For marine hydrokinetic energy to become viable, it is essential to develop energy conversion devices that are able to extract energy with high efficiency from a wide range of flow conditions and to field test them in an environment similar to the one they are designed to eventually operate in. FloDesign Inc. developed and built a mixer-ejector hydrokinetic turbine (MEHT) that encloses the turbine in a specially designed shroud that promotes wake mixing to enable increased mass flow through the turbine rotor. A scaled version of this turbine was evaluated experimentally, deployed below a purpose-built floating test platform at two open-water tidal energy test sites in New Hampshire and Massachusetts and also in a large cross-section tow tank. State-of-the-art instrumentation was used to measure the tidal energy resource and turbine wake flow velocities, turbine power extraction, test platform loadings, and platform motion induced by sea state. The MEHT was able to generate power from tidal currents over a wide range of conditions, with low-velocity start-up. The mean velocity deficit in the wake downstream of the turbine was found to recover more quickly with increasing levels of free stream turbulence, which has implications for turbine spacing in arrays.
Keywords: tidal energy conversion, marine hydrokinetic (MHK) turbine, UNH Tidal Energy Test Site, Muskeget Channel, scaled open-water testing

Introduction

The United States, like most countries, faces severe challenges in energy sustainability and security, which motivates research into renewable energy technologies. In-stream conversion of tidal energy, also referred to as tidal marine hydrokinetic (MHK) energy conversion, is believed to be one of the more environmentally sustainable ways to generate electricity.

Recent nationwide resource assessments sponsored by the U.S. Department of Energy (DOE) (Hagerman & Scott, 2011; Haas et al., 2011) showed that waves and tidal currents on the coasts could contribute significantly to U.S. electric energy production. Both West and East Coasts in the United States have locations with strong tidal currents that can be harnessed to produce electrical energy, and Haas et al. (2011) generated a database of these tidal energy resources. With an estimated harnessable power in the United States of 400 TWh per year from tidal current and waves combined, corresponding to an average power of about 46 GW, it is expected that emerging marine energy conversion technologies will be developed to utility scale and will contribute to the U.S. electric supply (Bedard et al., 2007). DOE projects that all water power technologies, including conventional hydropower, wave, tidal, ocean and river current conversion could potentially provide 15% of U.S. electric energy by 2030 (DOE, 2012a).

By comparison, the total net generation/consumption of electrical energy in the United States in 2011 was about 4,100 TWh, corresponding to an average power generation of about 470 GW (or 1.5 kW per capita) (DOE, 2012b). Wind energy, the fastest growing noncarbon renewable energy technology, contributed 120 TWh to this total, or about 13.7 GW average power generation (with 47 GW installed wind turbine capacity at the end of 2011). There was no contribution from tidal energy or wave energy conversion devices—yet. First pilot-scale projects in the United States (100s of kW) are about to be connected to the grid, e.g., Verdant Power (East River, New York) and Ocean Renewable Power Company (ORPC, Cobscook Bay, Maine).

The tidal energy resource is intermittent, but unlike other renewable energy resources (e.g., wind or solar) the tides are predictable with great accuracy due to their origin in celestial gravitational effects on the earth's ocean (Boon, 2004a).

Study Goals

For MHK energy to become viable, it is essential to develop energy conversion devices that are able to extract energy with high efficiency from a wide range of flow conditions. Reported here is the experimental evaluation of one such in-stream hydrokinetic energy conversion technology. A scaled version of this turbine was tested at two open-water tidal energy test sites in New Hampshire (NH) and Massachusetts (MA) in highly instrumented deployments, and also in a large cross-section tow tank at the University of New Hampshire (UNH). This is the first in a series of papers that report on various aspects of tidal energy conversion technology evaluation at the open water test sites in NH and MA.

Goals of the study included measurements of the tidal energy resource, performance of the turbine and turbine wake. The deployments served to verify the turbine performance in an open-water tidal environment, after earlier performance studies via Computational Fluid Dynamics (CFD), and wind tunnel and flume experiments. Another goal was to gain further experience with MHK deployments and testing at the two tidal energy test sites in NH and MA and to validate deployment methods and measurement protocols.

Mixer-Ejector Hydrokinetic Turbine

In general, MHK turbines, similar to wind turbines, can be divided into axial turbines, which are installed with a horizontal axis aligned with the flow (e.g., Siemens-MCT SeaGen), and cross-flow axis turbines, which can be installed with their axis in any direction as long as it is perpendicular to the flow (e.g., ORPC, Lucid Energy). Unducted turbines typically have low-solidity rotors that are predominantly lift-driven to achieve high hydraulic power conversion efficiencies. Either type of turbine can be fitted with a shroud or duct around the rotor, which can augment the mass flow rate through the rotor, thereby increasing the power that can be extracted (Hansen et al., 2000).

The FloDesign mixer-ejector hydrokinetic turbine (MEHT) is an axial ducted turbine. The basic governing principles for describing the performance of ducted turbines are outlined in Werle and Presz (2008) using a shroud coefficient or in Hansen (2008) using a velocity augmentation factor. From linear momentum theory, it can be shown that the maximum power coefficient, $c_{p,max}$, for an ideal ducted turbine is

$$c_{p,max} = \frac{P_{max,ideal}}{0.5\rho A_{rotor} U_\infty^3} = \frac{16}{27(1 + c_S)} \quad (1)$$

where $P_{\max,ideal}$ is the maximum power that can be extracted, ρ is the density of (sea) water, A_{rotor} is the area swept by the rotor, U_∞ is the undisturbed approach velocity upstream of the turbine and c_S is the shroud coefficient defined as the ratio of the shroud force, F_S, to the rotor thrust, F_T,

$$c_S \equiv \frac{F_S}{F_T} = \frac{F_S}{A_{rotor}\Delta p_{rotor}} \quad (2)$$

where Δp_{rotor} is the pressure drop across the turbine rotor. These simple results explain the attraction of ducted devices: One can expect to exceed the "Betz limit" of 16/27 (Betz, 1920), if the power coefficient is defined with rotor area as above, by mounting a highly loaded shroud around the rotor.

The design of the MEHT is derived from propulsion augmentation technology. Downstream of the rotor the primary duct or shroud of the MEHT transitions into a lobed mixer. The mixer introduces longitudinal vorticity into the flow, which allows for efficient mixing of turbine wake and free stream. In addition, downstream of the mixer there is a secondary duct, a larger diameter ring wing, which acts like an "ejector" for propulsion augmentation. This increases mass flow rate through the turbine rotor and effectively extracts energy from an upstream area significantly larger than the rotor cross-section. Classic propulsion augmentation ideas, where a primary jet's thrust is amplified by ingestion of free-stream fluid into a larger-diameter, constant area duct that exhausts to free-stream static pressure, were developed by von Karman (1949) and Heiser (1966). Werle and Presz (2009) realized that in low speed propulsion or power systems the primary and secondary fluid streams are not independent of each other and that the free-stream pressure is not reached until far downstream of the ejector plane. The analysis by von Karman was adjusted and extended to derive governing principles for low-speed power extraction systems that employ both a shroud and an ejector. The design of the MEHT is based on Werle and Presz (2009).

A FloDesign MEHT is shown in Figure 1. The scaled version that was deployed for this project had a rotor diameter of 20 in (0.51 m) and the secondary ring-wing shroud had a nominal outside diameter of 34.7 inch (0.88 m). Two models were designed via CFD studies in collaboration with Turbo Solutions Inc.: A stator-rotor configuration with nine and seven blades, respectively, and a seven-bladed rotor-only configuration.

A custom permanent-magnet rim generator, designed and constructed by FloDesign Inc., was used: A ring with

FIGURE 1

A FloDesign MEHT with 20-inch rotor, here shown with the stator-rotor configuration (Courtesy of FloDesign Inc.).

magnets was attached to the tips of the rotor blades, and the coils were housed in the primary shroud (shown in dark gray in Figure 1). The generator was characterized and calibrated in a water tank and was then used as an "instrument" during the deployments to establish hydraulic performance of the turbine itself.

Tidal Energy Test Sites

Numerical modeling and testing in laboratory facilities at smaller scale are standard practice as part of the MHK device "scale-up" process (cf. HMRC, 2003), eventually leading to open-water testing (still at scale) as a device developer advances through "Technology Readiness Levels" (TRL) (DOE, 2010). Testing in the natural environment removes laboratory problems such as low Reynolds number or blockage effects but introduces many other complexities including uncontrollable inlet flow (mean and turbulence), off axis flows and fluctuating apparent velocities due to platform motion as a function of wave climate.

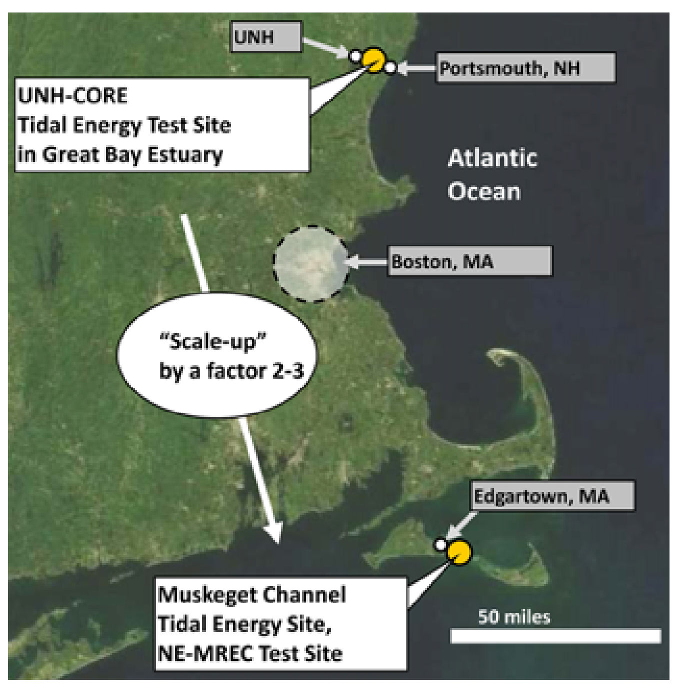
Dedicated open-water tidal energy test sites have great value, since different technologies can be tested in the same, well-understood environment. New England has a long history of ocean-related research and development, and significant MHK research and testing infrastructure is already available or presently being developed. A consortium of academic institutions and industry, the New England Marine Renewable Energy Consortium (NE-MREC), provides a complete set of facilities and open-water test sites for the testing needs defined by the DOE for MHK technology development in the TRL bands 1–9, with TRL 9 being grid-connected deployment of a full-scale device: The Center for Ocean Renewable Energy (CORE) at the University of New Hampshire (UNH) operates a sheltered "nursery" tidal energy test site for MHK turbines up to 4-m diameter in Great Bay Estuary, NH. The University of Massachusetts-Dartmouth (UMassD) is developing a full-scale test site in Muskeget Channel, MA. The locations of the two sites are shown in Figure 2. In addition to the MHK test sites utilized and described here, the University of Washington is pursuing a tidal energy test site in Puget Sound off Nodule Point (e.g., Thompson et al., 2012) and Florida Atlantic University is developing an ocean current test site off the East Coast of Florida (e.g., Hanson et al., 2010).

UNH-CORE Tidal Energy Test Site in Great Bay Estuary

The Great Bay Estuary system is a tidally driven estuary that is one of the most energetic on the East Coast of the United States. The Great Bay Estuary is well studied and surveyed (1976, 2007) and has been modeled numerically to understand its dynamics and circulation. The first-order dynamics of this system and tidal analysis results were discussed by Swift and Brown (1983), more recent numerical modeling was reported by Erturk et al. (2002) and Bilgili et al. (2005). The

FIGURE 2

Open-water tidal energy test sites in New England, UNH-CORE (NH) and Muskeget Channel (MA).



UNH-CORE Tidal Energy Test Site at the General Sullivan Bridge (GSB) is located in a constricted area in the estuary, with easy access from nearby marinas or the two local UNH marine facilities. The site has the fastest tidal current velocities in the estuary with maximum currents at over 5 knots (2.6 m/s) and typically greater than 4 knots (2.1 m/s), and hence, it is an excellent site for testing tidal energy conversion devices. The test site has a minimum depth of 8 m (26 feet) at LLW and can be used for turbines up to 4 m (13 feet) in diameter. A 35-feet × 10-feet (10.7-m × 3.0-m) test platform has been used since 2008, and a larger 64-feet × 34-feet (19.5-m × 10.4-m) test platform with a modular turbine deployment system was designed to accommodate larger turbines (Byrne, 2013). Funding for the larger test platform was secured, and the mooring and acoustic monitoring systems are currently undergoing an environmental assessment through DOE. The UNH-CORE Tidal Energy Test Site is well suited to support open-water MHK testing through DOE TRL 7.

Muskeget Channel Tidal Energy Site

Muskeget Channel is the north-south channel between the islands of Martha's Vineyard and Nantucket, MA, connecting Nantucket Sound to the North with the Atlantic Ocean to the South. The Town of Edgartown, MA holds a FERC Preliminary Permit to explore generating electricity from tidal currents with a pilot project of up to 5-MW capacity. In parallel, the Marine Renewable Energy Center (MREC) of UMassD is establishing an MHK test facility. While a satellite view shows open water on the order of 10 nautical miles between the two islands, detailed bathymetry reveals mostly shallows with a comparatively narrow, deep channel near Martha's Vineyard-Chappaquiddick between Wasque Shoal and Mutton Shoal, which has the highest tidal current velocities. This area was recently studied by Howes et al. (2009, 2011) for its suitability as a tidal energy site and environmental effects. With depths up to 50 m (164 feet) and tidal currents up to 2.5 m/s, this site is suitable for full-scale MHK device testing, which can be conducted either in test berths on pads with power and data connections (similar to the European Marine Energy Center) or in integrated turbine tests stands. The technical feasibility of different turbine deployment concepts was investigated by UNH-CORE in a 2-year study resulting in a conceptual design for the facility (Dewhurst, 2013). Once grid-connected, the Muskeget Channel test site will support open-water MHK testing through DOE TRL 9.

Tidal Current Predictions for UNH-CORE Tidal Energy Test Site

One of the goals of the turbine deployments was to conduct wake measurements at different locations downstream and to be able to compare velocity profiles the tidal current velocity had to remain approximately constant. It was therefore important to understand the temporal variation of the tidal current velocity during a tidal cycle before the deployments for experiment planning purposes.

Tides, and thereby tidal currents, are primarily driven by the gravitational interaction of the earth's oceans with the moon and the sun. The moon accounts for approximately two thirds of the tidal forcing, while the sun accounts for approximately the other third (Boon, 2004a). Due to their gravitational forcing, tides are deterministic (similar to the motion of a pendulum of a clock) and can be predicted from comparatively short-term measurements. Time series for the tides can be broken down into independent harmonic constituents as

$$h(t) = h_o + \sum_{j=1}^{m} R_j \cos(\omega_j t - \varphi_j) \quad (3)$$

Here $h(t)$ is the time series for tidal elevation (or tidal current), and R_j, ω_j, and φ_j are amplitude, frequency, and phase, respectively, of the j^{th} tidal constituent. Each constituent in this prediction relates to a particular solar or lunar cycle and follows a naming convention, e.g., M2 is the main lunar (M) semidiurnal (2) constituent. The harmonic constituents can be calculated from measured time series as short as a lunar month (29.5 days); however, longer time series are desirable to reduce the residual between measurement and prediction.

In 2007, NOAA/NOS measured tidal current data with bottom-deployed acoustic Doppler current profilers (ADCP) in Great Bay Estuary, including at the UNH-CORE Tidal Energy Test Site. Based on this data, NOAA publishes predicted times and magnitudes of ebb and flood peak velocities as well as time of slack water. The predictions and the raw data are available on their Website in the public domain (http://co-ops.nos.noaa.gov/).

For this project, the times series harmonic constituents were calculated from the raw NOAA/NOS data with the Simply Currents (SC) code that employs Harmonic Analysis Method of Least Squares (HAMELS) (Boon, 2004b). An iterative solution for the dominant harmonic constituents was determined from one lunar month of raw data and verified by comparing a 3-day tidal current prediction based on those constituents to 3 days of the actual recorded tidal current data. The solutions were then used to predict tidal currents for the testing dates of interest at the UNH-CORE Tidal Energy Test Site.

The predicted and measured tidal currents are compared in Figure 3. Two representative examples are shown, the best and the worst match of predictions and measurements. Tidal current velocity measurements were made during deployments with a Nortek Vector Acoustic Doppler Velocimeter (ADV) mounted on the bow of the test platform. Note that the Vector ADV output data at 32 Hz, which for this figure was averaged to match Simply Currents prediction interval of 12 min.

Predicted and measured currents agreed quite well on May 15. On May 17, they did not agree as well: slack water can be inferred to match; then tidal currents ramped up faster than predicted, but did not reach the predicted peak velocity. Many factors other than celestial gravitational effects affect the tides, including geographic and bathymetric factors. Meteorological effects can also play an important role in tides and tidal currents but are far more difficult to predict into the future. Therefore, tidal current velocity variation is rarely sinusoidal (Boon, 2004a). Polagye et al. (2010) concluded that predicting tidal height is far more accurate than predicting tidal current. The few comparisons of predicted and measured currents do not allow to determine a statistically significant uncertainty in current velocity predictions. Given these complexities, the agreement of predictions with measurement can be considered satisfactory, in particular for experiment planning purposes.

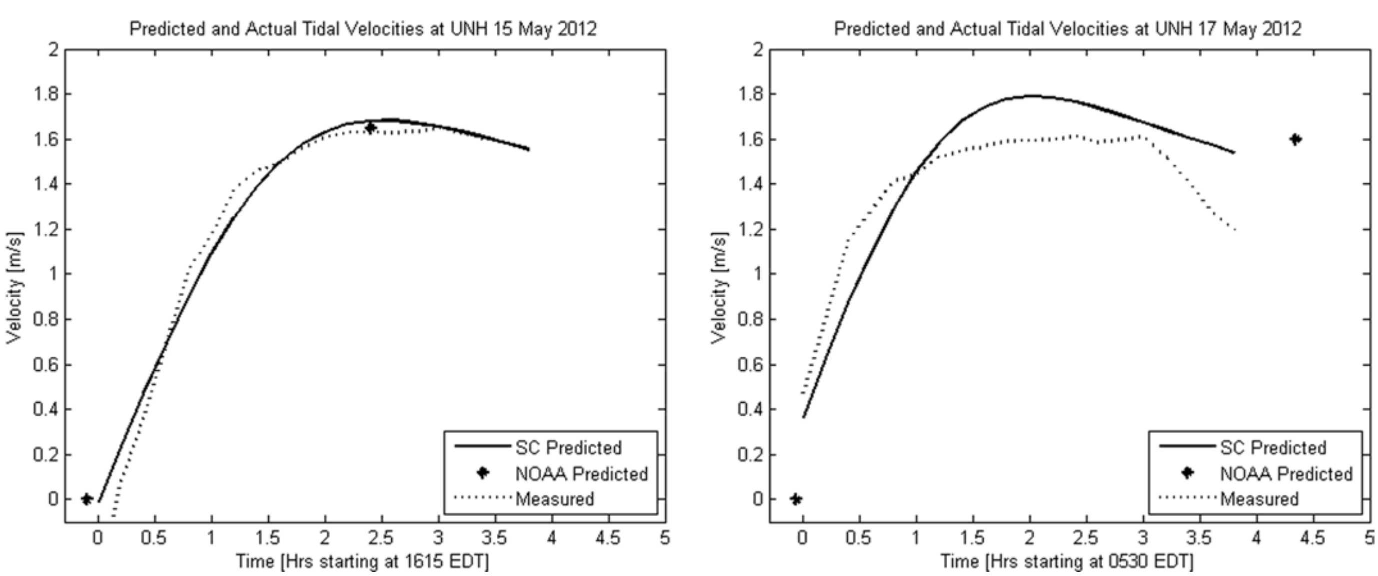
Tidal Energy Test Platform

The UNH-CORE Tidal Energy Test Platform v1 is a 35-foot (10.7-m)-long, 10-foot (3.0-m)-wide pontoon boat dedicated to MHK turbine testing. For this project, the platform was completely renovated, and a new turbine deployment mechanism, instrumentation mounts and wake traversing mechanism were installed. The deployment frame consisted of a generic turbine mounting box at the end of a 9-feet (2.7-m) custom hydrofoil tripod frame attached to a topside box beam frame. The box beam frame can rotate around its forward member via a shaft attached to flanged split bearings mounted on a load distributing beam and is locked in place at the aft member via custom locking clasps. This system enabled rapid and safe turbine deployment and extraction at the test site. A fixed gantry crane with a 2,000 lbf (8,900 N) capacity hoist was used to rotate the tripod turbine frame.

To allow wake measurements at various locations downstream of the turbine while deployed, all stringers connecting the pontoons aft of the moon pool were removed and replaced with an elevated platform that rigidly connects the pontoons but leaves the deck level open to allow full streamwise positioning of a traversing system. The new aft pontoon coupling, made from 6061-T6 aluminum box beam

FIGURE 3

Predicted and measured tidal current velocity during MEHT testing at the UNH-CORE Tidal Energy Test Site.



with gusseted corners, was analyzed for seaworthiness with finite element analysis (FEA) simulations under different loading and wave scenarios.

Two different types of decking were installed: A fiberglass reinforced polymer grated decking (ThruFlow) was selected for the forward half of the platform to allow reduction of shock loading and dissipation of energy from a wave strike. The aft half of the platform was covered with marine plywood. The grated decking does not provide the same structural support as the ¾ inch marine plywood; this was offset by increasing the number of stringers. A removable plywood working platform was installed over the moon pool. All materials were adequately prepared, primed, painted and/or sealed for the marine environment. A rendering of the UNH-CORE Tidal Energy Test Platform v1 is shown in Figure 4.

Instrumentation

Instrumentation for the deployments was provided by UNH-CORE, FloDesign, the National Renewable Energy Laboratory (NREL), and RDI Teledyne. Two Acoustic Doppler Velocimeters (ADVs) were used, a Nortek Vectrino (UNH) with a maximum sample rate of 200 Hz and a Nortek Vector (NREL) with a maximum sample rate of 32 Hz. The Vector was installed on the starboard bow with the probe head approximately 5 feet (1.5 m) below the water line.

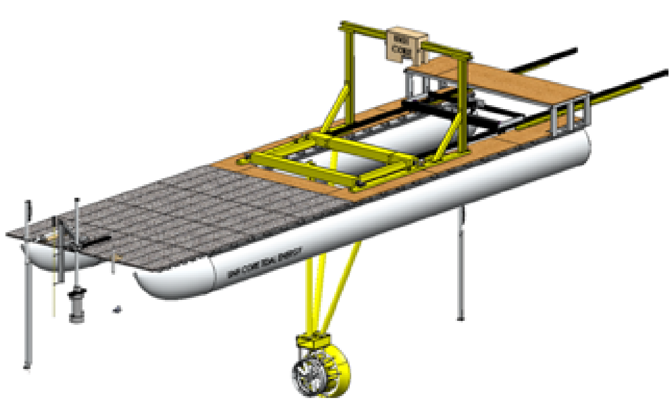
The Vectrino was installed on a traversing mechanism that allowed manual streamwise motion and automated cross-stream positioning. Its probe head was installed so that the measurement volume was at the depth of the of the turbine centerline, approximately 9 feet (2.7 m) below the waterline. Various mounts and stings for the two ADVs were tried. A sting using a schedule 40 aluminum pipe with a foil-shaped streamlining fairing that was mounted so it could rotate to align itself with the flow was found to work best and cause the least instrument motion in a turbulent tidal environment.

A Velmex Bislide was used to position the Vectrino ADV in the cross stream direction, and a 60-inch (1.5-m) traversing distance was the maximum possible due to the pontoon spacing. The ADV sting mounted to a support frame in such a way that the drag loading was transmitted to Accuride linear bearings on a traversing carriage, not the Bislide. The stream-wise positioning of the traversing system was performed manually utilizing linear bearings on t-slotted extruded rails. The total stream-wise travel was 20 feet (6.1 m) and required that the traversing rails be cantilevered off the stern by 7 feet (2.1 m).

Salinity was measured with a refractometer. For deployments reported here, salinity at the UNH-CORE site was measured at 22 parts per thousand (ppt) and for Muskeget Channel it was 33 ppt (± 0.5 ppt). An ADCP was mounted just below the waterline centered off the bow of the platform to monitor tidal energy resource. For the UNH-CORE test site deployments, a new RDI Sentinel V (on loan from RDI) was used, for the Muskeget Channel deployments, an RDI Sentinel Workhorse 1,200 kHz (UNH) was used. An electromagnetic flow meter (Marsh-McBirney Flo-Mate 2,000, UNH) was installed off the port bow of the test platform as a back-up velocity measurement and real-time verification of ADV output. An Ocean Sensor Systems, Inc. wave staff OSSI-010-002E (UNH) was mounted off the bow to the starboard of centerline. A Teledyne DMS-05 Inertial Measurement Unit (IMU) and 3 Meggitt Model 745 accelerometers (all NREL) were installed on the turbine mounting box. Two 20,000-lb load cells and swivels (NREL) were used to measuring mooring loads, and a Hemisphere V101 GPS Heading Unit (NREL) was used for position measurements. The IMU, accelerometers, load cell and GPS were recorded at 100 Hz to a National Instruments (NI) Compact RIO installed in a waterproof box with an independent NI-GPS unit for timing (all NREL). All other instruments were recorded to a CF-53 ToughBook laptop computer (UNH). The data obtained with the wave staff were used in combination with the

FIGURE 4

Rendering of UNH-CORE Tidal Energy Test Platform v1 with MEHT installed on tripod deployment frame.



Teledyne DMS IMU to assess platform motion; for details, see Dewhurst (2013) and Dewhurst et al. (2013).

Turbine power takeoff and performance evaluation were performed by FloDesign with their own equipment in a weatherproof enclosure. The three-phase AC output from the permanent magnet rim generator was monitored with a WT 3000 Yokogawa power analyzer and then converted to DC in a 3-phase bridge rectifier. The power was dissipated in a 5-kW DC Kepco electronic load bank, which also provided a signal for the Yokogawa power analyzer.

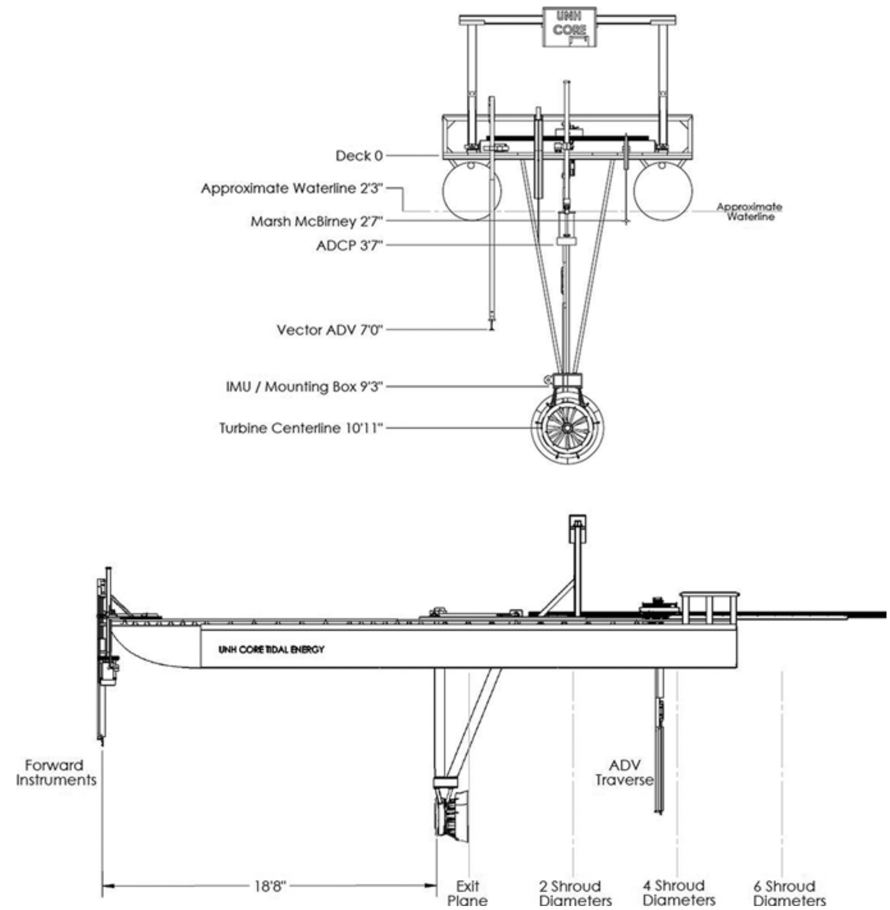
SeaView and GoPro video systems (UNH) were used to monitor the turbine and its environs during the deployments. The SeaView cameras (3×) streamed live video through a DVR, which enabled virtually unlimited continuous recording as well as real time monitoring. GoPro cameras (2×) provided much higher resolution video but were not viewable in real time and were limited by battery life.

Two inverter generators were used on board the test platform, one Honda EU2000 2 kW dedicated to the turbine deployment hoist and one EU 1000 1 kW dedicated to instrumentation, data acquisition systems and computers.

Front and side views of the UNH-CORE Tidal Energy Test Platform with most of the deployed instrumentation with respective deployment depths are shown in Figure 5.

FIGURE 5

Instrumentation deployment locations and depths on UNH-CORE Tidal Energy Test Platform v1 with MEHT installed.



Results

Before the first deployment at the UNH-CORE Tidal Energy Test Site, tow testing up to 4 knots (2 m/s) was performed on two occasions (in Portsmouth Harbor and in the Piscataqua River near the UNH tidal site) for general shakedown and to test the turbine–test platform interface, the new deployment mechanism, the turbine and generator, the wake traversing rig and all instrumentation and data acquisition. Data and video were reviewed, and lessons learned incorporated before the tidal site deployments. The decision was made to restrict the deployments to daylight operation at the test sites (transit in the dark was o.k.), which limited the slack times and tide cycles available for deployment.

UNH-CORE Tidal Energy Test Site Results

For the deployments at the UNH-CORE Tidal Energy Test Site, the test platform was staged at Great Bay Marina within view of the test site. A 22-feet (6.7-m) Eastern work boat owned by UNH was adequate to bring the test platform to and from the sheltered test site. The mooring was a bridled configuration between two bridge piers of the GSB, which are spaced 200 feet (61 m) apart. A bridle on the test platform connected to the load cells on each side. Two sections of 150 feet (46 m) of 5/8th three-strand polypropylene line, chosen for the mooring line due to its cost, strength and buoyancy, also formed a bridle to keep the test platform aligned with the flow and connected to two semipermanent mooring lines at the bridge piers. This configuration resulted in approximately equal mooring forces in each mooring load cell.

Three deployments over single tidal cycles were conducted around neap tide on May 15, 16 and 17, 2012, each on the flood tide. Example data are shown below. The MEHT is shown under test at the UNH-CORE Tidal Energy Test Site in Figure 6.

The MEHT demonstrated low-velocity start-up with a cut-in speed of about 1 knot (0.5 m/s) for both the stator-rotor and rotor only configurations. Around peak conditions on May 15 (corresponding to the wake measurement period), the mean power extracted was 499 W, resulting in a power coefficient based on rotor diameter of 1.36. Note that the derivation of power extraction from first principles bases the modified power coefficient for shrouded devices on rotor diameter (cf. Equation (2)); however, it has also been suggested that the largest diameter of the device should be used. Note that only nominal power values are presented here. For more details on turbine performance, cf. FloDesign's final report to the U.S. DOE (Barnes et al., 2013). Mooring forces peaked around 400 (1,800N) lbf.

Based on tidal current predictions (cf. Figure 3), it was inferred that a set of wake traverses should be completed in approximately 30 min; for comparison of wake profiles at different downstream locations the traverses had to be performed at approximately constant tidal current velocity. The measured time variation of the tidal energy resource is shown in Figure 7, with the actual wake measurement window indicated. The turbine wake was measured in 2-inch (5 cm) steps at two, four, six and seven shroud diameters downstream of the turbine exit plane. The results are shown in Figure 8, where velocity deficit was normalized to free stream velocity.

At 2 diameters downstream the open center body of the turbine can still be identified by the faster moving fluid compared to the location of the rotor. That effect is mixed out quickly and hardly distinguishable by 4 diameters. The wake velocity deficit decays quickly and by 7 diameters the velocity has been restored to approximately 80% of its free stream value. For each traverse, there was significant scatter as the probe is positioned in the highly dynamic and turbulent flow created by inserting an energy conversion device in a natural tidal flow. It can also be seen that the free stream is not quite reached because of the lateral traversing limit due to the pontoon spacing.

Turbulence imposes a cyclical load on the turbine parts in addition to the steady load. Cyclical or fatigue loading of MHK turbines can produce progressive damage that will ultimately lead to structural failure. Fatigue loading is difficult to characterize accurately, but it is generally agreed that it is correlated to turbulence intensity; therefore, this is an important quantity for turbine developers. Commercial computational fluid dynamic (CFD) codes, which are used frequently for turbine design, also require a turbulence intensity input when analyzing fluid

FIGURE 6

Tidal Energy Test Platform with MEHT at UNH-CORE Tidal Energy Test Site.

FIGURE 7

Tidal energy resource during May 15 test (ADV Vector on bow).

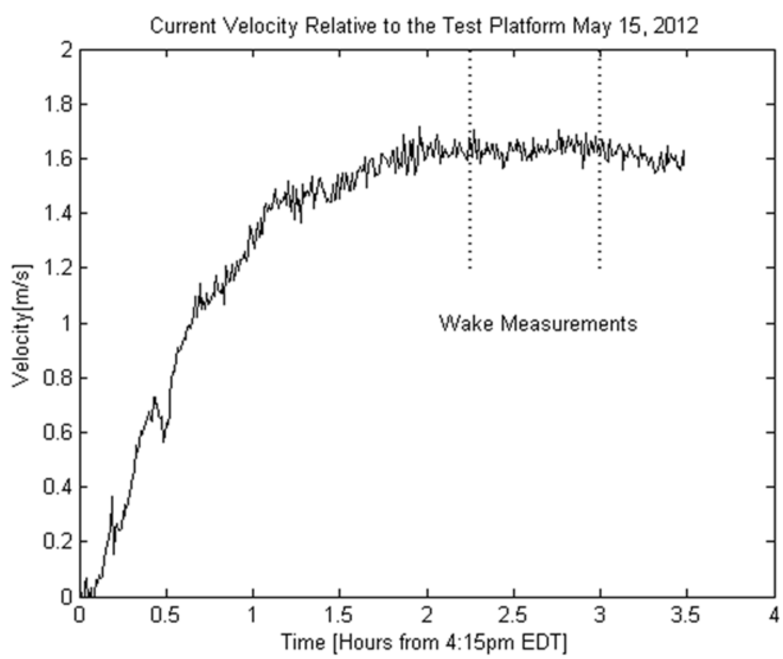
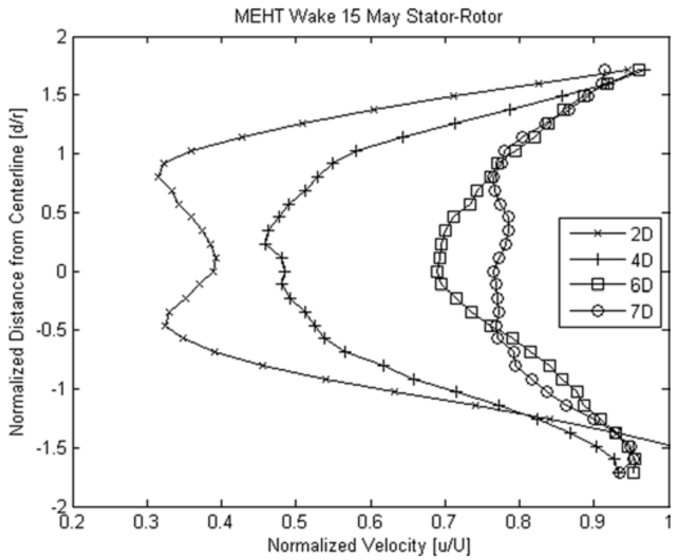


FIGURE 8

Wake velocities (velocity deficit normalized with free stream) at peak tidal flow.



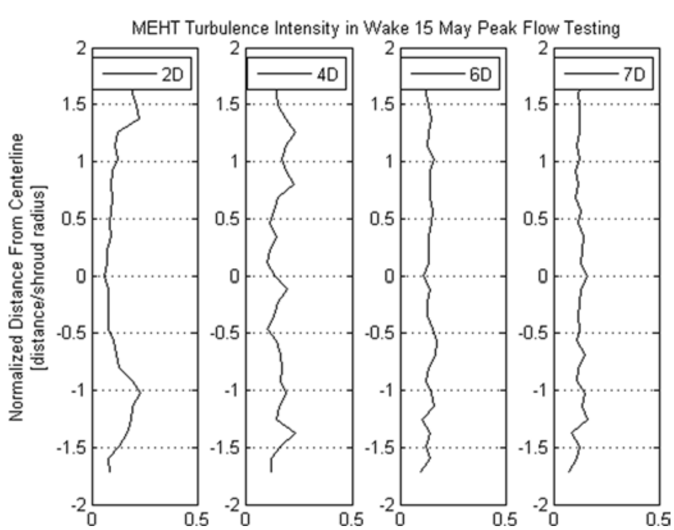
interactions. Turbulence intensity is the standard deviation of the fluctuating component divided by the mean.

$$TI = \frac{\frac{1}{N}\sum_{n=1}^{N}\sqrt{[(u-\bar{u})^2]}}{\bar{u}} \tag{4}$$

Figure 9 shows the local turbulence intensity for each downstream position, normalized to free stream velocity. Close to the turbine outlet the turbulence intensity shows distinct peaks in the wake of the ejector/ring-wing shroud. Moving downstream, the turbulence intensity quickly became more evenly distributed across the wake. The inflow turbulence intensity over the duration of the wake traversing was calculated at 7%, indicating that the flow at 7 diameters downstream was still more turbulent than the inlet flow. Comparable studies of tidal energy sites found turbulence intensities on the order of 10% (Thomson et al., 2012).

FIGURE 9

Turbulence intensity in the wake of the MEHT.



Muskeget Channel Tidal Energy Site results

A marine services company hauled the UNH-CORE platform overland to Fairhaven Shipyard on the Massachusetts South Coast. From there, the test platform was towed to Edgartown Harbor on Martha's Vineyard. For the deployments in Muskeget Channel, the test platform was staged in Edgartown Harbor. For each deployment attempt, it was towed from the harbor to the test location in Muskeget Channel (approximately 2 h) using a contracted 42-feet (12.8-m) research vessel, the R/V *First Light*.

Several mooring designs were considered and modeled. The load the turbine and platform would exert on the mooring at the maximum predicted flow and sea state conditions was calculated and simulated in wave tank test using a Froude-scaled 1:9 scale model of the test platform and the MEHT turbine. At Muskeget Channel the platform was moored on a single-point mooring, set on July 15 in approximately 70 feet (21 m) of water just north of the channel markers and Northwest of Mutton Shoal. The mooring was recovered after testing was concluded on July 20. The bridle from the platform attached to 100 feet (30 m) of 1-inch mooring line to a 3 feet (1 m) surface float, then connected to 280 feet (85 m) of 1-inch mooring line to a shot (45 feet) of ¾-inch chain to a 500-lb (227 kg) Danforth embedment anchor. The MEHT was deployed in Muskeget Channel on July 15, 16, and 19, 2012. Testing on July 15 was during ebb tide with maximum currents of 2.8 knots (1.4 m/s) and sea state 2–3 based on the Douglas (wind) sea scale. Testing on July 16 was during ebb tide with maximum currents of 2.8 knots (1.4 m/s) and sea state 3. The next successful deployment was on July 19 during flood tide with maximum currents of 3.6 knots (1.9 m/s) and sea state 1–2. Modeling and tank testing indicated that the test platform should not be deployed in sea states higher than three on the Douglas Sea Scale. Around peak conditions on July 16, the mean power extracted was 413 W, resulting in a power coefficient based on rotor diameter of 1.34 (Figure 10).

Muskeget Channel was a very dynamic testing environment. Measurements proved more difficult than in the laboratory or at the sheltered UNH-CORE test site. The turbine wake was measured at two, four and six shroud diameters downstream of the turbine exit plane. The results are shown in Figure 11, with velocity deficit normalized to free stream velocity.

The general shapes of the curves in Figure 11 are as expected. At four shroud diameters downstream nearly the entire wake has reached greater than 80% of the free stream velocity, and by 6 diameters it has almost 90% recovered. Wake recovery at the more turbulent Muskeget Channel site was significantly faster (i.e., over a shorter distance downstream) than at the UNH-CORE site. The centerline velocity deficit for the 2D profile does not align well with the centerline of the turbine, which is most likely due to off axis flow. The turbulence intensities at both test sites during the half hour at peak velocity are compared in Table 1.

Note that this is turbulence as "seen by the turbine" or "seen by the instrument," in this case the Vector ADV mounted on the bow, which explains the high values on the days of significant wave action. On the calm day in Muskeget Channel, the average turbulence intensity during the 30 min at peak velocity was 9.6%, which is comparable to what was found in studies of other tidal energy sites (Thomson et al., 2012).

The most value from the Muskeget Channel deployments was gaining a first-hand understanding of the natural environment the turbine was deployed in. It was a major logistical achievement, and all systems performed as expected. Given the success of the deployment, it can be expected that MREC and the town of Edgartown will continue to research ways to implement tidal turbines at that site.

Comparison to Tow Tank

The MEHT was also tested in the UNH Tow and Wave Tank, a 36.6-m (120-feet)-long, 3.66-m (12-feet)-wide, 2.44-m (8-feet)-deep facility

FIGURE 11

Wake velocity data from Muskeget Channel.

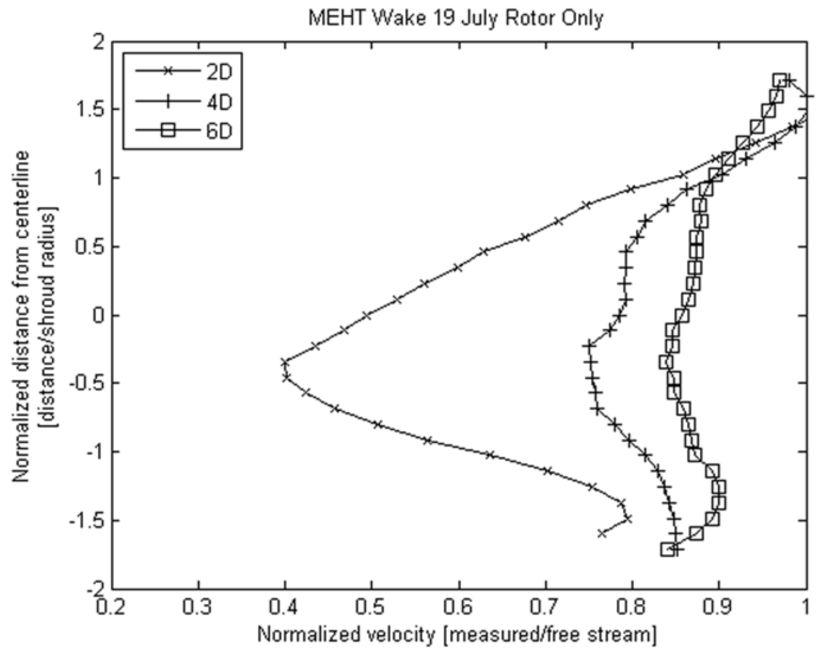


FIGURE 10

Tidal Energy Test Platform with MEHT at Muskeget Channel Tidal Energy Site.

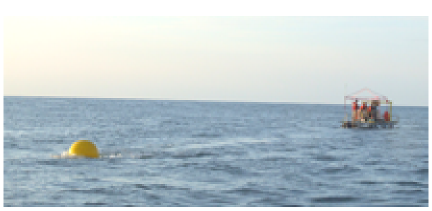


TABLE 1

Inlet flow turbulence intensities for all MEHT tests.

Date: Location	Turbulence Intensity
May 15: GSB	7.0%
May 16: GSB	7.4%
May 17: GSB	7.4%
July 15: Muskeget	24.1%
July 16: Muskeget	23.1%
July 19: Muskeget	9.6%

capable of towing at speeds up to 3 m/s with acceleration up to 2 m/s^2. The stator-rotor configuration of the MEHT was tested under yaw and with a rudder, and more detailed wake measurements were conducted. The tow tank provided unique opportunities for testing MEHT characteristics under controlled conditions that could not be explored during open-water testing. The results are not further discussed here (cf. Rowell, 2013, for details), except one example plot comparing the MEHT wake at 2D between UNH-CORE site, Muskeget Channel and the tow tank in Figure 12.

From this data, it can be inferred that the wake recovers over a shorter distance downstream the higher the free stream turbulence level, as it increases from tow tank to UNH-CORE Tidal Energy Test Site to Muskeget Channel.

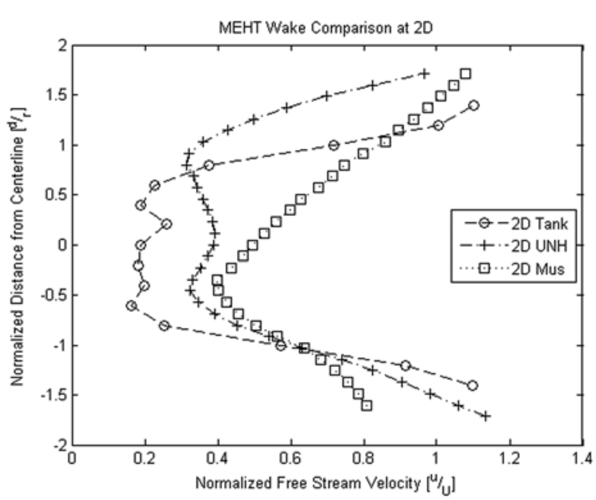
Summary and Conclusions

For MHK energy to become viable it is essential to field test devices in an environment similar to the one they are designed to eventually operate in. A scaled version of a MEHT was successfully evaluated experimentally, deployed below a purpose-built floating test platform, at two open-water tidal energy test sites in New Hampshire and Massachusetts, and also in a large cross-section tow tank. State-of-the-art instrumentation was used to measure the tidal energy resource and turbine wake flow velocities, turbine power extraction, test platform loadings and platform motion induced by sea state. The MEHT was able to generate power from tidal currents over a wide range of conditions, with low-velocity start-up. The mean velocity deficit in the wake downstream of the turbine was found to recover more quickly with increasing levels of free stream turbulence, which has implications on array spacing. Future plans for the MEHT include a scale up to 4–7 feet (1.2–2.1 m) rotor diameter.

For all kinetic energy conversion technologies—whether in wind or water—the power extracted is proportional to the projected area perpendicular to the incident flow direction intercepted by the turbine. Wind turbine technology has mostly converged to three-bladed, horizontal (axial) axis, upwind, pitch-controlled rotors, which have grown very large to reach higher into the atmospheric boundary layer. For MHK tidal energy devices, a technology conversion is less likely to occur, due to the fact (1) that tidal turbines will be limited in size by the cross-section (typically the depth) of the tidal site they are installed in and (2) that different tidal sites have different, predictable velocity ranges. Cross-flow and ducted devices are therefore more likely to play a role in the MHK energy arena, depending on site-specific parameters.

FIGURE 12

Wake comparison for all test sites at 2D.



Acknowledgments

The authors gratefully acknowledge funding through a U.S. Department of Energy SBIR phase 2 award (DE-FG02-09ER85576) and from the Marine Renewable Energy Center (MREC) at the University of Massachusetts-Dartmouth, John R. Miller, director. Thanks to FloDesign Wind Turbine Corporation for co-founding the MEHT program and to Mike Werle, Founder and Senior Technical Advisor, for providing technical guidance and oversight to the program. The UNH authors would like to thank FloDesign Inc. for entrusting UNH-CORE with the deployment of their hydrokinetic turbine. The loan of instruments by the National Renewable Energy Laboratory, Boulder, CO, for the deployments in 2012 was greatly appreciated, with special thanks to Eric Nelson and Rick Driscoll. Thanks to Paul Devine of Teledyne-RDI for the loan of a new Sentinel-V. Thanks to Jud DeCew, Nate Dufresne, Dave Shay, Toby Dewhurst, Ken Baldwin and Rob Swift at UNH and Dane

Mealey and Christian Gudmand at FloDesign Inc. for their help with the deployments.

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