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Towed Water Turbine Computational Fluid Dynamics Analysis

Robert G. Maughan

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TOWED WATER TURBINE

COMPUTATIONAL FLUID DYNAMICS

ANALYSIS

by

Robert G. Maughan

A report submitted in partial fulfillment
of the requirements for the degree
of
MASTER OF SCIENCE
in
Mechanical Engineering

Approved:

_________________________________________  _________________________________________
Dr. Robert Spall                             Dr. Leijun Li
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UTAH STATE UNIVERSITY
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2013
ABSTRACT

Towed Water Turbine Computational Fluid Dynamics Analysis

by

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Utah State University, 2013

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Department: Mechanical and Aerospace Engineering

Computational fluid dynamics can be used to predict operating conditions of towed water turbines which are used in long distance sailing applications to meet electrical demands. The design consists of a turbine fastened to a shaft which is attached to a generator by a rope. The turbine is pulled in water behind a sailboat and torque is transmitted through the rope to turn the onboard generator and produce power. Torque curves from an alternator, generator, and from computational fluid dynamics were used to determine the operating spin rate and output power of the system. On-water tests were conducted to determine the accuracy of the computation fluid dynamics approach. For the on-water tests the revolutions per minute, voltage, and current were measured in water behind a boat and in a 12 inch diameter pipe. Both scenarios were tested with a flow speed of 3 m/s. The results behind the boat were found using both an alternator and a generator while charging a 12 V and 88 AH battery. The values in the pipe were found while connected to heat dissipating dump load resistors. Scenarios of 3.46, 5.46, and 7.46 ohms of resistance were each analyzed while attached to the alternator and generator. The open-water power results consisted of 70 W for the alternator and 41 W for the generator. The results for the in-pipe turbine ranged from 66 to 245 W. Multiple approaches of efficiency of the turbine are considered as well as the efficiencies of an alternator and generator. (39 pages)
In long distance sailing applications, towed water turbines are a method to generate power to supply electricity to a variety of electronic devices on board. The design consists of a turbine fastened to a shaft which is attached to a generator by a rope. The turbine is pulled in water behind a sailboat and torque is transmitted through the rope to turn the onboard generator and produce power. By using computational fluid dynamics a turbine is analyzed and its spin rate and the amount of power that it can produce are predicted to within five percent of the actual values. On water tests are conducted behind a propelled boat and in a 12 inch diameter pipe to verify the validity of the method.
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INTRODUCTION

Sailboats have crossed oceans for decades. Modern sailboats use a variety of electrical equipment such as GPS, radar, and many other devices. A towed water turbine as seen in Figure 1 is one method to meet this electrical demand.

![Towed water turbine design.](image1)

Figure 1. Towed water turbine design.

When a turbine is pulled in water, torque on the shaft is produced and transferred through the rope to turn the generator. Predicting the spin rate of the turbine while attached to a generator or alternator can be difficult. The pitch of the turbine determines the free spinning rate. Figure 2 shows the spin rate in RPM for a variety of pitches when no external torque is applied. When the turbine is spinning a generator an external torque is applied and the free spinning rate can no longer be achieved.
Figure 2. Free spinning rates for variety of turbine pitches.

As the spin rate of the generator increases, the produced electrical power and the torque for the turbine to overcome also increase. To determine the actual spin rate of a turbine at a given flow speed two curves must be used. The first is a torque curve of the generator which most manufactures do not provide. However, manufactures generally do provide a power curve which includes voltage, current, and RPM data that can be used to create an electrical torque curve. If the efficiency of the generator is known, the desired mechanical torque curve can be created from the electrical torque curve. The second curve is created using a computational fluid dynamics method. It contains the torque produced by a turbine at a given flow speed and RPM. The intersection of the two curves is the operating point at which the turbine will spin and determines the amount of electrical power that will be produced. These results are compared to actual on-water experimental results to determine the accuracy of the CFD approach. Both an open-water and an in-pipe scenario are considered for this design.
Other methods exist for producing power onboard a sailboat. However, many of them introduce complications and are not simple solutions. Diesel generators are expensive and loud to operate and require space to store the fuel onboard. Solar panels are an alternative possibility but need a large area to produce sufficient power. Small wind turbines generally spin at a high rate and can present a hazard to those onboard. Because of this hazard they are limited to a small blade diameter and are not able to harness much power. The towed water design also harnesses its power from the wind, however, not directly like a wind turbine. The wind power in the sails is transferred to the boat and the relative velocity of the boat to the water allows for the towed water turbine to produce power. Because of this a much larger area in the sails can be used to capture wind power as opposed to a small diameter wind turbine. Water turbines could also be implemented by rigidly connecting to the back of the sailboat. However, this requires a number of components to mount the turbine and some sort of gearing to transfer the power out of the water to a generator in the boat.

The design of the turbine depends on the electrical demand on the sailboat. Some typical sailboat components and their electrical loads are seen in Table 1 [6].
<table>
<thead>
<tr>
<th>Equipment</th>
<th>Avg amps</th>
<th>hrs/day</th>
<th>amp-hr/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabin Lights</td>
<td>3</td>
<td>4</td>
<td>12</td>
</tr>
<tr>
<td>Running Lights</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Standard Anchor Light</td>
<td>1</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>VHF Receiver/Transmit</td>
<td>0.5</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>GPS</td>
<td>0.5</td>
<td>3</td>
<td>1.5</td>
</tr>
<tr>
<td>Instruments</td>
<td>0.5</td>
<td>3</td>
<td>1.5</td>
</tr>
<tr>
<td>Stereo/Tape Deck</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Bilge Pump</td>
<td>4</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>Marine Refrigeration</td>
<td>5</td>
<td>12</td>
<td>60</td>
</tr>
<tr>
<td>Autopilot</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>TV/VCR</td>
<td>6</td>
<td>0.5</td>
<td>3</td>
</tr>
<tr>
<td>Laptop Computer</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Microwave Oven</td>
<td>80</td>
<td>0.017</td>
<td>13.6</td>
</tr>
</tbody>
</table>

| Total average daily load of 120 amp hours |

Table 1. Typical electrical usage on a sailboat.

The total electrical consumption is about 120 amp hours per day on an average long distance cruising sailboat. If the turbine were in the water and operating 24 hours per day, it would require 5 amps of current to be continually produced by the generator.
NUMERICAL METHOD

The Reynolds-averaged Navier Stokes equations were solved using the general purpose computational fluid dynamics code STAR-CCM+ [1]. A two layer $\kappa$-$\varepsilon$ model was applied for turbulence closure. All transport equations were integrated to the wall, consequently no wall functions were used. Second-order upwinding was used for the convective terms for all transport equations. Pressure-velocity coupling was accomplished using the SIMPLE algorithm. All residuals for all equations were driven below $1 \times 10^{-4}$ during the iterative process.

The rotation of the turbine blades was first accounted for using a steady rotating reference frame model. An inner rotating region and an outer stationary region were defined as seen in Figure 3 and Figure 4. In the outer region the equations of motion were solved using stationary equations. In the inner region the equations of motion were solved using a rotating reference frame including coriolis and centripetal acceleration terms. A local reference frame transformation is performed at the interface of the two regions so that flow variables in one region may be used to calculate necessary fluxes at the boundary of the other region. The residuals for this rotating reference frame method could not be driven below $10^{-2}$. Instead, an unsteady method where the coriolis and centripetal terms are dropped was used. In this method, the inner region and the turbine blades are rotated. A time step of 0.002 seconds was used with 20 inner iterations per time step to assure convergence within a time step. A total physical time of 0.8 seconds was used.
Figure 3. Open-water turbine model regions including inner and outer regions.

Figure 4. In-pipe water turbine model regions including inner and outer regions.
GEOMETRY, BOUNDARY CONDITIONS, AND MESH

A 4 blade, 9 inch diameter, 5 inch pitch turbine was analyzed using the unsteady rotating reference frame approach. The turbine hub is 3 inches long and 1.81 inches in diameter. The turbine was designed using the marine turbine design software package PropCad [4].

The geometry in which computations were calculated is seen in Figure 3 and Figure 4. For the open-water setup the outer region is 1.75 m long and has a diameter of 1.0 m. A slip condition was implemented on this outer wall. The outlet is specified with a zero gradient condition. The inner region is centered 0.5 m from the inlet. It has a length of 0.2 m and has a diameter of 0.3 m. The turbine is centered on this inner region and its walls were given a no slip condition. An interface region was used where the inner and outer regions meet. For the in-pipe setup the outer cylinder is specified with a no-slip condition and is 0.3048 m (12 in) in diameter and 1.75 m long. The turbine is placed 0.5 m from the front edge. The outlet was specified as a pressure outlet condition. The inner cylinder is 0.26 m in diameter and has a length of 0.2 m. For both setups the inlet is specified with a uniform velocity of 3 m/s (5.83 knots). The Reynolds number corresponding with the in-pipe scenario is 6.0E8.

For an individual simulation the flow speed of 3 m/s and a given RPM are analyzed. The torque produced by the turbine at these conditions is calculated. The axial force or drag is also determined during the same simulation. Spin rates from 0 to 1100 RPM for the open-water and 0 to 1300 RPM for the in-pipe scenario were analyzed. With a 9 inch turbine these numbers correlate to tip speed ratios (TSR) of 0.0 to 4.4 for the open-water and 0.0 to 5.2 for the in-pipe scenario.

The mesh in Figure 5 for the open-water analysis contains a total of 1,425,574 polyhedral cells. The inner rotating region contains 758,956 cells while the outer stationary region contains 666,618 cells. A representative surface mesh on the turbine surface can be seen in Figure 7. The
mesh near the wall of the turbine consisted of 16 prism layers with an overall thickness of 0.005 m. The mesh for the in-pipe analysis in Figure 6 consisted of a total of 1,811,985 cells. The inner rotating region contains 1,369,686 cells while the outer stationary region contains 442,299 cells.

Figure 5. Open-water turbine mesh containing 1,425,574 cells.

Figure 6. In-pipe turbine mesh containing 1,811,985 cells.

Figure 7. Representative mesh on turbine surface.
TESTING

A 3-D printer was used to make the prototype for the on-water testing. The turbine was designed using the software package PropCad [4]. The output file from PropCad is not in a format that can be used by the CFD software or the 3-D printer. SolidWorks [5] was used to patch the files and convert them to a workable format. Commercial versions [9] of the simple towed water design are available, however, the turbine for this study was created from a file in which could be loaded into the CFD software.

The first tests were conducted with a WindZilla [7] generator and alternator while charging a 12 V and 88 AH battery. They were mounted to the back of a propelled boat as seen in Figure 8. A rotating mount was used to ensure there was no angle between the rope and the shaft of the alternator or generator. A 3-phase rectifier was used with the alternator to convert the alternating current to direct current power for charging the battery. A blocking diode was used in connection with the generator to ensure no power would flow from the battery to the generator. A 30 foot double braided torque rope was used to attach the turbine and shaft to the alternator or generator. The double braid in the rope keeps it from twisting up or unraveling. The 30 feet of rope ensures that the turbine will remain under water. If a short rope is used the turbine will jump out of the water and tangle the rope. The on-water tests consisted of recording the revolutions per minute, voltage, and the current at a flow speed of 3 m/s in open water behind the boat. A handheld GPS device was used to obtain the desired boat speed.
The first on-water tests were conducted during the fall on a small reservoir. Because the second sets of tests were performed during the winter, the reservoir was frozen. These tests were instead conducted at the Utah Water Research Laboratory which is part of Utah State University. The facility is located just below a reservoir on the Logan River. The tests were performed in a 12 inch diameter pipe as seen in Figure 9 with a controlled flow of 3 m/s. An elbow with a welded flange centered on the straight pipe allowed for a twelve foot shaft to connect the turbine and the alternator or generator. The turbine was placed 8 feet from the end of the elbow to allow for the water velocity profile to become nearly fully developed. The centered bearing in the right picture of Figure 11 ensured the turbine remained in the middle of the pipe. The drag on the turbine also contributed to keeping the turbine centered and the shaft straight. The plastic bearing in the left picture of Figure 11 was designed with loose fittings to allow for some water in the pipe to leak through. This created a thin film of water to decrease friction and provide cooling to keep the plastic from melting while spinning at high speeds. The water used in the pipe was pulled from
the Logan River and was approximately 38 degrees Fahrenheit. The RPM was measured with a non-contact tachometer. Two digital multimeters were used to read the current and voltage to determine the power. All these measured values for the experiment were found while connected to dump load resistors which dissipate the generated power in the form of heat. Total resistance values of 3.46, 5.46, and 7.46 ohms each were used. The two large resistors in Figure 9 are each 0.73 ohm and can dissipate 300 W. The smaller resistors are each 1 ohm and can also dissipate 300 W per resistor.

![Figure 9. In-pipe turbine setup with 12 inch diameter pipe.](image9.jpg)

![Figure 10. Pipe being lifted by crane on left and water filled pipe with turbine on right.](image10.jpg)
The corresponding generator and alternator tests for the open-water scenario consisted of developing a mechanical torque curve while connected to the 12 V and 88 AH battery. In order to spin the shaft at a given RPM the torque required will be different for both the alternator and the generator. The electrical power curves provided by the manufacturer [7] are seen in Figure 12. For comparison to CFD, mechanical power must be considered and not electrical power as is provided in the manufacturer’s power curve. There is a loss that ensues when the generator or alternator converts mechanical shaft power to electrical power. To determine the efficiency and develop a mechanical torque curve, tests were conducted using a drill and a rotary torque sensor as seen in Figure 13. The wiring and setup procedure for the rotary torque sensor is found in the APPENDIX. The sensor determines the torque that is created between the generator or alternator and the drill. By taking this number and multiplying it by the revolutions per minute and by \((2\pi/60)\) the mechanical power in watts is determined. The electrical power is divided by the mechanical power to find the efficiency. This can be repeated for the desired RPM range to reproduce the manufacturer’s power curve for this case and to create a mechanical torque and power curve to be compared to the CFD results.
As previously stated, the first alternator and generator tests were conducted while charging the 12 V and 88 AH battery. After the tests, an attempt was made to ensure their accuracy. At the same revolutions per minute, the power outputs were not always consistent. It was concluded that the resistance across the battery was changing depending on how charged it was. When the battery is discharged the resistance is significantly less than when the battery is fully charged. For a more controlled experiment dump load resistors as seen in Figure 14 were

Figure 12. WindZilla generator power curve on the left and alternator power curve on the right while charging a 12 V and 88 AH battery.

Figure 13. Alternator efficiency test using a rotary torque sensor.
used to dissipate the power as heat instead of charging the batteries. This ensured the resistance for the generator or alternator to overcome did not vary. The mechanical torque curves were again created for the alternator and generator with dump load resistance values of 3.46, 5.46 and 7.46 ohms.

Figure 14. Dump load resistors.
RESULTS

To predict the operating spin rate of the turbine at a given flow speed, two curves must be used. The first is a torque curve from the generator and alternator. This torque curve cannot be determined from the manufacturer’s power curve alone. It is possible to take the power provided by the manufacturer and divide by the corresponding RPM and by \( \frac{2\pi}{60} \) which would give units of N*m. To obtain the mechanical torque on the turbine, the efficiency of the generator or alternator must be included. By spinning the alternator or generator with the torque sensor in line as shown in Figure 13, the torque curves in Figure 15 are produced while charging a 12 V and 88 AH battery. If the manufacturer could provide an efficiency of their alternator or generator for the same resistance the torque sensor would not be necessary.

![Figure 15. Alternator and generator torque curve while charging 12 V and 88 AH battery.](image)

The second curve required in determining the spin rate and output power is the torque curve from the CFD analysis. This curve is produced by providing the CFD software with a range
of spin rates with the rest of the parameters remaining the same. The output from the CFD will be the torque produced by the turbine at the given RPM. Plots of the fluid velocity can be seen in Figure 16 and Figure 17. The CFD torque curve can be placed on top of the generator and alternator torque curves as seen in Figure 18. The intersection between the curves is the operating point of the turbine and found using the curve fits in Equation 1 through Equation 3.

Figure 16. Velocity vector plot along centerline of open-water turbine at 800 RPM.
Figure 17. Velocity scalar plot along centerline of open-water turbine at 800 RPM.

Figure 18. Alternator, generator, and CFD torque curves while charging a 12 V and 88 AH battery.
\[ y = 0.01131328x - 3.36378861 \quad \text{(Alternator)} \]  

\[ y = 0.00202810x - 0.97877864 \quad \text{(Generator)} \]  

\[ y = -0.00000140x^2 - 0.00250586x + 4.95304227 \quad \text{(CFD)} \]

Once the spin rate is known a power curve of the generator and alternator can be used to determine the predicted electrical power produced. This curve as seen in Figure 19 was produced by spinning the alternator and generator with a drill and measuring the RPM and the electrical power output.

![Figure 19. Alternator and generator electrical power curves when charging a 12 V and 88 AH battery.](image)

A summary of the predicted and actual values is found in Table 2. Notice that the predictions are somewhat close but are a little low. When analyzing the results it was noticed that when spinning the generator and alternator with a drill as opposed to the turbine at the same RPM
values, the power did not always match. It was concluded that this was due to the resistance of the battery which changes depending on whether the battery is fully charged or not. When the tests were conducted the charge level of the battery or its resistance were not measured. The discrepancy in the results could partly be due to this resistance change. Another factor that could affect the results is losses due to the 30 foot rope. Especially at higher RPM’s, the rope sometimes tends to form small knots which increases the loss of torque.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>CFD-Predicted RPM</th>
<th>Actual RPM</th>
<th>RPM Error %</th>
<th>CFD-Predicted Power(W)</th>
<th>Actual Power(W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternator</td>
<td>569</td>
<td>540</td>
<td>5.4</td>
<td>110</td>
<td>70</td>
</tr>
<tr>
<td>Generator</td>
<td>1000</td>
<td>880</td>
<td>13.6</td>
<td>55</td>
<td>41</td>
</tr>
</tbody>
</table>

Table 2. Open-water turbine results.

The power goal to meet the electrical demand for the example sailboat in Table 1 was to produce 5 amps of current continuously for 24 hours. While using the alternator the turbine produced 70 W of power at a boat speed of 3 m/s. The voltage for this condition was 15.5 V and the current was 4.5 amps. If this boat speed were maintained, this turbine could produce 90 percent of the electrical demand. It is important to remember that these values could change depending on the charge status of the battery. The turbine is able to produce more power on a fully discharged battery than it is on a charged battery.

To further determine the accuracy of this CFD method, it is necessary for the resistance to remain constant when creating the torque curve for the generator or alternator and when performing the actual on-water tests. To accomplish this, dump load resistors were used as opposed to charging a battery as seen in Figure 14. The discovery of this problem came during the winter when the reservoir for the first test was frozen. Because of this the next tests were conducted in a 12 inch diameter pipe at the Utah Water Research Laboratory as was discussed
earlier. The same torque curves that were produced while charging the battery were reproduced while connected to the dump load resistors. For both the alternator and generator, 3 different values of resistance were tested. The torque curves for the alternator and generator in this configuration are in Figure 20.

![Torque Curve Graph](image)

**Figure 20.** Alternator and generator torque curve while connected to dump load resistors.

Because the flow in the pipe is not able to bypass the turbine like it can in the open-water flow the CFD analysis changes. The CFD analysis was redone with a 12 inch pipe with a no slip condition as the outer boundary. Plots of the fluid velocity in the pipe at a turbine spin rate of 800 RPM can be seen in Figure 21 and Figure 22. The generator and alternator torque curves with the overlapping CFD torque curve is seen in Figure 23. The intersection between the curves is the
operating point of the turbine and found using the curve fits in Equation 4 through Equation 10. The electrical power as a function of RPM is found in Figure 24.

Figure 21. Velocity vector plot along centerline of in-pipe water turbine at 800 RPM.

Figure 22. Velocity scalar plot along centerline of in-pipe water turbine at 800 RPM.
Figure 23. Alternator, generator, and CFD torque curves while connected to dump load resistors.

\[ y = 0.00325341x + 0.16975160 \text{ (Alternator-3.46 ohms) } \] (4)

\[ y = 0.00243791x + 0.08186650 \text{ (Alternator-5.46 ohms) } \] (5)

\[ y = 0.00189970x + 0.08783500 \text{ (Alternator-7.46 ohms) } \] (6)

\[ y = 0.00094569x + 0.18241437 \text{ (Generator-3.46 ohms) } \] (7)

\[ y = 0.00074473x + 0.11131915 \text{ (Generator-5.46 ohms) } \] (8)

\[ y = 0.00060927x + 0.10051489 \text{ (Generator-7.46 ohms) } \] (9)

\[ y = 0.00000132x^2 + 0.01355420x + 15.73276573 \text{ (CFD) } \] (10)
As seen in Table 3 the CFD method was able to predict the spin-rate within 2.9 to 4.8 percent of the experimental results. It is expected that the actual spin rate is less than the predicted spin-rate. This is due to the friction losses that occur in the bearing holding the turbine in the pipe and the friction on the turbine shaft. The water that was allowed to leak through the bearing helped keep the bearing cool and also provided a thin film for lubrication to reduce friction to decrease this loss.
Table 3. In-pipe water turbine results.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>CFD-Predicted RPM</th>
<th>Actual RPM</th>
<th>RPM Error %</th>
<th>CFD-Predicted Power(W)</th>
<th>Actual Power(W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternator-3.46 ohms</td>
<td>1005</td>
<td>980</td>
<td>2.6</td>
<td>263</td>
<td>245</td>
</tr>
<tr>
<td>Alternator-5.46 ohms</td>
<td>1074</td>
<td>1040</td>
<td>3.3</td>
<td>230</td>
<td>214</td>
</tr>
<tr>
<td>Alternator-7.46 ohms</td>
<td>1119</td>
<td>1080</td>
<td>3.6</td>
<td>220</td>
<td>190</td>
</tr>
<tr>
<td>Generator-3.46 ohms</td>
<td>1205</td>
<td>1150</td>
<td>4.8</td>
<td>90</td>
<td>82</td>
</tr>
<tr>
<td>Generator-5.46 ohms</td>
<td>1233</td>
<td>1190</td>
<td>3.6</td>
<td>78</td>
<td>74</td>
</tr>
<tr>
<td>Generator-7.46 ohms</td>
<td>1249</td>
<td>1200</td>
<td>4.1</td>
<td>69</td>
<td>66</td>
</tr>
</tbody>
</table>

When using the turbine in sailing applications the efficiency of the turbine can be viewed in a couple of ways. The first is comparing the power out to how much power goes in. The power consumed is the penalty for obtaining the output power and is manifested in drag. A plot of the drag as a function of RPM in the open-water and in the pipe can be seen in Figure 25. In an in-pipe situation the drag may not be an important factor to consider, except for the wear that it may cause on the bearing holding the turbine in place. The power lost due to the drag can be determined using Equation 11.

\[
\text{Power Lost to Drag} = \text{Drag} \times \text{Velocity}
\]  

(11)

What comes out of the turbine is the mechanical power transferred to the shaft which is seen in Figure 26. It is important to remember that this is the mechanical power and has not yet been converted to electrical with a conversion loss. The efficiency as a function of RPM in Figure 27 is then the mechanical power out divided by the power lost due to drag. The drag created by the turbine may not significantly affect the overall speed of the sailboat. This is due to the physics of how the sailboat works. A sailboat is able to achieve a maximum speed based on the water-line length of the boat. Once the sailboat reaches maximum speed, called the hull displacement speed, it cannot overcome and pass the wave that it creates. If the wind exceeds the speed to reach the hull displacement speed, any extra wind speed is lost to wave resistance. A towed turbine can take advantage of the excess of wind power instead of being lost to wave resistance. In the article
“Towed Water Generator” [8], for a turbine that produced 3.1 amps, the change in boat speed for use of their turbine was approximately 0.1 knots.

Another measure of efficiency to consider is the power coefficient found in Figure 28. The power coefficient is the ratio of how much power the turbine is able to pull out of the water verses the total power that is available. The total power available in a column of water is found by using Equation 12, where $\rho$ is the density of water, $V$ is the velocity of the fluid, and $A$ is the swept area covered by the turbine blades and hub. This type of efficiency is important due to the limited space available on a sailboat. The higher the power coefficient the smaller the turbine diameter can be for storage when not in use. There is a large power difference between the pipe and the open-water setups even though the same turbine is used. In the open-water scenario, the water is able to travel around the blades. In the pipe scenario, the flow is forced through the blades by the wall. Another important factor of the power coefficient curves is the optimum operating condition. For both scenarios, the maximum power coefficient occurs between 600 and 700 RPM. When choosing a generator or alternator, selecting one with a torque curve that crosses the CFD torque curve in the 600-700 RPM range would provide the optimum amount of power. If a generator or alternator is already selected, a turbine could be designed with its maximum power coefficient to be in the range where the two curves cross.

$$Available \ Power = \frac{1}{2} \rho V^3 A$$  

(12)
Figure 25. Drag as a function of RPM.

Figure 26. Mechanical power as a function of RPM.
Figure 27. Drag efficiency as a function of RPM.

Figure 28. Power coefficient as a function of RPM.
The overall effectiveness of the system can be evaluated by looking at how much electrical power is produced compared to the power available in a 9 inch column of fluid. This parameter is evaluated at each operating condition and found in Table 4. These numbers include losses in converting power from the water to the shaft and then losses in the alternator or generator.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Actual Electrical Power (W)</th>
<th>Available Power (W)</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alternator-Battery</td>
<td>70</td>
<td>554</td>
<td>0.13</td>
</tr>
<tr>
<td>Generator-Battery</td>
<td>41</td>
<td>554</td>
<td>0.07</td>
</tr>
<tr>
<td>In Pipe</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alternator-3.46 ohms</td>
<td>245</td>
<td>554</td>
<td>0.44</td>
</tr>
<tr>
<td>Alternator-5.46 ohms</td>
<td>214</td>
<td>554</td>
<td>0.39</td>
</tr>
<tr>
<td>Alternator-7.46 ohms</td>
<td>190</td>
<td>554</td>
<td>0.34</td>
</tr>
<tr>
<td>Generator-3.46 ohms</td>
<td>82</td>
<td>554</td>
<td>0.15</td>
</tr>
<tr>
<td>Generator-5.46 ohms</td>
<td>74</td>
<td>554</td>
<td>0.13</td>
</tr>
<tr>
<td>Generator-7.46 ohms</td>
<td>66</td>
<td>554</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Table 4. Total available power to electrical power efficiency.

Mesh convergence tests were performed to increase the validity of the CFD results. Three different mesh densities were used to find the torque in the appropriate RPM range as seen in Figure 29 and Figure 30. Notice for the open-water turbine the fine and regular meshes mostly lie on top of one another, especially in the regions of interest. For the in-pipe turbine the regular and fine meshes lie perfectly on top of one another except for below 200 RPM. Below 200 RPM the turbine is spinning slowly and flow separation occurs from the turbine blades as seen in Figure 31. For comparison, the in-pipe turbine at 800 RPM is shown in Figure 32 where the flow remains attached to the turbine blades. These results are considered acceptable, as the inconsistency below 200 RPM is not in the region of interest for the problem. In order for the results to converge below 200 RPM, an even more refined mesh would be required.
Figure 29. Mesh convergence results for open-water turbine.

Figure 30. Mesh convergence results for in-pipe turbine.
Figure 31. In-pipe flow separation from turbine blade at 100 RPM.

Figure 32. In-pipe attached flow from turbine blade at 800 RPM.
To further ensure the accuracy of the results, Figure 33 and Figure 34 contain plots of the wall $y+$ values for the open-water and pipe turbine at 800 RPM. The majority of the values on the blades are near one. This distribution was considered acceptable.

Figure 33. Wall $y+$ values for open-water turbine at 800RPM.

Figure 34. Wall $y+$ values for in-pipe water turbine at 800RPM.
To determine the possibility of cavitation the absolute pressure was plotted on the downstream side of the turbine blades as seen in Figure 35 and Figure 36. Notice the lowest pressures are far above the water vapor pressures for reasonable water temperatures.

Figure 35. Absolute pressure on downstream side of blades for open-water turbine at 800RPM.

Figure 36. Absolute pressure on downstream side of blades for the in-pipe water turbine at 800RPM.
For the generator or alternator, the manufacturer will generally provide a power curve as stated previously. However, the curve only provides the electrical power the device can produce. It does not provide anything about the efficiency in converting from mechanical to electrical power. For comparison to CFD results, it is important to use the mechanical torque required to spin the turbine and not the torque derived from the electrical power output. Many sources indicate that an alternator or generator have a flat line efficiency. However, this may not always be the case. While connected to the battery, the efficiency of the WindZilla alternator and generator are a function of RPM as seen in Figure 37. Once the alternator and generator exceed their startup power they decline as the RPM increases. This is likely due to the difficulty in pushing more and more power into the battery. For the second set of tests while connected to the resistors the alternator efficiency slightly increases with RPM while the generator remains mostly flat as seen in Figure 38. In this case the resistance is constant and not a function of RPM.

Figure 37. Efficiency of the WindZilla alternator and generator while charging a 12 V and 88 AH battery.
Figure 38. Efficiency of the WindZilla alternator and generator while connected to dump load resistors.
SUMMARY

This paper showed how computational fluid dynamics can be used to predict operating conditions of towed water turbines which are used in long distance sailing applications to meet electrical demands. Tests were conducted in both open-water and in-pipe conditions. The open-water power results consisted of 70 W for the alternator and 41 W for the generator. The results for the in-pipe turbine ranged from 66 to 245 W. The open-water results were obtained while charging a 12 V and 88 AH battery. Although the conditions of the battery charge were unknown during open-water testing, the results obtained do represent a condition of charging a 12 V and 88 AH battery. It is important to remember that these values can change somewhat depending on the charge level of the battery. The resistance for the in-pipe testing was controlled using dump load resistors. Scenarios of 3.46, 5.46, and 7.46 ohms were each analyzed. The results indicated that the CFD method was able to predict the experimental spin rate to within 2.9 to 4.8 percent. This error is likely due to the friction that occurred on the bearing and the shaft holding the turbine in the pipe. The efficiency of the turbine was analyzed with respect to how much drag was produced and to how much power was available. The efficiency of the generator and alternator were determined while connected to a battery and to dump load resistors.
REFERENCES


[4] HydroComp, Inc., 13 Jenkins Court, Durham, NH

[5] SolidWorks Corporation, Waltham, Massachusetts


APPENDIX

The rotary torque sensor is capable of determining both the torque and the spin rate on its shaft. The DP41-B meter from Omega is capable of displaying the torque but cannot display the spin rate. Omega does not have a meter that can read out the spin rate at the range of RPM values for this experiment which is why a digital tachometer was used. A ten cable wire was not available and so a ten and an eight wire cable were used. The color codes for the wires are in Figure 39. The positions for the torque wires are in Figure 40. This device is set up for DC power. The locations for the power wires are in Figure 41.

Figure 39. Color codes for rotary torque sensor cable.

Figure 40. DP41-B meter wire diagram
The following instructions are for programming the DP41-B meter to read out torque. The device was set up to read out in N*m but could be programmed to read out other units.

**DP41-B BRIDGE SETUP AND SCALING WITH UNKNOWN LOADS**

I) SET JUMPERS

A) Bridge Input with Internal Excitation

   S1: L

   S2: A, B, H, G

II) SCALING WITHOUT KNOWN INPUTS

A) Press “MENU” to “INPUT” then press “RESET” and use “MAX” to select “BRIDGE”

B) Press “RESET” twice to store and go to “RDG.CNF” then press “RESET” to “RD.SC.OF”

C) “RD.SC.OF” press “RESET” then press “MAX” to select “ENABLE”

D) Press “RESET” then use “MAX” to select “DIRECT” “RESET” twice to store and go to “RDG SC”

E) Calculate “RDG SC” value using the formula:

   “RDG SC” = display range / (sensor mV/V*10000)
EX: 0-1000 microstrain = 1.3 mV/V full scale output

“RDG SC” = 1000 / (1.3*10000) = 0.07692

F) Press “RESET” then enter the “RDG SC” value calculated above. Use the “MAX” to change the blinking digit and “MIN” to move to the next digit. When correct value is entered press “RESET” to store. Display change to “RDG OF”

G) Press “RESET” and enter “000000” the press “RESET” to store and advance to “DEC PT”

H) Press “RESET” to “DP.ACTV” then press “RESET” and use “MAX” to select “YES”.

I) Press “RESET” to store and advance to “SET DP” then press “RESET” and use “MAX” to select desired decimal point “RESET” to store and advance to “FILTER”

J) Press “MENU” until “INP.CNF” is displayed

K) Press “RESET” then “MENU” until “MODE” is displayed

L) Press “RESET” then “MENU” until “RATIO” is displayed

M) Press “RESET” the “MAX” to select “ENABLE” then press “RESET” to store and advance to “IN.SC.OF” then press “MIN” until “RUN” appears. Unit will then return to the RUN mode and begin reading.

N) At this point the meter should be reading in engineering units but may have an offset. To correct the offset apply zero load to the transducer and note the display reading. In order to correct the offset you must enter the opposite of this value in the “RDG.OF”. For example if the reading is 151 you must enter -151.

O) To enter the offset press “MENU” until “RDG.CNF” is displayed then press “RESET” until “RDG OF” is displayed. Press “RESET” and enter the desired value using the “MIN” and “MAX” buttons. Press “RESET” to store and then press “MIN” until “RUN” is displayed to return to RUN mode.