Design Maximization of Tidal Basin Power Generators

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I. INTRODUCTION

In a world where the demand for energy is increasing exponentially and conventional energy supplies are declining rapidly, the buzz words in energy engineering have changed from "oil, gas and combustion" to "renewable, alternative and green". The idea for low carbon energy sources certainly isn't novel, but the pertinence of these technologies is growing. In recent years, trends have shown that the largest consumption of fossil fuels is not the transportation industry, but rather electrical power generation. Given this motif, the world has accepted a new view of generating power, by looking to renewable resources, such as the sun, wind, water, geothermal energy, and the changing tides.

Alaska, being unique in its environment, has given careful thought to many of these options. The sunlight is not intense enough to use solar power on a large scale. The wind is not always blowing. Hydropower is already used to its utmost capacity. There are very few places where geothermal energy is plausible. The only renewable resource left, tidal power, until very recently, has been widely overlooked.

Tides are caused by the force of gravitational attraction between the Earth, moon and sun. Because the moon is closest to the Earth, it has the greatest affect. During the Earth's rotational cycle, the points closest and farthest from the moon bulge outward causing a flood tide, while on opposite sides of the Earth, ebb tides are created[1]. Dr. Alexander Gorlov insists that tidal energy is one of the best candidates for the approaching energy revolution. This idea is praised by Dr. Stuart Anderson who dramatically stated the importance of tidal power, "wind power is so far ahead of other developments that everything else is out of sight, but this complements wind power, and we need to bring it on. To turn our back on the sea would be a tragedy"[2].

There are three sources of energy hidden in the ocean. They are potential energy, kinetic energy, and thermal energy. There are different systems to capture each of these energies. Potential energy in the ocean comes from the changing height of the tides. This can be converted to electrical power by creating a barrage or dam to get the maximum potential energy difference, then running the water through a turbine[3]. The kinetic energy of the ocean comes from the physical movement of the waves. The kinetic energy systems often resemble underwater wind turbines. They are referred to as "marine current" or "tidal current" turbines[4]. The thermal energy of the ocean comes from the temperature-saline gradient. It can be turned into useful heating or electrical energy by use of a heat exchanger[5].

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Alaska has the resource. The Cook Inlet, near Anchorage, Alaska, experiences one of the largest tidal differences in the world, but lacks the infrastructure to harness such power. The goal of this project is to design and build a tidal basin model, then to determine the efficiency of the model based on the actual and theoretical power outputs. From the efficiency of the base model, the design parameters could be varied to determine the best configuration for design maximization.

II. CONSTRUCTION OF A PHYSICAL MODEL

The determination of the actual efficiency of a tidal basin power generator required the construction of a physical model. This further provided the basis for understanding how the fluid would behave throughout the process of draining through the turbine. The model was built in two steps, first the tank was retrofitted for pipe insert, and second the turbine leg was constructed.

The model was built from a 30-gallon HDPE chemical storage tank as the basin. Three inches from the bottom of the tank a two-inch diameter hole was cut using a hole saw. A rubber gasket was inserted on the inside and outside of tank to act as a tank adapter. This provided a water proof connection to the turbine leg.

Four inches of two-inch diameter PVC pipe was inserted and glued into the gasket. This is the base of the turbine leg. Next, a two-inch diameter PVC ball valve was attached to the pipe, and another leg of two-inch diameter PVC was attached to the outlet of the ball valve. The turbine leg was now ready for the turbine to be attached.

The turbine used in the model was a DC fan motor, like one used to cool the insides of a computer. When a DC motor is forced by mechanical means of energy to spin, it then becomes a generator. The leads for the motor can be attached to a voltmeter to measure the amount of electricity being generated by the moving water. The DC far motor was glued to the end of the turbine leg, making the entire leg 12 inches long. The complete model is shown in figure 1.

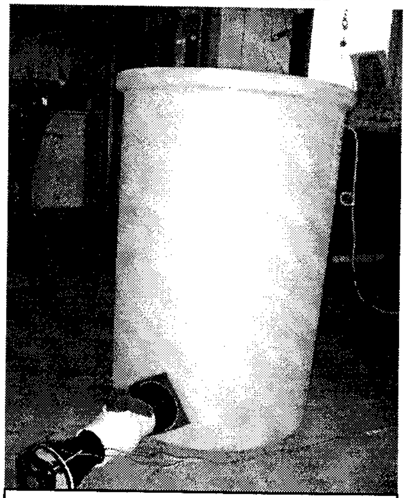

Figure 1. Basin Model

To quantify the power generated by the tidal basin model, a circuit was completed to include the leads of the motor. A data logger was connected to a lap top computer; the logger was wired in series to the motor which was connected to a multi-meter. The data collection sequence allowed for continuous data collection of current and voltage.

III. CONSTRUCTION OF A THEORETICAL MODEL

Some key assumptions are made in this model, in order to make it valid. It is assumed that the flow of water is steady and incompressible. The temperature is constant. The viscosity of the water is constant. Frictional losses are not negligible. Fluid in the transitional region is split in two, half of it behaves like laminar flow, and half of it behaves like turbulent flow.

The conservation of energy and the conservation of mass are two of the most fundamental relationships known to the world of physical science. The conservation of energy in fluid mechanics is known as the Bernoulli equation[6]. The starting point for the derivation of the theoretical model begins with the Bernoulli equation, equation 1.

$$\frac{P_1}{\rho g}+\frac{v_1^2}{2g}+z_1+h_p=\frac{P_2}{\rho g}+\frac{v_2^2}{2g}+z_2+h_L+h_t \qquad (1)$$

Some terms in the equation can be immediately discarded based on the definition of the control volume. *P* is pressure, *v* is velocity, ρ is density, *g* is the acceleration of gravity, *z* is the relative height, h_p is the head of pump, h_l is the head loss, and h_t is the head of the turbine. The pressure at the inlet and the outlet of the control volume are both equal to atmosphere pressure, and are both therefore zero. There is no pump, so the head of pump term can be eliminated. The height at the outlet is zero according to the selected datum, so z_2 can be deleted. The resulting equation is somewhat simpler, but it is evident that the conservation of mass is needed.

The conservation of mass, shown in equation 2, says that the mass into a system is equal to the mass out of the system. Since the density is assumed constant, the equation yields a simple ratio between the velocity at the inlet and the velocity at the outlet, based on the cross-sectional areas, *A*, of the two. The combination of the two equations gives equation 3. In this equation, there are three unknowns. This implies that further simplification is required.

$$m_{in}=m_{out}+m_{acc}\longrightarrow \rho_1A_1V_1=\rho_2A_2V_2\longrightarrow V_1=\frac{A_2}{A_1}V_2 \qquad (2)$$

$$Z_1+\frac{V_2^2}{2g}\left(\frac{A_2^2}{A_1^2}-1-h_L\right)=h_t \qquad (3)$$

The head loss term is dependent on the Reynolds number, a dimensionless number that helps define fluid flow behavior. The Reynolds number, equation 4, is dependent on density ρ, velocity *v*, diameter *D*, and viscosity μ[6]. If the Reynolds number, *Re*, is below 2300, then the flow is laminar. If the Reynolds number is above 4000, then the flow is turbulent. Head loss, in equations 5 and 6, depends on whether the flow is laminar or turbulent. If the flow is turbulent, then equation 5 should be used. If the flow is laminar, than equation 6 should be used. In these equations, *f* is the friction factor, *L* is the length, and K_L is the minor loss[6].

$$\mathrm{Re} = \frac{\rho V D}{\mu} \tag{4}$$

$$h_L = \frac{V_2^2}{2g}\left[f\frac{L}{D} + \sum K_L\right] \tag{5}$$

$$h_L = f\frac{L}{D}\frac{V_{avg}^2}{2g} \tag{6}$$

The friction factor can be determined by a number of equations, the most widely used of which is the Coleman-Colebrook equation[6]. Equation 7 is an estimation of the implicit Coleman-Colebrook equation. If the flow is laminar, then a simpler version can be used, equation 8. The roughness coefficient, ε, is a material dependent number.

$$f = \left[-1.8\log\left(\frac{\varepsilon / D}{3.7}^{1.11} + \frac{6.9}{\mathrm{Re}}\right)\right]^{-2} \tag{7}$$

$$f = \frac{64}{\mathrm{Re}} \tag{8}$$

The last key equation in this model is the determination of power. Power can be found by applying equation 9[6].

$$Power = h_l m g \tag{9}$$

After combining the equations, there are still too many unknowns. A relationship had to be determined relating the height and the velocity of the water. This function is not linear; the velocity of the water is constantly changing due to its phase flow. The best way to determine the relationship between height of the water, Z, and velocity, v, is experimentally.

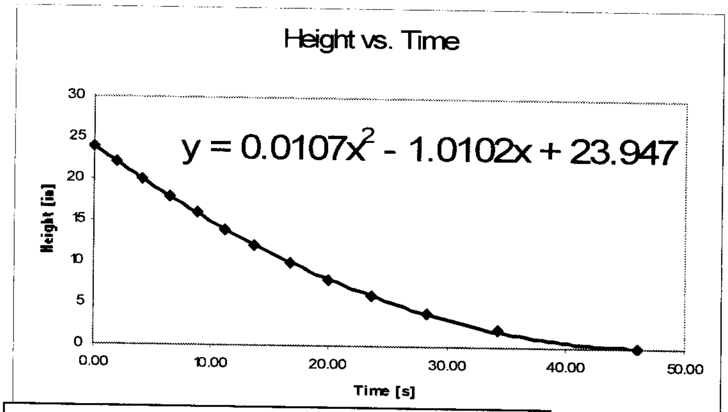

Figure 2. Height-Time Relationship

The tank was graduated every two inches by permanent marker. The tank was then filled with water, as it would be for power testing. The gate was opened, and the water flowed freely through the turbine. Every time the water reached a graduated mark, the stop button on the split timer was pressed. This kept a fairly accurate log of the height of water versus time. The experiment was run multiple times to decrease the factor of human error.

The experiment gave the equation shown in figure 2. This equation was differentiated with respect to x, time, to give the equation 10. Equation 10 was set equal to equation 11, and solved for velocity, v, in equation 12[6]. With this final equation, the theoretical power output of the turbine could be easily determine at any time, t.

$$\frac{dz}{dt} = 0.0214t - 1.012 \tag{10}$$

$$\frac{dz}{dt} = \frac{-V_2 A_2}{A_1} \tag{11}$$

$$V_2(t) = -0.1252t + 5.9116 \tag{12}$$

The mathematical expressions were programmed into VBA object mode in MS Excel. This allowed for easy interface and data input. With the dimensions of the tank, or any tank, and the original height of the water, the theoretical power output can be estimated.

IV. EXPERIMENTAL DESIGN

The testing of the physical model power output was required to find the actual power output. To test the model, the basin was filled with water. The height of water was recorded. The data logger started to log, the gate was opened, and water was allowed to flow freely through the turbine to generate electricity. The experiment was repeated multiple times on various days to abate human error.

In addition to recording the power and current, the temperature of the water was also recorded. This allowed for a more accurate estimation of the water's viscosity and density.

Once all of the data was collected, analysis could begin. The power output of the turbine was found by using equation 13, where P is power, I is current, and V is voltage[7]. The power output for every test was plotted against time.

$$P = IV \tag{13}$$

V. RESULTS

When the power output was plotted with time, it became obvious that there were flaws in the data collection method or in the theoretical model. From figure 3, the flaws are particularly evident in the two tests ran, because the actual power output was greater than the theoretical power output. This problem in the experimental design prevented further analysis within the time allotted for research.

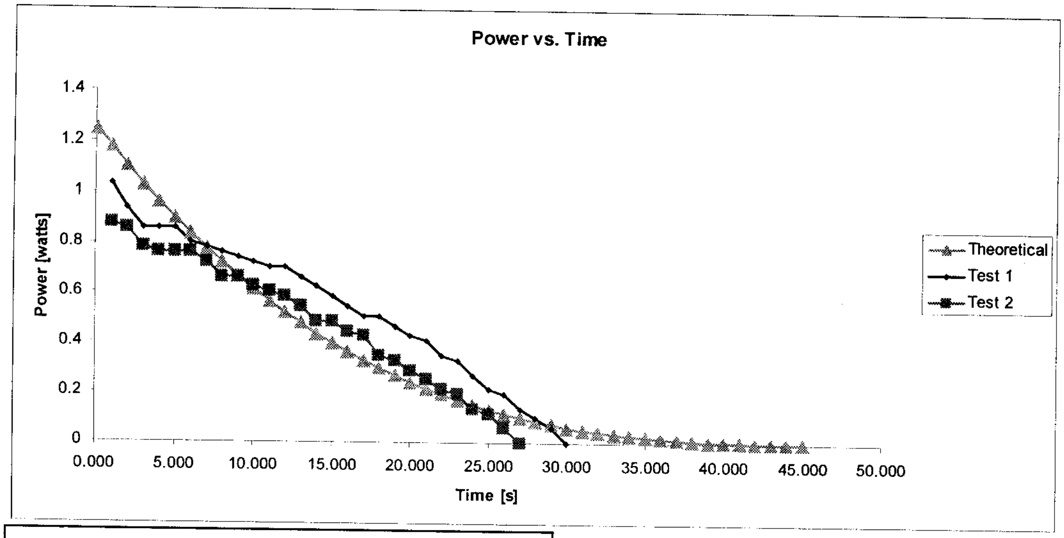

Figure 3. Power-Time Relationship

VI. DISCUSSION AND CONCLUSION

Further research will be required to meet the initial objects of this project. There are three areas within the realm of this project that could stand to be expanded upon. First, there could be an improvement on the estimation of frictional losses. Minor losses were estimated based on tables in a fluid mechanics text. Manufacturer provided minor losses for the valves and pipe fittings might provide a more accurate representation of the losses. Second, the fluid flow behavior was not accounted for in the transitional region. This region also happens to be where the actual power output overcomes the theoretical power output. Methods to account for transitional flow behavior are available in academic literature models. Unfortunately, the available models involve many of the assumptions made in the theoretical model development for this project. The last improvement would be a mathematically derived, rather than experimentally derived relationship for velocity out of the tank to time.

Additional experimental opportunities related to this subject might include varying design parameters such as the D_1/D_2 ratio, or the L/D ratio. This could lead to a development of the design that maximizes fluid flow velocity and power.

The applications of the work presented here is a foundation that can provide a starting point for engineers interested in design maximization of tidal potential energy systems. The technology has not yet been perfected, but energy minded individuals understand the relevance and what it means to Alaska's future.

VII. REFERENCES

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