Preliminary Results of Design of a River Current Energy Conversion System

Robert Gresham, Levi Thornton
Department of Mechanical Engineering
West Virginia University Institute of Technology
Montgomery, WV 25136
Undergraduate Mechanical Engineering Students
Email: ragresham@mix.wvu.edu, lcthornton@mix.wvu.edu

Farshid Zabihian
Department of Mechanical Engineering
West Virginia University Institute of Technology
Montgomery, WV 25136
Assistant Professor
Farshid.Zabihian@mail.wvu.edu

Abstract

Increasing concern for the environment and continuing research and development of renewable energies has recently lead to the exploration of zero head hydrokinetic energy conversion system. The majority of the world's hydropower comes in the form of dams and other large head hydrokinetic energy conversion systems, but the invasive nature and large start-up costs of these types of systems has lead the current research in the field to explore zero head hydrokinetic converters. One appealing attribute of zero head hydrokinetic systems is that they convert energy from the pre-existing flow in a body of water, meaning that they do not require the large structures and obtrusions to the natural environment that their high head counterparts do. This project focuses on the application of hydrokinetic energy conversion in rivers and streams, termed River Current Energy Conversion Systems (RCECS). The goal was to apply the engineering design process to the design of an RCECS from the ground up. Specifically, this project focusses on the conceptual design, a crucial part of this process. The conceptual design is such an important part because the flow speed is so low relative to other power applications that the maximum efficiencies and power outputs of the system, as well as any variation in the stream conditions and how they can affect the output of the system can have a substantial effect on the system's output. For this project the students first had to identify the parameters and conditions that would begin to limit the design of the RCECS. Mounting conditions, local stream velocities, rotor turbine blade designs, identification and application of subcomponents and power transportation all played a major role in the conceptual design of the RCECS. It was found that the rotor blade designs are the greatest factor in determining the power output and efficiency of the system, and a large portion of this project focuses on the optimization methods that are available and the techniques in creating the optimum rotor blade design. Currently the students are creating an optimized rotor design, and once this design has been created and fabrication methods have been reviewed and weighted, the design will continue on down the line until an entire system can be designed based on the engineering design process.

Introduction

The majority of current technology used for energy production cause detrimental effects to the environment and society. Nearly 70% of electricity generated in the U.S. comes from fossil fuels, which have been proven to be harmful to the environment and also are undergoing stricter governmental regulations each year [1]. As the world grows and population continues to rise, in turn so does the demand for energy. As fossil fuel consumption becomes a more regulated industry and facts about the consumption of fossil fuels being harmful to the environment continue to surface, the need for renewable energy sources becomes more and more relevant. This need and a realistic look at energy consumption defines the problem, the first step in the engineering design process. With this problem comes the need for a solution, the need for clean and renewable energy sources. For this project, the students chose to analyze hydropower, specifically hydrokinetic power, as a possible solution to the problem.

Hydropower has been used as early as 2000 years ago when the Greeks first introduced the water wheel for the grinding of wheat into flour [2]. Since then we have seen numerous advances in hydropower, probably the most notable being the creation and implementation of dam hydropower, which converts potential energy of a dam head to kinetic energy when water ways are opened well below the dam head turning a turbine which creates mechanical power which is then converted to electrical power. Although dams are a feasible alternative power generation source, they drastically alter the natural environment and have a tremendous startup cost. The construction of hydropower dams permanently alters the natural flow of the river causing changes in water velocity and sediment transportation [3]. Any species of fish that's life cycle involves upstream or downstream migration is drastically affected. Dams also flood a large portion of usable land and can alter the thermal and chemical properties of the river water [4].

The problem is further defined as a way to find non-invasive forms of hydropower that can coexist with the natural environment and that can be used as supplemental power in a reasonably priced and efficient way. Non-invasive systems that coexist harmoniously within our natural ecosystem are the future of hydrokinetic power production. Using local rivers and streams allow rural areas to minimize their dependence on international suppliers of energy and the need to move energy or fuel over large distances. Since the idea is to not affect the environment drastically, only small scale hydrokinetic energy conversion systems would be feasible, allowing power generation to be put back in the hands of the consumer and away from large industries. With technological improvements, RCECS is now becoming a viable alternative.

Hydrokinetic power, as the name implies, is a renewable resource that uses the potential energy of water as fuel, resulting in minimal harmful emissions. There is a huge amount of natural untapped potential energy throughout the world and in West Virginia, specifically the area surrounding WVU Institute of Technology (WVU Tech). The National Renewable Energy Laboratory analyzed the technical potential for small scale hydropower in the United States considering only the power potential that did not require a large damn or reservoir to be built. The technical potential of the entire United States was estimated to be 259TWh annually [5].

The big difference between existing hydroelectric plants and the new technology in hydrokinetic power generation is that hydrokinetic power is minimally invasive to the environment and converts kinetic energy to electric energy based on the already existing flow and movement of the water, rather than creating an artificial water-head using dams or penstocks [6]. The operation of a hydrokinetic energy conversion system is referred to as a zero head energy converter for the previously mentioned reason, and it is the ability to operate and produce power from existing flow with minimally invasive mounting and operational techniques that sets hydrokinetic energy apart from other hydropower systems. For this project the students have chosen a hydrokinetic energy conversion system that is applicable to their local area. As defined by Khan, Iqbal, et al., "River current energy conversion systems (RCECS) are electromagnetic energy converters that convert kinetic energy of river water into other usable forms of energy [7]."

The students have fully defined the problem to be that the majority of past hydropower systems, although a good source of alternative energy, are very invasive and costly. Also included in this Introduction section are the beginnings of the second phase of the engineering design, gathering information. With the problem defined and a possible solution, RCECS, presented, the students continued to gather information on RCECS so that they could move forward with the engineering process. In the next section of this report, Background, the students continue to gather information on RCECS and begin to organize it in a way that makes the information beneficial and applicable to this project.

Background

Now that the problem has been defined, the students began to define the components that would need to be designed and optimized in order to fabricate a functioning and efficient RCECS. It is important to note that the gathering information stage can sometimes span the entire amount of time the project lasts, and in this project that seems to be the case. However, this initial gathering of information was crucial to this project because it defined the components of the RCECS helped the students gain a better understanding of the functionality of the system. General components of a RCECS, as recognized by the students, are the mounting structure; the blades, arms and drivetrain; duct augmentation; gearing, bearings, and generator; and the transportation and conversion system of power from the RCECS to a household or grid. Another important aspect of RCECS that dictates several of the component designs is axis orientation. Each of these individual systems is discussed in detail in the following sub sections.

Mounting Structure

The three basic mounting structures for RCECS are floating structure mounting, bottom structure mounting, and near surface structure mounting. Each of these mounting structures entails a unique set of challenges, advantages, and disadvantages. Figure 1 shows the basic principle of each of the mounting structures. Relatively self-explanatory, the near surface structure mounting is mounted to the shore near the surface of the water; the floating structure mounting floats near the surface; and bottom structure mounting is mounted to the bottom of the water.

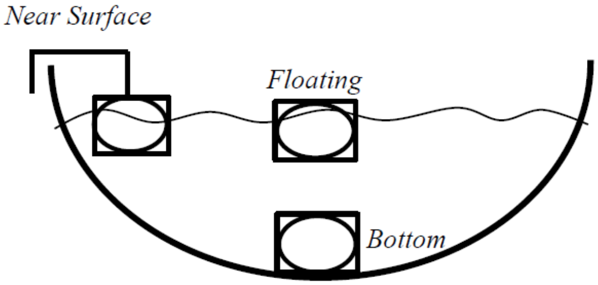

Figure 1. Mounting Structure Options

Axis Orientation

The first thing that must be considered when beginning to build the turbine for an RCECS is axis orientation. For this project the students limited their research to vertical and horizontal axis turbines, although there has also been research and testing with crossflow axis orientation. With both vertical and horizontal axis orientation there are several factors to consider when making design decisions.

Horizontal axis turbines are oriented with the flow perpendicular to the blades. With horizontal orientation, blade design is a major factor. This is because the flow of the water is not directly with the river current the direction of inlet and outlet flows from the blades depends on several factors including attack angle, chord length, blade width and blade length. These factors determine the speed of the blades and ultimately have the largest effect on power output and efficiency of the RCECS. Also, horizontal orientation introduces the decision of whether to orient the generator on the same axis as the turbine or introduce a change in direction in the gearing of the system. This orientation does however have the advantage of being self-starting, having higher efficiencies and not being subjected to vibrations as a result of constant changes in attack [6,8]

Vertical axis orientations introduce their own unique set of advantages and disadvantages. With vertical axis the orientation of the generator is already in line in an optimal position of being perpendicular to the water surface, which eliminates the need to change the direction of the kinetic energy transfer or deal with alternate orientations of the generator. Vertical axis orientation of blades also has drawbacks. First the vertical orientation of the blades causes the blades to work against each other as they turn where blades on one side of the axis move against the current and on the other side they move with the current. This resulting force difference often makes it necessary for there to be some sort of input power and starting mechanism in order for the turbine to start turning and generating power. Also the loading on the blades is cyclical and can be detrimental to the life of the RCECS. This and other concepts are discussed in more detail in the Methods section of this report.

Blade Design

Blade design for turbines is a very important component in RCECS design for optimizing the power output of the system. The amount of river current kinetic energy that is transferred to the power generator is primarily done in the turbine, which in turn makes the design process of the blades a crucial part of the system design. For each axis orientation, both horizontal and vertical, the blade design plays a crucial role in the effectiveness of the system. Several methods for optimizing rotor blade design are included in the methods section of this report.

Drivetrain, Gearing, Power Generation and Transportation

The drivetrain, gearing, power generation and transportation make up the inner workings of the RCECS and ultimately the method of transporting the usable power to a household or power grid. The drive train is responsible for taking the kinetic energy from the turbine to the rest of the system. The gearing is responsible for any change in direction of kinetic energy deemed necessary as well as increasing the angular velocity in order to create more power. The power generator is responsible for converting the river current kinetic energy to usable power in the form of electricity and then it needs to be transferred to a household or grid [6].

Methods

The students have acquired research from colleagues, the university library, Dr. Farshid, and, companies working on similar topics in order to gain a comprehensive understanding of the topic to make effective decisions. After acquiring research, a conceptual comparison of both river current energy systems and ocean wave energy conversion systems was completed. A decision to choose a river energy conversion system was made. This decision was made due to the availability of local rivers and streams and the lack of availability of oceans or a wave tank nearby to conduct testing. A river energy conversion system, unlike ocean wave energy, has the potential to be used to solve the problem of our local region. As the students, at this point, had gathered information on the basics of hydrokinetic energy conversion and made their first decision in the design process, we now see the project entering the third and fourth stages of the engineering design process, concept generation and evaluation of concepts. In this phase the students continued to gather research, identify the critical components of the design, and began to make decisions as to the design concept for the RCECS. This section displays the concept generation and evaluation of concepts portion of the design process and presents new information more pertinent to the design and fabrication of an RCECS. The following subsections show this process.

Axis Orientation

The decision of whether the axis orientation was horizontal or vertical played a large role in the conceptual design of the RCECS. This decision effected many aspects of the design, including but not limited to the drivetrain and gearing, rotor hub design complexity, necessity of a starting mechanism, orientation of the electromagnetic generator, and mounting conditions. Because this part of the evaluation of concepts played such a vital role in the overall conceptual design, the students had to continue to gather more in depth information on the horizontal and vertical axis orientations.

Horizontal axis turbines have a much more even distribution force based on its geometry and orientation to the flow. The flow of the river current is always perpendicular to the tangential velocity of the blades. Horizontal axis turbines tend to be more efficient because the blades can gain power during the entire rotation due to even fluid flow over the blades. Vertical axis turbines however only gain power during part of the rotation with the other part of the rotation fighting against the direction of the stream flow causing high vibrations [9].

Torque ripple, denoted by γ and also known as pulsation, is a measurable example of the fluctuations in torques over time. Torque ripple causes unwanted vibration, noise, and stress issues. It is calculated by the difference of the maximum and minimum torque, denoted by T_{max} and T_{min}, divided by the average torque, T_a as the following equation shows.

$$\gamma = \frac{T_b}{T_a} = \frac{T_{max} - T_{min}}{T_a} \quad (1)$$

The students reviewed an experimental analysis of vertical axis turbines torque ripple based on various blade designs to see if the issue of torque ripple could feasibly overcome if a vertical orientation was chosen [10]. Table 1 sums up the results of the findings of the study. For the purposes of our research the blade types below can be simplified as S representing straight blade and H indicating different types of helical blades with a higher number following the H indicating a higher solidity value. Solidity, denoted as “σ”, is the ratio of the blade area over the area of the entire rotating region. The results below show that a straight blade of similar solidity has a thirteen times higher torque ripple than a helical bladed design. Students also discovered that although a higher solidity increased the maximum torque it also increased the torque ripple [10].

Blade Type	Solidity	Average Torque (Nm)	Torque Difference (Nm)	Torque Ripple
Helical 2	0.2	0.96	0.23	0.24
Helical 3	0.3	1.2	0.41	0.34
Helical 4	0.4	1.28	0.65	0.51
Helical 5	0.5	1.36	1.01	0.74
Straight	0.18	0.56	1.89	3.35

Table 1. Torque ripple based on solidity and blade type [10]

The conclusion of this analysis indicated that, in order to have an optimal vertical axis turbine with minimal torque ripple and a high maximum torque, helical blades would have to be manufactured with an ideal solidity ratio. The students concluded that with the available resources helical vertical axis blades would be more difficult than horizontal axis blades to manufacture because horizontal axis turbine blades would bypass the difficulty of cyclic fatigue loading issues [10].

The analysis of torque ripple in vertical axis turbine blade design began to show the flaws in the vertical axis orientation's ability to maintain loads for long periods of time as well as the unpredictable nature of loading on rotor blades in the vertical axis turbine. Other drawbacks to the vertical axis orientation were the fact that the turbines often were not self-starting and that there was not much information on the optimized rotor blade design for vertical axis oriented RCECS.

With the horizontal axis oriented RCECS, on the other hand, the loading on the rotor blades was more predictable and in almost all cases these rotors were self-starting. These two factors played a larger role than others in the decision making process. Also of importance in this decision making process was the manufacturability of the blades. In order to manufacture a rotor that was as efficient as possible, for the vertical axis the students would have had to choose a helical blade, which would have been nearly impossible with the time constraints as well as funding limitations and manufacturing processes available. With the horizontal orientation, although not necessarily less complicated to design, the students could use their knowledge of 3D CADD modeling along with a basic understanding of blade element theory to create solid models which could then be 3D printed as molds for free at WVU Tech and manufactured using carbon fiber molding. All of these factors were considered in a decision matrix, Table 2, which ultimately lead the students to choose the horizontal axis orientation.

		Horizontal		Vertical	
Design Criterion	Weight Factor	Score	Rating	Score	Rating
Even distribution of forces	0.1	9	0.9	5	0.5
Self-starting	0.12	10	1.2	1	0.12
Manufacturability of rotor blades	0.15	6	0.9	7	1.05
Efficiency of blades	0.1	7	0.7	5	0.5
Durability	0.15	7	1.05	5	0.75
Reliability	0.08	8	0.64	5	0.4
Information Available on rotor blade design	0.12	7	0.84	6	0.72
Freedom of mounting conditions	0.1	9	0.9	8	0.8
Simplicity of gearing and drive train	0.04	4	0.16	8	0.32
Location/Orientation of generator	0.04	4	0.16	9	0.36
			7.45		5.52

Table 2. Decision matrix for horizontal vs. vertical axis orientation

Blade Design

As previously mentioned, the blade and rotor design of a RCECS is a crucial design process considering the resulting component of the RCECS has a tremendous impact on the overall efficiency of the system as well as the power output. The design of turbine rotor blades for hydrokinetic application is based primarily off of the blade-element-momentum theory, which is discussed in further detail in the following subsections. In almost all full scale testing and application of hydrokinetic energy converters the students researched, designers used optimization coding and 3D CADD modeling techniques in order to design rotor blades that were efficient, strong enough to withstand the constant stresses created by the movement of the water and the rotor, and able to produce the amount of power desired from the system. The students spent about a month of this project gaining an understanding of blade-element-momentum theory as well as how the optimization coding uses this theory along with cavitation constraints to produce an optimal blade design. The following subsections detail this particular gathering information stage of the project.

1. Blade-Element-Momentum Theory

Blade-element-momentum theory considers the turbine blade as independent sections, each with its own velocity profile and momentum forces, and the combination of these sections results in the overall blade design [12]. The reason why this method is effective and being so widely used in hydrokinetic turbine design is because it simplifies a very complex design by considering each section of the blade as independent from the rest, which although in reality is not true, it is a safe assumption in this process. This is critical because in order to analyze the blade consideration must be given to the fact that tangential velocity will increase as the blade moves away from the rotor hub to the tip, giving each section of blade its own unique velocity and momentum profiles.

2. Rotor Blade Optimization Utilizing the Genetic Optimization Algorithm

With a better understanding of the impulse and momentum theory and how it applies to blade design, the students figured out that the majority of the research they had acquired was done using a genetic algorithm called WT_Perf, which is free to download from the National Renewable Energies Laboratory (NREL) website.

The students have been approved by the NREL and been given log in information in order to download the coding for blade design. The above mentioned WT_Perf coding has been updated to include cavitation constraints as well as other updates and is now downloadable as HARP_Opt, which is the coding the students have downloaded and will be working with to complete their rotor blade design

The hydrodynamic rotor optimization code uses the coding WT_Perf from the National Wind Technology Center along with a cavitation constraint in order to produce a stall-regulated rotor blade that based on the blade-element momentum theory (BEM) [12]. The coding creates the turbine blade design using BEM and the input lift and drag characteristics of the foil (either airfoil or hydrofoil) to optimize the rotor's ability to extract power from the moving fluid. The BEM theory makes the assumption that the flow is incompressible, inviscid, and at steady-state; there is no cavitation; the forces on the blade are determined solely by the lift and drag characteristics of the foil shape; and the blade elements function as 2-D hydrofoils with no interaction between blade elements. The coding also introduces a cavitation constraint, which considers the σ, the non-dimensional cavitation number, and C_{Pmin}, the minimum local pressure coefficient of the hydrofoil. Cavitation occurs when the vapor bubbles form and then collapse as the fluid move from areas of high pressure to low pressure and back again to high pressure. The cavitation constraint is crucial for hydrokinetic rotor design because not only does cavitation disrupt the flow and take away from the efficiency of the rotor design, but the force caused by cavitation can be damaging to the blades and ultimately cause the system to fail or be rendered an ineffective means of power production.

Because of this cavitation constraint, the program tends to favor thicker foils to thinner ones. The way the coding works is that it converges on an optimal design and then ensures that no cavitation occurs. Just based on physics and fluid mechanics, it makes sense that the coding picks a thinner design where there is a larger pressure difference over a smaller area, however, these designs are also the most susceptible to cavitation. Once the cavitation constraint is not met, the coding must run the entire algorithm over, making convergence harder and more time consuming [12].

3. Rotor Blade Optimization Utilizing Experimental Data

The hydrofoil class NACA-44XX and the RISϕ-A1-XX were identified as applicable candidates for this project. The four digit NACA, National Advisory Committee for Aeronautics, numbering system defines the necessary input parameters that can be entered into equations to generate the cross section of a hydrofoil. The first digit is the maximum camber as a percentage of the chord length. The second digit is the position of the maximum camber in tens of percent of the chord. The last two digits describe the maximum thickness of the airfoil as a percent of the chord and have a limit of forty percent [14].

The NACA-44XX hydrofoil was identified based on an analysis of Verdant Powers hydrofoil design [15] as well as an analysis of the simulation results of the HARP_Opt software by [12]. This selection indicates that the maximum camber is 4% of the cord and is located 40% of the chord from the leading edge. The maximum thickness is represented by the “XX” The simulation ran by [12] included seven airfoils from the NACA-44XX family ranging from NACA 4417 to the NACA 4411 as well as the Riso-A1-18, Riso-A1-21, and the Riso-A1-24. The simulation converged on all of the Riso airfoils, but only converged on the thickest NACA hydrofoils due to cavitation issues on the thinner hydrofoils.

4. Summary of Blade Optimization Methods

The next step in the process of the design of the optimal rotor blade is for the students to evaluate the multiple concepts for their accuracy, amount of time required, and feasibility based on the students’ current knowledge and time and financial constraints. In order to do this, and in doing so move the blade design onto the embodiment design portion of the engineering design process, a decision matrix will be created, similar to Table 2, and a decision will be made as to which optimization method is most feasible for this project. This is scheduled to take place over the break, and once this evaluation of concepts is completed, the students will move forward to embodiment design and ultimately detailed design and fabrication of the rotor blades.

Mounting Configuration

The mounting configuration for a horizontal axis RCECS can be any of the three mounting structures mentioned in the Background section of this report. However, special considerations must be taken for each, especially when it comes to location and orientation of the electromagnetic generator. Water proofing is still a major factor in the drive train and rotor configuration, which are discussed in later subsections, but this eliminates the need to waterproof the housing for the electromagnetic generator which converts the kinetic energy of the river current to electric power.

Both of these structures have the distinct disadvantage of possible accumulation of river debris, which can ultimately sink the entire system. The Ruby hydrokinetic project illustrates a real life example of debris build up issues which ultimately ended the project. The Ruby hydrokinetic project was launched in the summer of 2008. A 5 kW RCECS developed by New Energy Corporation was installed in the Yukon River at Ruby, Alaska with a budget of $65,000 dollars [11]. The RCECS was a floating structure deployed 800 ft off shore, making maintenance on the system costly and time consuming. Initially the costs were incurred and regular clearing of debris was done in order to keep the system afloat, however as time passed the researches decided to see if there boom system would alleviate the accumulation of debris. This proved to be the downfall of the system, as a substantial amount of debris accumulation and lack of regular maintenance ultimately rendered the system ineffective [11].

The advantage of bottom mounting structures are that they eliminate the problem proposed by surface floating debris, but with these types of mounting structures almost all components of the system must be completely water proof in order to function properly.

Also with the floating structure there must be an anchoring system in place. Although this is a less complicated problem to settle, the direction of flow of the river must be considered, and the anchoring structure must be at multiple points in order to keep the turbine blades perpendicular to the flow of current for maximum power output. This problem is not the case in near-surface and bottom-structure mounting because the systems are permanently mounted at the bottom of the stream.

Although each of these structures provides unique challenges, RCECS presents an advantage over ocean based hydrokinetic energy conversion systems or even wind power, and that is little alteration has to be made to the pathway of the stream and the turbine does not need to change direction to account for changes in flow direction [8] Because the river current is flowing in an almost constant direction, the mounting structures can be fixed, and once they are set there is no need to change the direction of the structures in order to account for varying direction in the river current flow. The small change in direction of the river flow over time can be modified with a duct augmentation system.

The students have made a tentative decision to do either a near-surface mounting structure or a floating structure. This decision was made based on the portability of these mounting structures, removing the possibility of a permanent structure. Also this decision provides the students with a flexibility of location and easy access if maintenance needs to be done on the system.

Fabrication

The majority of the students work during the course of this project focused on the conceptual design phase of the engineering design process, specifically defining the problem, gathering information, concept generation and evaluation of concepts. These were all necessary in order to gain an understanding of the RCECS system, the theories that govern its functionality and ultimately determine how well the students can apply the engineering process to the embodiment design phases of the RCECS.

Although once the students had completed the conceptual design of the RCECS for the most pertinent component, the rotor blades, little time was left for explorations into the embodiment design phase. However, the students did begin to explore the product architecture and configuration design phases of embodiment design by speaking to members of the WVU Tech community about materials and manufacturing processes available to them in order to determine the most feasible fabrication and implementation methods.

Testing

In order to validate the design and fabrication of the RCECS, a testing method must be determined. This process is reflected in the configuration design phase of the engineering design process. Once the students have finalized the design methods to be used and have created the product architecture that will reflect the finalized design, testing must be done in order validate the design process. In order to do this, the students have begun concept generation of two different testing methods, site testing and tank testing, each with its own set of advantages and disadvantages.

Site testing has the unique advantage of placing the RCECS in a real world environment where debris, severe weather and any other atmospheric elements that may not be replicated in a controlled environment can be observed. The site testing also carries with the immediate validation that, if the RCECS does what the students expect it to do, it will have done so in the real world environment. With this in mind, site testing also has its disadvantages. In order to site test a structure, whether it be floating, near surface or bottom mounted, must also be designed and tested so that it will hold up. This construction makes the RCECS a fixed design where changes that the students wish to make to the individual components in order to further optimize the design may be costly, difficult and time consuming. This leads us to the tank testing method.

Although the tank testing method does not carry with it the immediate validation that the RCECS works in a real world environment, it creates a controlled environment where flow velocities and other parameters can be manipulated, and individual components can be altered relatively easily compared the fixed nature of the site testing method.

The testing concept is still in the conceptual design phase, as students are gathering information, generating concepts and evaluating those concepts in order to determine which testing method will be the best fit for this project. The students have, however, begun to look into the required equipment for the testing process as well as concepts that will be pivotal in creating and validating a testing method. From [18] the students found that they will need speed transducers to measure the speed of the rotor as well as the rotational speed of the input and output shafts of the gearing and drive train, a load cell to determine the stress the rotor and hub exerts on the mounting structure, and an aquadopp or other flow measurement devise in order to measure the velocity of the flow into and out of the rotor.

If tank testing is chosen, dimensional analysis will play a major role in validating the results of the project. In order to do this, the students will need to define all the variables that effect the efficiency and power output of the system, of geometric, kinematic and dynamic nature, and create dimensionless numbers which can then be used in order to find similitude in the model and tank testing method with the real world environmental application of RCECS. The tip speed ratio and solidity dimensionless numbers are two examples of this that will show kinematic and geometric similitude, respectively. The tip speed ratio, when compared with the model and what a final prototype would be, will represent similarity between the kinematic motion of the rotor hub, specifically the angular velocity and fluid velocity. The solidity is a ratio that shows how the area of the rotor blades as to the overall area of the rotor effects the power output of the system and can be used to show geometric similarity between the model and prototype.

Before any of this though, the students made some calculations in order to determine what type of geometric size would be needed in an optimal situation and design to produce enough power from the RCECS to power one household. "In 2013, the average annual electricity consumption for a U.S. residential utility customer was 10,908 kilowatt-hours (kWh), an average of 909 kWh per month [16]."

The following data of energy consumption was converted into the required constant power of 1.245kW. Assuming the Betz limit as an upper bound estimate for efficiency, the actual power required was calculated to be 2.100kW. A water velocity of the Kanawha river near the Kanawha falls area was researched to be 0.6258m/s on average [17]. Using the power equation, given below, with a given water density, ρ, flow speed, and power required, the necessary area was calculated. From this area, the necessary blade radius, to power a common household with a hydrokinetic turbine at the Betz limit of efficiency, was calculated to be 2.34m. A similar calculation was done with the flow velocity assumed to be equal to 1.5m/s which is a more ideal condition. The resulting blade radius required in this situation was calculated to be 0.629m, approximately 2ft. Sample calculations are provided in the appendix at the end of the report.

$$P_{theory} = \frac{1}{2}\rho A U^3 \quad (8)$$

The conclusion of the calculation was that with the given tools, knowledge, and financial resources designing a full scale turbine of this size was not feasible at this time. A small scale model must first be developed in order to perform adequate testing. If the scaled results are promising an attempt to request funding for a larger scaled prototype will be attempted. The size of the small scale model will be determined based on the fabrication limitations. The result of the second calculation indicates that the stream velocity is of vital importance and can drastically reduce the size of the blades required.

Conclusion

This project contained several difficult tasks that the students had to overcome in order to reach the point it is at today. Some of these difficulties were for seen and relatively easy to deal with, while others set the project back from the results the students initially thought they could achieve during the semester.

The largest difficulty by far was the lack of knowledge and experience with hydrokinetic energy conversion available to the students. Although WVU Tech provided the students with access to engineering data bases and journals that had a tremendous amount of information on the subject, the majority of the information the students had to find, verify and apply to this project was new to them, and a majority of the time the students spent on the project was sifting through these sources, trying to gain an understanding of the concepts behind them, and figuring out how to apply them to their project.

Another hurdle the students had to jump through was the complex design of the rotor blade. As previously mentioned, the rotor and hub design are the primary influences on the systems power production and efficiency. Initially the students thought the design would be relatively simple in theory, and at most it would be a derivation from rotor and hub designs used in wind turbines. However, this did not prove to be the case. The students spent almost a month of the semester researching blade-element-momentum theory, optimization software, and optimization methods that could apply to the rotor blade design. Despite the setbacks and difficulties of this project, the students were able to gather a great amount of information on RCECS and were also able to gain an understanding of how these systems work as well as how they are applied and implemented. The students feel that the success of this project lies in the understandings and knowledge gained, and with this success comes confidence that in the spring 2016 semester the students can begin the design phase and fabrication phases of the project and ultimately build an RCECS that can be tested.

Discussion

The importance of this project to the learning process is the development of design skills in an engineering environment that simulates the real world environment. The students are required to present a proposal, interim report and final report, as well as weekly progress reports and presentations, all of which would be required of a design team in the corporate engineering environment. Also, in following the engineering design process, the students are learning to approach problems from an analytical and objective stance. Rather than a just push through, twist a wrench, get an answer and move on approach to solving problems, the students are learning to take time, evaluate each decision in a specific manner and come to conclusions in a structured, searching manner.

These types of skills are extremely useful in the field of engineering. As engineers, we don’t want to simply throw a large factor of safety on a design, or build it the cheapest and fastest way. We want to take time, follow a process, understand the importance of each decision and come to the best, most efficient and effective solution. Although this paper seems more like a report on the most recent technologies associated with the topic, RCECS, it is an extremely important part of the process. In hindsight, the students may have taken on more than two undergraduates can handle, but the emphasis and the education here is not necessarily based on the results, but how well the students can follow the engineering design process, make educated decisions and show the evidence for each decision made in the process.

It is hope that future students at WVU TECH can continue on with the project and that this report has laid a foundation for which to start on. Each system has been carefully analyzed and the necessary information has been gathered. Future projects could include fabrication methods, the building of a testing facility, and the fabrication and testing of the RCECS systems discussed in this report.

REFERENCES

[1] Bedard, Roger. "Economic and Social Benefits from Wave Energy Conversion Marine Technology." *Marine Technology Society Journal Mar Technol Soc J* 41.3 (2007): 44-50. Web.

[2] "History of Hydropower." *History of Hydropower*. Office of Energy Efficiency and Renewable Enery, n.d. Web. 03 Sept. 2015. <http://energy.gov/eere/water/history-hydropower>.

[3] Anderson, E. P., Freeman, M. C. and Pringle, C. M. (2006), Ecological consequences of hydropower development in Central America: impacts of small dams and water diversion on neotropical stream fish assemblages. River Res. Applic., 22: 397–411. doi: 10.1002/rra.899

[4] Marmulla, Gerd. *Dams, Fish and Fisheries: Opportunities, Challenges and Conflict Resolution*. Rome: Food and Agriculture Organization of the United Nations, 2001. Print.

[5] Lopez, A., B. Roberts, D. Heimiller, N. Blair, and G. Porro. "U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis." (2012): n. pag. Web.
[6] Khan, M.j., G. Bhuyan, M.t. Iqbal, and J.e. Quaicoe. "Hydrokinetic Energy Conversion Systems and Assessment of Horizontal and Vertical Axis Turbines for River and Tidal Applications: A Technology Status Review." Applied Energy 86.10 (2009): 1823
[7] Khan, M.j., M.t. Iqbal, and J.e. Quaicoe. "River Current Energy Conversion Systems: Progress, Prospects and Challenges."*Renewable and Sustainable Energy Reviews* 12.8 (2008): 2177-193. Web.
[8] Mukherji, Suchi Subhra. "Design and Critical Performance Evaluation of Horizontal Axis Hydrokinetic Turbines." Thesis. Missouri University of Science and Technology, 2010. (n.d.): n. pag. Web. 24 Sept. 2015. <http://en.openei.org/wiki/Marine_and_Hydrokinetic_Technology_Glossary>.
[9] Mukherji, Suchi Subhra. "Design and Critical Performance Evaluation of Horizontal Axis Hydrokinetic Turbines." Thesis. Missouri University of Science and Technology, 2010. (n.d.): n. pag. Web. 24 Sept. 2015.
[10] Shiono, Mitshiro, Kdsuyuki Suzuki, and Sezji Kiho. "Output Characteristics of Darrieus Water Turbine with Helical Blades for Tidal Current Generations." Output Characteristics of Darrieus Water Turbine with Helical Blades for Tidal Current Generations. Nihon University, n.d. Web. 04 Oct. 2015.
[11] Johnson, Jerome B., and Dominique J. Pride. *River, Tidal, and Ocean Current Hydrokinetic Energy Technologies: Status and Future Opportunities in Alaska*. Tech. N.p.: Alaska Center for Energy and Power, 2010. Print.
[12] Sale, Danny. *A Hydrodynamic Optimization Method and Design Code for Stall-Regulated Hydrokinetic Turbine Rotors*. Tech. no. OMAE2009-79513. N.p.: National Renewable Energy Laboratory, 2009. Print.
[13] El-Wakil, M. M. "Chapter 5: Turbine Blade Design." Power Plant Technology. New York: McGraw-Hill, 1985. 177-201. Print.
[14] "NACA 4 Digit Airfoil Generator." *Airfoil Tools*. N.p., n.d. Web. 29 Nov. 2015. <http://airfoiltools.com/airfoil/naca4digit>.
[15] "Improved Structure and Fabrication of Large, High-Power KHPS Rotors."*Office of Science and Technology Information*. Verdant Power, n.d. Web. 28 Oct. 2015. <http://www.osti.gov/scitech/biblio/1084212>.
[16] "How Much Electricity Does an American Home Use?" U.S. Energy Information Administration, n.d. Web. 15 Oct. 2015. <http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3>.
[17] "Flows and Velocities." *National Weather Service - Ohio River Forecast Center*. N.p., n.d. Web. 16 Oct. 2015. <http://www.erh.noaa.gov/er/ohrfc/flows.shtml>.
[18] Jeffcoate, Penny, Ralf Starzmann, Bjoern Elsaesser, Stefan Scholl, and Sarah Bischoff. "Field Measurements of a Full Scale Tidal Turbine." *International Journal of Marine Energy* (2015): n. pag. Web.