Design of a Lab-Scale Ocean Wave-Powered Desalination System

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Abstract

We propose an autonomous and self-powered wave energy harvesting system. Such a system would provide a decentralized and environmentally resilient source of clean electricity and freshwater for remote coastal communities. The wave energy is harvested using a large oscillating flap hinged at the sea bed, whose kinetic energy is then transferred into hydraulics; the pressurized seawater is used to generate electricity and freshwater. Existing hydraulic equipment and ocean wave data is used to model a simulation of the full-scale system.

This system has to be scaled down for in lab testing purposes. In this study, we use space and power constraints to specify a lab-scale, use a secondary oil hydraulic system to simulate the motion of ocean waves, and look at the relationship between the different scales to appropriately compare the lab-scale to the full-scale system. Equations for fluid flow, and computations on system efficiency and size are used to select specific hardware. The equipment and existing lab space are used as constraints on the design of custom parts for component fixtures, and select appropriate piping instruments. Consequently, we develop an assembly model for the hardware-in-the-loop testing system along with a bill of materials and construction guidelines.

Introduction

Globally, 300 million people rely on desalinated water. However, the desalination process is expensive energy-wise, and relies on the grid [1]. The supply of freshwater is therefore linked to the reliability of large centralized grids.

In our proposed solution, by using ocean waves to energize seawater, the seawater behaves as both the flow for electricity generation and as the feed for desalination via reverse osmosis (RO). Figure 1 shows an illustration of this system. The wave energy converter (WEC) coupled to a hydraulic cylinder converts wave

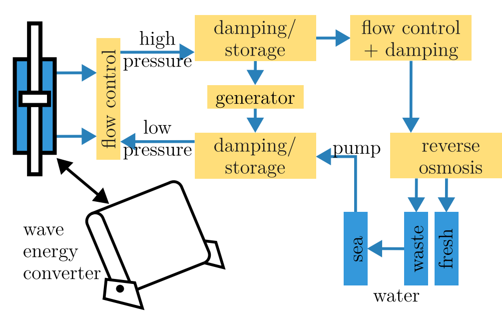

Figure 1: Illustration of the core processes and elements in the desalination system.

motion to hydraulic power. The flow is divided into a high pressure line and a low pressure line. Accumulators are used to damp flow pulsations and stabilize flow rates. High pressure flow into the generator produces electricity; flow into the RO elements yields fresh water and brine. Seawater is continually pumped into the system to replace the discharged water in the RO components.

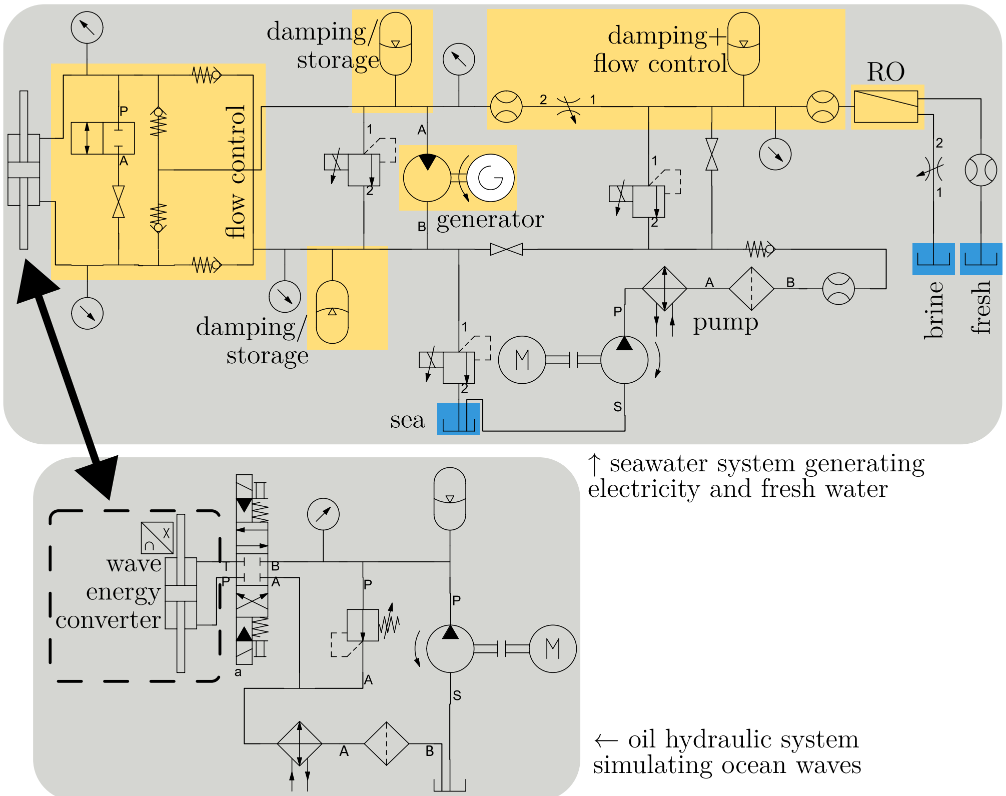

Figure 2: Schematic of the desalination system to be implemented in the lab.

Figure 2 is a schematic that will be used to implement the lab-scale system; an oil based hydraulic system's linear actuator is used to simulate the motion of the WEC. Additionally, this system is intended to have autonomous controls for the different sea conditions via the on/off valve in the first flow control section, and the throttling valves. A large tank will serve as the source of seawater, and the outlet for mixed brine and freshwater.

In this study, we designed the lab-scale version of the system for validating the simulation model, which can then be extrapolated to predict the full-scale system behavior. We determined the effect of scaling on parameters of the system, identified or designed custom parts needed to build the test system, and validated the performance of the identified components.

Materials and Methods

The scale between the power rating of the full-scale and lab-scale, x, was set based on lab constraints and effects on system parameters. Constraints on the design include that the test stand must fit on a 100 inch by 48 inch bedplate, be powered by an electric motor with a maximum power of 150 kW, and fit within a specified budget. Scaling laws were determined, such that they maintain a dynamic similarity between the full-scale and lab-scale system, as shown in Table 1. The mathematical relationships, such as the amount of water needed at lab-scale, were further used to determine the scale.

With a set scale, components for constructing the system were identified. Components such as seawater compatible valves, gauges, and reverse osmosis elements were identified. Decision matrices were used to determine the ideal hydraulic cylinder configuration. Other parts, such as racks for accumulators and fixtures for the cylinders, were custom designed with the intention of being constructed in-house.

Component/parameter	**Relation**
Pump/motor displacements	x
RO membrane area	x
RO number of membranes	1
Pipe pressure drop	$x^{1.75}$
Pressure at any point	1
Flow rate at any point	x
Accumulator volume	x
Motor-pump displacement ratio	1
Power rating	x

Table 1: Scaling laws for dynamic similarity

Selected components were re-evaluated to determine performance. Parameters such as achievable pressure differential, ΔP, and flow rates due to a particular servo valve were compared against the system's required pressure and flow rates. Figure 3 compares the maximum required pressure differential to the achievable pressure differential based on the energy losses through an MTS 252.33 servo valve; the maximum required flow rate is compared against the achievable flow of the oil pump. Performance evaluations such as this helped determine whether the combination of the oil pump, servo valve, and hydraulic cylinder would be capable of simulating the motion of the WEC.

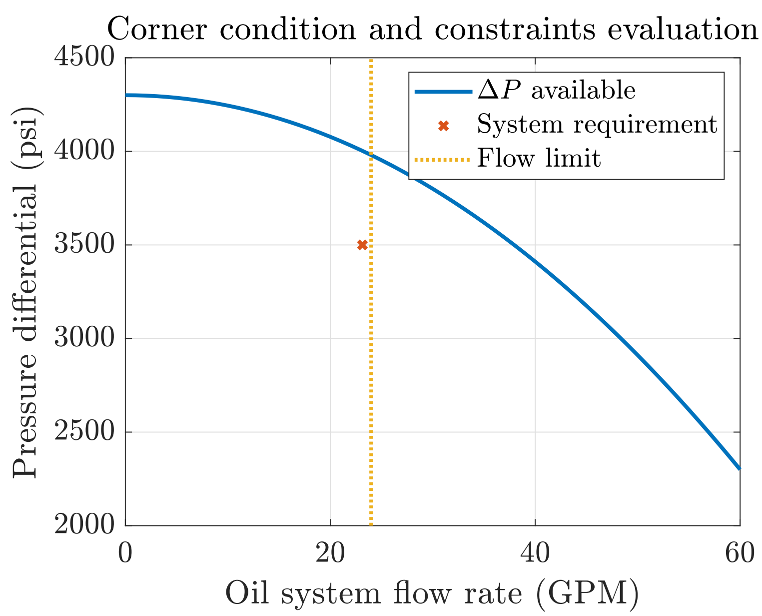

Figure 3: Maximum system requirements for pressure differential and flow rates compared to the achievable pressure differential (4300 psi supply) and flow rate.

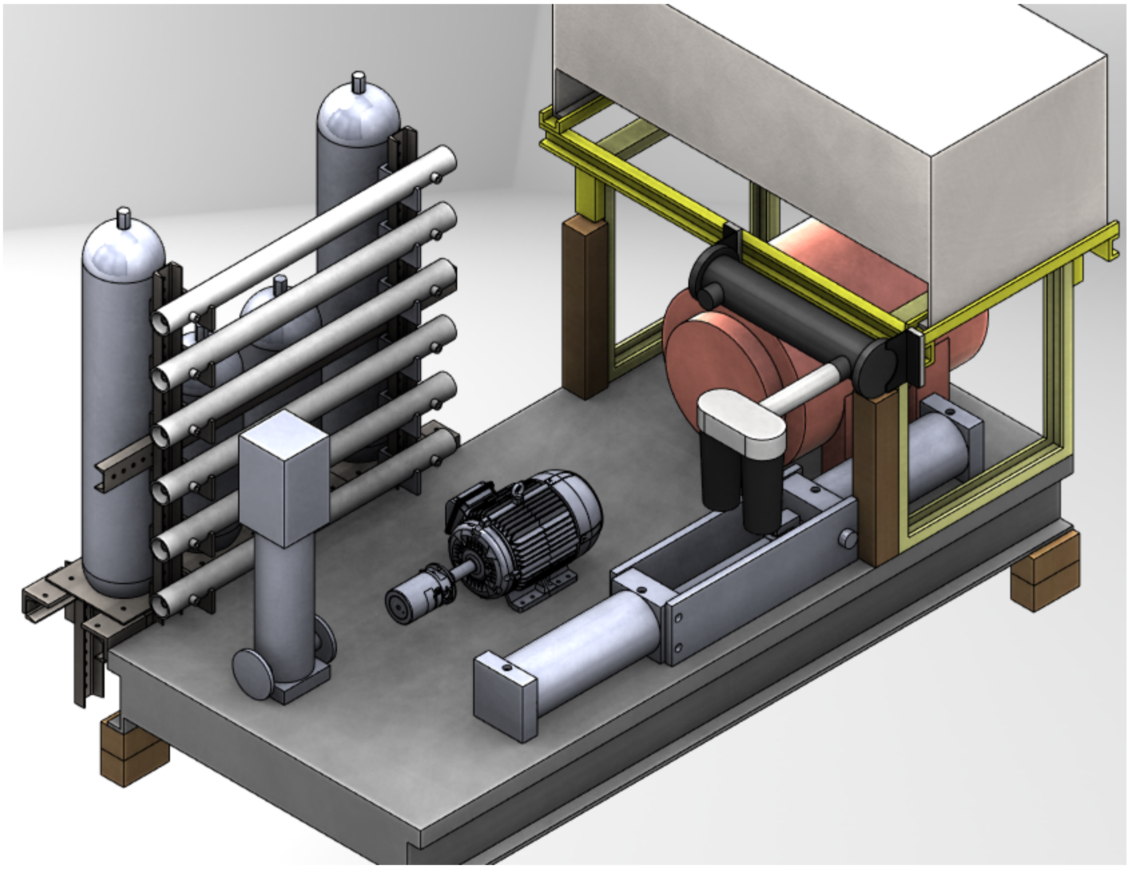

Figure 4: Lab-scale mock-up in 3D CAD

Results and Discussion

Through the scaling studies, the scale was set to 1.12% of the full-scale system. At this scale, the average power supplied to the seawater cylinder is 4.64 kW; in contrast, at full-scale, the average power supplied would be 414 kW. The maximum and average fluid flow rates through the lab-scale seawater system is 46 GPM and 7.5 GPM respectively. The difference in magnitudes in the flow rate indicate the varying nature of waves. To damp the pressure ripples and stabilize the flow, two 15 gallon accumulator banks are needed on the high-pressure branch of the seawater system. To produce ample freshwater, 16.8 m^2 of reverse osmosis membrane area is needed.

The parameters at the scale helped determine the needed parts. Currently, 32 items for use have been identified, excluding piping, fittings, and custom parts. The majority of these parts will be bought second-hand to reduce cost.

A 3D CAD assembly model, shown in figure 4, was created to provide a sense of appropriate component placement. For example, this helped in the decision of placing the accumulators on the floor to save space. The CAD model for the custom accumulator and RO rack is shown in figure 5. The custom parts are to be made with A36 steel. Steel channels, angles, and plates need to be cut and drilled. These are to be mounted with heavy hex bolts.

Conclusions

This study was a small section of a larger project to produce a self-powered renewable desalination system. Lab constraints and scaling laws were used to determine the scale and components required. Additional performance calculations and use of 3D modelling helped evaluate chosen components.

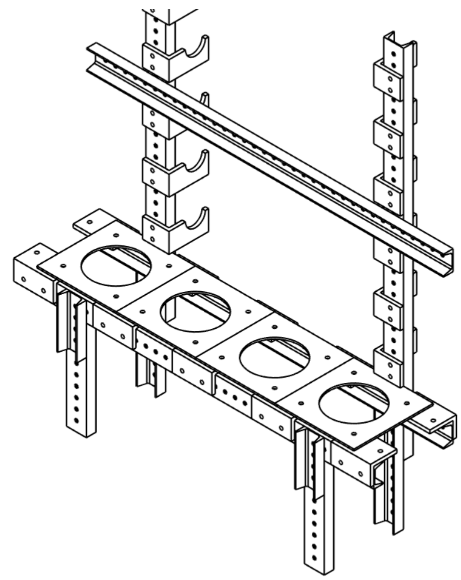

Figure 5: Custom rack for housing accumulators and reverse osmosis pressure vessels.

The next steps of the project is to complete the design and manufacture the physical lab-scale desalination system. Hydraulic cylinders and components will be finalized. The 3D models and bill of materials will be used to purchase parts and construct the final assembly. The system will be tested by using the oil system to simulate waves, and use the seawater system to quantify the yield in electricity and freshwater. These will be completed by the end of October 2023 at the University of Minnesota. Additionally, autonomous controls will be refined and tested to improve the reliability and production capability of the lab-scale system. Positive system performance will then indicate the possibility of implementing a full-scale ocean wave-powered desalination system.

References

[1] Water Science School , 2019, "Desalination — U.S. Geological Survey," www.usgs.gov [Online]. Available: https://www.usgs.gov/special-topics/water-science-school/science/desalination.