Uranium Extraction from Seawater: Investigating Hydrodynamic Behavior and Performance of Porous Shells

by

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Abstract

As global economies grow and demand more energy, scientists work to develop alternative sources to meet demand. Developing countries, e.g. China and India in particular, will turn to nuclear power to meet their energy needs, increasing demand for uranium. There are enough land-based uranium reserves to cover current demand for about 120 years. However, increasing demand will shorten this estimate and require mines to tap into harder-to-extract reserves resulting in higher prices and greater environmental footprints. An unlimited supply of uranium, roughly 4.3 billion tonnes, is dissolved in the ocean at a concentration of 3 parts per billion. Chemists have been developing polymers to extract uranium from seawater to provide fuel and price security for the nuclear power industry. Coupling a system that extracts uranium with an existing offshore structure, such as a wind turbine, reduces the cost of deployment and operation as well as the overall price of uranium from the ocean.

In ocean-based systems, trace metals such as uranium are passively removed via adsorbent polymers. These polymers are not inherently strong or durable, however. One solution is to enclose them in a shell structure that bears the environmental loads. This work aims to characterize the flow of water in and around porous shells containing uranium adsorbent to inform the design of a uranium extraction device. Shells with different hole patterns were fabricated and tested. The corresponding flow in and around the shells was examined qualitatively using computational fluid dynamics (CFD) and dye flow studies. The form drag of the different shells was determined experimentally and verified through CFD. The results were used to model a chain of uranium adsorbent shells submerged in the ocean and subject to various currents. The dynamic forces due to vortex-induced vibration were studied to determine resonant frequencies. Findings will be used to inform uranium extraction system design in an offshore environment.
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Chapter 1

Introduction

The U.S. Energy Information Administration (EIA) predicted that total world energy consumption would increase by 48% to 240 trillion kWh between 2012 and 2040 [1]. They expect long-term economic growth in developing countries will drive this increase in demand for energy. The EIA also predicted that net world electricity generation would increase by 69% to 36.5 trillion kWh between 2012 and 2040, with most growth occurring in developing countries [1]. In developed countries population growth has slowed, but electric power generation is still projected to increase by about 1.2% per year to meet demand. In the United States in particular, energy production is expected to increase by 20% and energy consumption is expected to increase by 5% between 2016 and 2040 as the U.S. becomes a net energy exporter by 2026 [2]. On the other hand, in developing countries population size, installed infrastructure, and demand for appliances and electronics will grow considerably, resulting in an increased need for electric power generation of 2.5% per year [1].

In the United States, energy-related carbon dioxide emissions are expected to fall 0.2% per year. The EIA predicted that the amount of energy used per unit of economic growth and the amount of carbon dioxide emitted per unit of energy will fall 37% and 10%, respectively by 2040 [2]. These improvements assume that energy efficiency continues to improve and use of carbon-intensive energy sources decreases. On a global scale, however, a rise in world
energy-related carbon dioxide emissions from 32.3 billion metric tons to 43.2 billion metric tons between 2012 and 2040 is expected due to heavy dependence on carbon-intensive fossil fuels in developing countries [1].

Concern for energy security and greenhouse gas levels is predicted to drive further development of renewable energy sources and nuclear power plants. The EIA predicted that by 2040 about 29% of electricity generation will come from renewables and about 12% will come from nuclear power [1]. Lower capital costs and tax credits are making wind and solar power attractive in the near term, but wind power holds long-term potential to be competitive as well [2]. Wind turbine performance, reliability, and applicability in various geographic locations continues to improve and scale up, which draws the cost down [3]. The U.S. Department of Energy (DOE) predicted that wind power capacity will increase by 8 to 11 GW per year between 2013 and 2050 [3]. They predicted that by 2030 there will be an established offshore wind market with 22 GW installed. By 2050, 86 GW will be installed off the East Coast, the West Coast, the Gulf of Mexico, and the Great Lakes [3]. Again, these improve-
ments hinge on continued investments in the technology and operating practices. While the power generation capacity of nuclear power plants in industrialized countries is predicted to drop by 6 GW between 2012 and 2040, global nuclear power capacity will increase because of additional capacity in countries such as China and India [1].

With increased nuclear power capacity, global uranium requirements will increase. A joint report from the OECD Nuclear Energy Agency and the International Atomic Energy Agency predicted that uranium requirements would rise to a quantity between 72,000 tons and 122,000 tons by 2035 [4]. If uranium requirements were to remain the same as those for 2012, then currently identified resources will be sufficient for 120 years [4]. However, these uranium reserves exist at different price points corresponding to how easy they are to recover and process into fuel, and an increase in demand for uranium would force the industry to pursue more uranium at a higher cost of extraction.

While terrestrial sources of uranium exist in finite quantities, seawater contains an essen-
tially unlimited supply of the element. The ocean contains about 4.29 billion metric tons of uranium isotopes at a concentration of 3.3 ppb [5, 6]. This resource would ensure fuel supply security for centuries, create a price ceiling on the fuel, and minimize the environmental footprint and health affects associated with tradition pit mining techniques [7].

Research groups around the world are working to develop practical, large-scale recovery technologies, including the U.S. DOE’s Office of Nuclear Energy in partnership with several national laboratories, universities, and international collaborators [8]. The multi-faceted project is divided into several focus areas, and the Precision Engineering Research Group at the Massachusetts Institute of Technology is involved in cost analysis and deployment modeling [7]. Researchers realized that the material properties of the uranium adsorbent could not satisfy the mechanical strength and chemical adsorbent capacity requirements simultaneously. As a result, they designed a recovery system that consists of a series of durable, permeable shell enclosures that house uranium adsorbent material [9].

The objective of this thesis is to characterize the flow of seawater in and around these shell enclosures when they are dispersed along a rope submerged in seawater. The research involved qualitative computer modeling and experimental validation through drag measurements and dye trials to describe the flow in and around three different shell designs. The static deformation of a long, submerged chain of shell enclosures subject to realistic current conditions was modeled in order to inform full scale system design. Finally, the dynamic response of the submerged chain of shells was investigated experimentally to determine response frequencies of vortex-induced vibrations and effective added mass.

1.1 Ocean Mining

According to the National Research Council, more than 11,340 kg of new, non-fuel minerals are used per person per year in the United States [10]. Every sector of the economy, from health care to transportation and energy, relies on non-fuel minerals and mineral products.
As energy and manufacturing industries grow and advance to meet the demands of the U.S. and the global economy, they will require greater amounts of base metals, precious metals, rare earth elements, and other elements [10]. As mineral stockpiles become depleted, their availability and reliability from land-based sources becomes uncertain. The oceans, however, contain numerous minerals dissolved as ions in low concentrations [5]. Considering the large volume of the oceans, estimated to be about $1.3 \times 10^9 \text{ km}^3$, they have the potential to be “an infinite repository of materials” [5].

Uranium is one such mineral that would benefit from the supply and cost security potentially afforded by ocean mining. Demand for uranium is expected to increase, and it is uncertain how long that known, terrestrial reserves will last. The cost of any given mineral depends on its abundance and availability, both of which are difficult to calculate with great certainty. Geology, technology, environmental standards, social norms, politics, and economics all influence abundance and availability [10]. Significant investments in mine development at present are needed to ensure future uranium needs are met [4, 5, 10].

Fortunately, research regarding ocean mining, and in particular uranium from seawater, began in the 1960s and has led to several promising developments [11]. Adsorption of uranium via an adsorbent material was determined to be more feasible and effective than other methods of adsorption [11]. Numerous lab studies have been performed to optimize the adsorbent material, and chemists continue to develop materials with higher uranium selectivity, ion capacity, chemical stability, and mechanical durability [11, 12, 13]. Functionalized polymeric adsorbents, in particular polyamidoxime-based adsorbents (−C(NH$_2$)=NOH) are highly selective and easy to handle, making them the most attractive material so far [11, 13, 14, 15]. Laboratory tests with natural seawater showed that these materials have an adsorption capacity of 3 to 4 g U/kg adsorbent [15, 16]. The adsorbents are made by irradiating high-surface-area polyethylene fibers with an electron beam, grafting acrylonitrile and carboxylic acid to the surface, and converting the cyano groups (−CN) to amidoxime groups with hydroxylamine [15]. The amidoxime group forms a complex with a uranyl tricarbonate
ion \((\text{UO}_2\text{(CO}_3)_3^{4-})\), the most common uranium ion species in seawater [11]. After some time exposed to seawater, an elution bath removes the ions from the fibers so that the fibers can be reused. Elution is typically done via acid leaching followed by alkaline treatment, which significantly degrades the fibers over time [15]. Another method that does very little damage but needs to be tested on fibers subject to real seawater involves sodium carbonate leaching followed by hydrogen peroxide treatment [15].

A system that extracts uranium from seawater involves not only a means of adsorption and elution as described above but also a means of moving seawater. In general, seawater can be actively pumped through the adsorbent or allowed to flow naturally. Devices designed for deployment of adsorbent in pumped and natural systems are described in 1.2.

### 1.2 Uranium Extraction Device

To determine an appropriate uranium extraction device, it is useful to do an energy and cost analysis of potential devices. 240 tonnes of uranium are required to power a 1 GW nuclear power plant for a year [17]. Given a uranium concentration in seawater of 3.3 ppb and assuming an extraction efficiency of 50\%, \(160 \times 10^9 \text{ m}^3\), or 164 gigatonnes, of seawater are needed per year [17]. By comparison, the total volume of water pumped for desalination is on the order of ten gigatonnes, less than a tenth of the volume required to extract fuel for a 1 GW nuclear power plant [5]. An order-of-magnitude estimate of the energy return on energy investment (EROEI) performed in [5] found that actively pumping seawater would have an EROEI less than 0.1, which is of little to no use. The same study then looked at the EROEI of a system deployed in the ocean that took advantage of natural currents, and found that the EROEI would be about 2.5 [5]. While this value is low compared to other energy sources, it is greater than unity, and thus, use of natural currents is preferable in terms of energy.

The costs of uranium from seawater extraction devices were analyzed in several studies.
Cost is primarily driven by adsorbent fabrication, capacity, durability, deployment strategy, mooring equipment, and length of time deployed [18]. For a detailed review of the designs and cost estimates for uranium extraction devices proposed between 1960 and 2015, see [18]. Estimates for passive, current-dependent systems using polyethylene fibers ranged between $330/kg U to $2,100/kg U (2010 USD). Figure 1-3a is a summary of the cost estimates covered in [18]. Figure 1-3b shows the fluctuations in the price of terrestrial uranium in US dollars per pound U [19]. The price spiked to $300/kg U in 2007 because of increased demand and a short period of perceived scarcity. As of March 2017, the price stood at about $53/kg U [19]. Comparing the price of terrestrial U sources to seawater extraction shows that traditional terrestrial sources are still considerably cheaper, but that seawater extraction could put a ceiling on the price of U. The price ceiling would help stabilize the U market in the long-term [18].

In general, the cost of mooring large structures in the ocean tends to dominate the overall system cost [18, 20]. Thus, researchers at the Massachusetts Institute of Technology proposed the design of a uranium extraction system coupled with an existing offshore structure, such as a wind turbine [21]. In [21], Picard et al. described a continuously moving symbiotic system, which they predicted would collect uranium for $403/kg U. The system consisted of belts of braided adsorbent moved continuously through seawater between sets of rollers. One roller in each set was mounted at the base of the wind turbine spar. The other was mounted on a platform extending from the spar above the surface of the water. The components of an elution system were also mounted on the platform so that the adsorbent would undergo the chemical process to remove the collected material when it reached the top. Picard et al. designed the system with six belts, which provided redundancy and would reduce system downtime [21]. They figured a service vessel would attend once a month to collect the elution products and do maintenance. Their cost analysis showed significant savings attributed to sharing mooring costs and performing adsorbent elution on site. Figure 1-4 shows a drawing of the proposed system [21].
(a) Cost estimates summarized in [18] showing the evolution of uranium extraction technology. The validity of these estimates depends heavily on the assumptions used at the time, some of which were later disproved.

(b) Fluctuations in the price of terrestrial uranium in US dollars per pound U [19]. Prices are significantly lower than theoretical costs of uranium from seawater, except for a spike in 2007.
Figure 1-4: Coupled uranium extraction system and offshore wind turbine designed by Picard et al. [21].
Haji et al. later revised the design to address a pitfall [17]. The braided adsorbent material has low tensile strength, so it would likely not survive ocean currents in the form of a net as proposed by Picard et al. [17]. Haji et al. overcame this by designing strong, permeable shell enclosures for the fibers, dispersed along the length of high-strength mooring rope, resembling a conventional ball-chain belt [17]. Inside the shell enclosure would be a ball of adsorbent fibers, similar to a pom-pom. The ball-chain would take the tension and environmental loads instead of the fibers. Figure 1-5a shows an example of a shell with a fiber ball. The system would have four sets of rollers equally spaced around the platform, and each roller would continuously move ten ball-chain belts. The ball-chains would stay submerged for twenty-three days before undergoing elution in the on-site tanks [22].

1.3 Hydrodynamic Phenomena

The previous assertion that the adsorbent material would not make a strong enough net is based on the fact that the nets are subject to wind, wave, and current loads. To get a sense of exactly how strong the nets need to be to remain intact, these environmental loads need to be quantified. Loads due to steady, incident flow past the ball-chains will be further discussed below.
1.3.1 Current-Induced Loads

As water flows past a submerged object, the fluid exerts force on the object due to differences in pressure between the front and back sides and viscous shear stresses in the boundary layer. These forces, form or pressure drag and frictional or viscous drag, respectively, sum to the total drag on a body. Total drag depends on the shape of the body, the roughness, and the ratio of inertial force to viscous force, i.e. Reynolds Number. Reynolds Number is given by equation 1.1 where \( \rho \) is density, \( U \) is velocity, \( l \) is a characteristic length scale, \( \mu \) is dynamic viscosity, and \( \nu \) is kinematic viscosity.

\[
Re = \frac{\rho Ul}{\mu} = \frac{Ul}{\nu} \tag{1.1}
\]

An object with a cross-sectional span-to-chord ratio of about one is considered a bluff body [24]. The submerged ball-chains in the uranium extraction device can be considered a bluff body with a circular cross-section. At low Reynolds Numbers, less than about 24, total drag force is dominated by the viscous forces in the boundary layer [25]. As the Reynolds Number increases, the boundary layer on a bluff body will begin to separate from the body and move in an unsteady, eddying motion, becoming turbulent. Figure 1-6 depicts the flow separation on a bluff body. The viscous forces become less important than the pressure distribution over the body, and form drag begins to dominate. At high Reynolds Numbers, greater than about 200,000 for a smooth sphere (lower for rougher surfaces), the boundary layer becomes fully turbulent, and the wake region becomes narrower [25]. The difference in pressure between the front and the back becomes less pronounced.

Form drag force depends on the drag coefficient, which is typically found experimentally for a given object. Equation 1.2 is used to find the drag coefficient as a function of Reynolds Number where \( D \) is the drag force, \( \rho \) is the density, \( U \) is the free-stream velocity, and \( S \) is the frontal area.

\[
C_D(Re) = \frac{D}{\frac{1}{2}\rho U^2 S} \tag{1.2}
\]
The coefficient of drag for a smooth sphere and smooth cylinder have been well studied in the past [26, 27]. However, the coefficient of drag of a porous sphere is less well understood. A few studies have been done on a Wiffle ball, which showed that the coefficient of drag for the Wiffle ball was higher than that of a solid sphere [28, 29]. However, these studies did not provide enough quantitative information to directly apply the coefficient of drag they found to this investigation.

1.3.2 Vortex-Induced Resonance Oscillations

The shear forces acting on the separated flow around a bluff body cause vortices to form behind the body. Instability increases with time, and the vortices are shed asymmetrically in the wake of the body in a pattern known as a Kármán street [26]. The non-dimensional frequency of vortex shedding is given by the Strouhal Number,

\[ St = \frac{f_v D}{U_c} \]

where \( f_v \) is the frequency of vortex shedding, \( D \) is the characteristic diameter, and \( U_c \) is the free-stream velocity. Vortex shedding causes lift and drag forces on the body, which can excite oscillating cross-flow (perpendicular to the fluid flow) and in-line (parallel to the fluid flow) motion of the body known as vortex-induced vibrations [30]. Vortex-induced vibrations
(VIV) are often given as a function of reduced velocity,

\[ U_r = \frac{U_c}{f_n D} \]

where \( f_n \) is the natural frequency of the body in water. In general, VIV are stable and self-limiting because of a balance between excitation and fluid damping [24]. VIV are greatest when the frequency of vortex shedding is at or near the natural frequency of the body, a phenomenon known as lock-in [30]. The amplitude of the cross-flow motion is typically on the order of one diameter at a reduced velocity of about 6 [24]. The amplitude of in-line motion is typically less than half a diameter [24]. While VIV are not large in amplitude, they have a significant impact on the fatigue stress on the body. Higher frequencies of vibration result in a shorter fatigue life. VIV also result in higher mean drag because a larger wake is formed when the body oscillates [24, 30]. Greater drag forces result in higher tension and higher reaction forces at connection points.

A means of limiting drag and simultaneously suppressing VIV would be ideal for a body deployed in an incident flow. Fairings can be used to make a body more streamlined and prevent vortex-shedding, but they must also be fit with bearings in order to self-align with incident flow, increasing cost and introducing another point of failure [24]. Some passive devices designed to suppress VIV include strakes and vortex-generating tabs, which force vortex shedding at specific points along the length to minimize vibrations [24]. However, they can be expensive to manufacture and install. Furthermore, they increase drag and provide additional surfaces to protect from biofouling. Neither fairings nor strakes are ideal, therefore, it may be more practical to damp vibrations via other mechanisms or avoid velocities that induce resonance altogether.
1.4 Biofouling

Biofouling refers to the undesirable accumulation of micro and macro-organisms on wetted surfaces [31]. It can sink offshore structures, cause increased fuel consumption on ships, clog piping, render membranes and sensors ineffective, and initiate bio-corrosion. Preventative measures are costly, as are removal efforts, maintenance, and repairs to systems and structures. In 1996, the global cost of marine antifouling measures was estimated to be about $700 million annually [31]. That cost has only continued to increase. Therefore, biofouling is a subject of great interest and research. The field continues to evolve as scientists learn more about the underlying science and discover more effective and environmentally friendly methods of antifouling.

Biofouling occurs in four stages. Upon first being immersed in non-sterile water, surfaces adsorb proteins, polysaccharides, ions, and other molecules in the water, forming an organic conditioning film [32]. Then naturally occurring bacteria settle on the conditioning film, attach, and colonize. The bacteria secrete extracellular polymeric substances (EPS) to form a nutrient-rich biofilm on the surfaces. EPS help the bacteria adhere to the surface and protect them from antibacterial agents [33]. The biofilm grows in thickness and attracts other organisms including single-cell algae and protozoa. Finally, the spores and larvae of larger organisms such as algae, sponges, barnacles, and muscles settle and attach to the biofilm [32]. They secrete an adhesive and cure it to cement themselves to the surface [32].

The interaction between biofilm and macro-organisms is extremely complex, determined by environmental factors, surface chemistry, micro-topography, and microbial products, yet a stable community with a diversity of organisms forms in about a month [33, 34]. The rate of biofouling is determined by salinity, temperature, nutrient level, rate of water flow over the surface, and intensity of sunlight. These factors vary by season, location, and depth below the water surface [31]. Generally, colder water temperatures and lack of sunlight inhibit biofouling growth. The rate of biofouling is also affected by competition for space and nutrients between different organisms on the same surface [32]. Organisms that colonize
the surface early on get covered over by later colonizers [32]. Scientists at the Woods Hole Oceanographic Institution found that protist grazing can reduce biofilm thickness by one third [35].

Because biofouling is a detriment to wet systems, ships, and structures, scientists developed several methods of engineering surfaces aimed at preventing biofouling or making removal easier. Beginning in the 1950s, antifouling paints containing toxic biocides were popular because they were highly effective [31]. Commonly used biocides included oxides of lead, arsenic, mercury, and copper [36]. They leached from the paint to the settling organisms, causing them to die. However, it was discovered that the toxins accumulated in marine organisms throughout the food chain, so countries started banning the use of certain leachable biocides [31].

Current research aims to develop non-toxic, environmentally-friendly coatings with antifouling and fouling-release characteristics [33, 34]. Most technologies employ chemical mechanisms, physical mechanisms, or a combination of both. No single, universal solution has been discovered [37].

**Chemical Mechanisms and Enzymes** Natural chemicals with antifouling properties are of great interest to researchers. Over 2,000 chemistries discovered in marine organisms with antifouling, anti-attachment, or anti-microbial properties have been described, yet many of these mechanisms are not fully understood [37]. Experimental coating technologies have been adapted to include natural chemical antifoulants. However, the lifespan of natural chemicals is on the order of days or months, whereas a coating ideally needs to last for years. The long-term environmental effects and coating durability have yet to be determined as well [37]. Enzymes have been found to be effective at breaking down EPS, disrupting cell functions, and breaking up proteins, thereby reducing biofouling [33]. However, enzymes that are universally effective have yet to be identified. Rather, their effectiveness varies based on the substrate [37].
Surface Chemistry The surface chemistry of the substrate is an important factor affecting organism adhesion. There is a range of substrate surface energies for which biofouling is minimized because proteins and cells do not adhere well to the conditioning film [33, 34]. Figure 1-7 shows the Baier curve, which is the relationship between surface energy, or surface tension, and degree of biofouling. Foul-release coatings take advantage of this ideal surface energy. Even though organisms settle on the surfaces, they are easily removed by shear forces associated with moving water [37]. Silicone-based paints are currently the most commonly used foul-release coatings because of their low surface energy [38]. Surfaces that adsorb and tightly bind water molecules have been shown to prevent bacterial adhesion [33, 39]. Thus, hydrophilic and amphiphilic polymer coatings have also been the subject of much research [33, 38].

Mechanical Mechanisms Studies of marine organisms that naturally do not experience biofouling revealed the role of surface topography in antifouling and foul-releasing. The skin of many sharks, skates, rays, and porpoises have ridges and grooves on the order of 1 \( \mu \text{m} \) that help prevent biofouling [33]. Lab-fabricated replicas of these micro-structures were tested and found to be effective at reducing biofouling for three to four weeks [33]. Fur-
ther studies showed that the width and spacing of topographic features necessary to deter biofouling had to be tailored to the size of specific biofouling organisms [33].

There is no singular physical characteristic of a substrate that can be changed to completely prevent biofouling, and likewise there is no singular chemical mechanism that can be changed to the same effect. This suggests that an effective solution will be a combination of multiple tactics. Furthermore, once the inevitable biofouling process begins, mechanical cleaning may be necessary to remove it. This is routinely the case for ships and structures, but it runs the risk of damaging existing coating technologies and releasing pollutants into the environment.
Chapter 2

Hydrodynamic Performance of Single Shells

To draw a connection between adsorbent shell enclosure design and uranium uptake, more information was needed as to how the flow interacted with the shell. Qualitative information about where the flow went when it came in contact with the shell and quantitative information about drag was obtained through computation fluid dynamics simulations and experimental trials in the MIT Towing Tank.

2.1 Drag Predictive Modeling

The flow through and around adsorbent shell enclosures was modeled in SOLIDWORKS Flow Simulation and STAR-CCM+ to determine the drag coefficients of the shells and to qualitatively understand the flow through the shells.

2.1.1 Flow Simulation Setup

Three adsorbent enclosure designs were selected for simulation. The first was based on the hole pattern of a classic Wiffle ball. The second was a Wiffle ball with slotted holes. The
third had a similar distribution of holes to the classic Wiffle ball but larger diameter [23]. Figure 2-1 is a drawing of the shells modeled. The orientation of these designs relative to the direction of the water flow did not matter because of symmetry.

The physics of the STAR-CCM+ simulations included constant density, K-Epsilon turbulence, liquid water, Reynolds-Averaged Navier-Stokes, segregated flow, and steady, three dimensional turbulence. A velocity boundary condition was imposed at the inlet, and a static pressure boundary condition was imposed at the outlet. The other sides were modeled as walls. A polyhedral mesh with two prism layers next to the shell and along the walls was used to model the domain, which gave an acceptable quality mesh in accordance with STAR-CCM+ mesh quality measures. Residuals and force on the shell were monitored for convergence. All simulations converged in about 4,000 iterations. Figure 2-2 shows the meshed shells and domains with their respective cell quality (1 = perfect, 1e-5 = bad).

2.1.2 Qualitative Flow Description

Convergence was achieved for the three modeled shells with flow velocities of 0.1, 0.3, and 1.0 m/s, corresponding to Reynolds Numbers 9430, 28,291, and 94,304, respectively. Figure 2-3 shows velocity streamlines on planes that bisect the wiffle shell. Figure 2-4 shows velocity streamlines on planes that bisect the shell with big holes. Finally, Figure 2-5 shows velocity streamlines on planes that bisect the slotted shell as well as an additional plane that cuts the shell through the slots.

The velocity gradients show that the fluid accelerates around the outside of the wiffle and
the slotted shells, and decelerates inside the shells. On the other hand, the fluid accelerates through the shell with big holes, and there is only a small increase in velocity around the outside. The flow inside the wiffle shell seems to form several small eddies, whereas the flow inside the slotted shell forms one large pair of eddies, and the flow mostly passes straight through the shell with big holes.

The flow through the wiffle shell seems to exhibit weak velocity dependence. The velocity at the center of the shell subject to 1.0 m/s flow is nearly zero, however, there is slightly more flow through the center at 0.1 m/s. There is little to no velocity dependence in the other two shells distinguishable in these images.

### 2.1.3 Simulated Drag Force

The force on the shell was monitored for convergence, and the final value recorded for each simulation. The force was used to calculate the coefficient of drag as a function of Reynolds
Figure 2-3: Velocity streamlines on the center planes of the wiffle shell.
Figure 2-4: Velocity streamlines on the center planes of the shell with big holes.
Figure 2-5: Velocity streamlines on the center planes as well as the slots of the slotted shell.

Number using eq. 1.2. Figure 2-6 is a plot of the coefficient of drag found through simulation in STAR-CCM+. Given that the flow regime is expected to be transitioning from laminar to turbulent, it was expected that $C_d$ decrease or remain constant with Reynolds Number. However, the trend of the data was in the opposite direction. Therefore, it is believed that there may be an error in the simulation setup or the force monitor.

The flow through the same wiffle shell was simulated for another investigation in SOLIDWORKS Flow Simulation over the Reynolds Number range of 8,571 to 47,619 [23]. Drag force and residuals were monitored for converge. No other information is known about the simulation setup. Yet, the results seem more consistent with expectations. Figure 2-7 shows the values of $C_d$ found in SOLIDWORKS Flow Simulation.
Figure 2-6: Coefficient of drag found through simulation in STAR-CCM+.

Figure 2-7: Coefficient of drag for wiffle shell found through simulation in SOLIDWORKS Flow Simulation [23].
2.1.4 Future Simulation Work

The simulations performed in STAR-CCM+ provided a good baseline understanding of the flow through and around the wiffle shell, slotted shell, and shell with big holes. However, the coefficient of drag seems unreasonable. Therefore, more work should be done to refine the mesh and try different turbulence models or solvers to get a more reasonable solution. While the quality of the mesh was acceptable, it could be revised to give better resolution of the boundary layer on the shell and the wake region. More work should be done to quantify the flow through the shells at various fluid velocities. Finally, a sensitivity analysis of the simulation should be performed to verify the results.

2.2 Drag Measurement

The drag force on model adsorbent shell enclosures induced by a uniform current was measured experimentally to calculate the drag coefficients at different Reynolds numbers. CFD simulations can produce drag force measurements, but there remains some uncertainty about the accuracy of modeling turbulence, so it is still customary to measure drag force experimentally.

2.2.1 Drag Experimental Setup

The same three adsorbent enclosure designs investigated in 2.1 were selected for fabrication and testing. The shells were 3D printed from Accura Xtreme White, a durable plastic material, in 0.004 inch layers. The shells are shown in Figure 2-8. Reynolds scaling was used to ensure that the scaled models tested in the tow tank would be representative of a real-world scenario. The full-scale shell diameter, properties of seawater, and current velocities representative of those seen in the ocean gave a range of Reynolds numbers between about 7,000 and 100,000. A model shell diameter of 0.1 m was chosen such that there would be no side or bottom effects from the walls of the towing tank. Table 2.1 shows the full-scale values
Figure 2-8: Adsorbent enclosure designs fabricated and tested to determine coefficient of drag.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Full Scale Dimensions</th>
<th>Model Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>shell diameter (m)</td>
<td>0.25</td>
<td>0.10</td>
</tr>
<tr>
<td>kinematic viscosity (m²/s)</td>
<td>1.43e-6</td>
<td>1.06e-6</td>
</tr>
<tr>
<td>velocity range (m/s)</td>
<td>0.04 - 0.64</td>
<td>0.07 - 1.19</td>
</tr>
</tbody>
</table>

Table 2.1: Full-scale and model parameters found through Reynolds scaling.

used to compute the range of Reynolds numbers and the corresponding scale-model values. The empty shells were through-bolted on a threaded rod and mounted to an ATI Industrial Automation Gamma force/torque six-axis sensor [40]. The sensor was then mounted to the carriage of the MIT Towing Tank with the shell sufficiently submerged to avoid surface effects. While the sensor collected data, the carriage was towed at speeds between 0.1 and 1.0 m/s, repeating each run once before incrementing the speed by 0.05 m/s. The water surface was allowed to settle in between each run. A solid sphere was also tested as a baseline drag force for comparison. The experiment was repeated over a velocity range of 0.1 to 0.6 m/s with a fiber ball half the diameter of the shell enclosed in the shell. Finally, the experiment was rerun with just the shell with big holes completely filled with fiber. Figure 2-9 shows the experimental setup in the towing tank.
Figure 2-9: Wiffle shell and force sensor mounted to the carriage of the MIT Towing Tank.
2.2.2 Drag Force Measurement

The data collected by the force sensor was processed to get the measured drag force. Because the signal on the sensor was weaker at lower velocities, the data was less consistent and had more error. Above about 0.2 m/s, the data was more consistent because the signal was stronger. Figure 2-10 shows that drag force increased quadratically with velocity as expected. There are two data points for each shell shape and velocity combination corresponding to the two runs performed. The frontal area of each shell was initially calculated in SOLIDWORKS from the projection of half the shell onto a flat plane. However, the coefficient of drag was
Figure 2-11: Coefficient of drag as a function of Reynolds number with frontal area equal to a solid circle of the same diameter.

recalculated using the same frontal area as that of a solid sphere for all shapes. This frontal area may be more realistic given that the shells have a fiber ball and a backside that are not represented in the projection in the CAD model. Using this area, the corresponding coefficient of drag, $C_d$, was calculated and plotted as a function of Reynolds number. $C_d$ was larger for the three shells than the solid sphere. The largest $C_d$ corresponded to the shell with big holes. The fiber ball that filled half the shell had little effect on the drag. However, the fiber ball that filled the shell with big holes resulted in a notably higher $C_d$.

### 2.2.3 Drag Coefficient Comparison with Simulation Results

The flow around the wiffle shell was modeled in SOLIDWORKS Flow Simulation for Reynolds Numbers ranging from about 8,500 to 47,500 and the corresponding drag coefficient calculated. The results were plotted and a curve fit to the data having the equation, $C_d =$
Figure 2-12: Comparison of experimental $C_d$ to simulated $C_d$.

The $C_d$ of the sphere determined experimentally was larger than typical values published in literature and included in Figure 2-11 as a solid black line [27]. The error could be due to the proximity to the surface or the rod and nuts attached to the sphere. Both could have increased the drag force and corresponding drag coefficient. Alternatively, the water in the tank may not have settled enough between runs, which would have resulted in more

2.2.4 Discussion of Results

The $C_d$ of the sphere determined experimentally was larger than typical values published in literature and included in Figure 2-11 as a solid black line [27]. The error could be due to the proximity to the surface or the rod and nuts attached to the sphere. Both could have increased the drag force and corresponding drag coefficient. Alternatively, the water in the tank may not have settled enough between runs, which would have resulted in more
turbulent water and increased drag. In general the shells experienced more drag than the solid sphere because the flow separated from the shells earlier and resulted in a wider wake region. The shell with big holes disturbed the flow more than the wiffle or slotted shells. The addition of the fiber ball to the slotted shell had little effect on the drag because the fiber ball had little to no effect on the flow around the shell. There was a small increase in drag on the wiffle shell with the fiber ball because, with more holes, the fiber ball had more effect on the flow around the shell. The shell with big holes was affected the most by the addition of the fiber ball. Because a large proportion of the surface area has a much rougher texture, the flow separates earlier and increases the size of the wake region. This could imply that biofouling, which would increase the roughness of the shells, would also increase the drag on the system.

The experimental results demonstrate the expected, downward trend in $C_d$ that corresponds with a transitioning flow regime. The results refute the findings of the STAR-CCM+ flow simulations, whereas the ratios of shell $C_d$ to sphere $C_d$ based on SOLIDWORKS flow simulations show better agreement. There is room to improve the simulation as well as the experiment. A force sensor designed for smaller forces may result in better data at lower Reynolds Numbers. For first order analysis, SOLIDWORKS Flow Simulation at the appropriate Reynolds Number will probably yield usable $C_d$ values, but if higher accuracy is required, then more representative simulation parameters or solvers should be used.

2.3 Flow Visualization

The objective of the dye trials was to visualize the flow in and around the adsorbent shell enclosures to qualitatively get a sense of how the different shell shapes affected the flow. In general, the higher the water velocity that the fibers see, the greater the adsorption rate [41]. Therefore, it is pertinent to have an understanding of whether one shell shape may be better for increasing the flow through the shells, or if one shell shape causes too much turbulence.
and the fiber balls break apart.

2.3.1 Dye Experimental Setup

The same three adsorbent shell enclosure designs used in 2.1 and 2.2 were made from clear plastic spheres with a diameter of 0.1 m. They were mounted one at a time to the MIT Towing Tank carriage as before with a threaded rod and clamped fixture. Two GoPro Hero4 video cameras were also mounted on the carriage as shown in Figure 2-13 such that one camera recorded the flow around the shell from the side and the second camera recorded the flow from the front opposite side. The video was recorded at a resolution of 1280 by 720 at 240 frames per second.

The set-up also included blue and red dye that was piped through flexible tubing from a Mariotte’s bottle mounted on the carriage to the shell in the water. A switch turned the dye flow on or off. The rate of dye flow was adjusted via a valve such that the flow features could be observed without dispersing too rapidly or clouding the water too heavily. Dye was delivered at a constant rate during the trials.

Three sets of dye trials were conducted. In the first, the dye was inserted inside the shell as the carriage moved in order to observe the behavior of the flow inside and exiting the shell.
Figure 2-14: The dye inserted in the shell with big holes (c) flowed out whereas the dye lingered in the wiffle (a) and slotted (b) shells.

Then the dye was trailed in front of the shell in order to observe the flow into and around the empty shell. Finally, the shell was filled with fiber while the dye trailed in front to see the effect of the fiber ball and how much dye it captured. In the latter two sets, the dye tubing was secured to a slender rod attached to the carriage in front of the shell as shown in Figure 2-13. The carriage speed was varied between 0.1 and 0.3 m/s to gauge whether the flow behavior was dependent on velocity.

### 2.3.2 Qualitative Comparison Between Shells

**Dye Inside**  When the dye was inserted in the wiffle and slotted shells, it swirled around and some exited through the holes, whereas the dye flowed out of the shell with big holes mostly unobstructed. Figure 2-14 shows a representative frame taken from the video of the dye trials with the dye inserted inside the shell. As the velocity of the carriage increased, the turbulence inside the shells also increased and dispersed the dye.

**Dye Outside**  With the dye trailing in front of the shells, there seemed to be a slight dependence on velocity. When the carriage was moved at slow speed, 0.1 m/s, there was very little difference in the behavior of the dye as it moved past the different shell shapes.
A little dye entered the shells and swirled around before exiting. When the carriage speed increased to 0.2 m/s, some dye went inside the wiffle and slotted shells, but most of the dye went around. The dye went through the shell with big holes mostly unobstructed. When the carriage speed was increased over 0.3 m/s, much of the dye went around all the shells. Figure 2-15 shows a representative frame taken from the video of the dye trials at 0.25 m/s with the dye trailing out front of the shell.

Dye with Fibers The shells were filled with fiber, and the dye was allowed to trail in front again. The shell with big holes seemed to capture more dye than the other shells, and the dye was entrained deeper in the fiber ball. The wiffle shell captured and entrained slightly more dye than the slotted shell. Figure 2-16 shows a representative frame taken from the video of the dye trials when the shells were filled with fiber. Because of the fast frame rate, the pictures came out dark and grainy. The experiment was rerun at 0.25 m/s with red dye and different camera settings to obtain better images of the fiber balls at the end of the dye trial (Figure 2-17).
Figure 2-16: The shell with big holes (c) entrained more dye deeper in the fiber ball than the wiffle (a) and the slotted (b) shells. The wiffle captured slightly more dye than the slotted shell.

Figure 2-17: Clear shells at the end of a dye trial run at 0.25 m/s. The fiber ball in the shell with big holes (c) entrained more dye, whereas (a) and (b) held onto the dye/water mixture in the shell.
2.3.3 Shell Influence on Uranium Extraction Device

Observing the dye flow mostly around the slotted shell, slightly through the wiffle, and almost straight through the shell with big holes suggested that the shell with big holes sees the most flow through, which would be better for uranium adsorption. The fibers would reach saturation faster and could be cycled more frequently. If the fiber ball, however, needs more protection from the current or other environmental factors, the wiffle or slotted shell may be a better design.

The shell shape dependence observed in the dye trials somewhat contradicts results from the flume tank experiment [23]. There was no significant difference between the uranium adsorption in the fibers enclosed in the different shell shapes tested. However, the dye trials showed clear differences in how much water flowed through the different shapes. The disparity could be attributed to the different velocities. In the flume tank experiment, the water moved at 0.048 m/s whereas the lowest velocity tested in the dye trials was 0.1 m/s. At 0.1 m/s there was little difference in how much dye flowed through the different shell shapes. The shape seemed to affect the flow at higher velocities. More work should be done to quantify the flow through the different shell shapes at different velocities to determine whether shape and hole pattern could be detrimental to uranium adsorption.

The observations from the dye trials seem to agree well with the results from the qualitative CFD simulations. Both showed the flow mostly passing straight through the shell with big holes and mostly going around the wiffle and slotted shells. The little dye that did enter the wiffle and slotted shells swirled around in the internal eddies. Because of the good agreement between simulation and experiment, STAR-CCM+ would be a good tool to test different shell designs to get a qualitative sense of the flow in and around the shells.
Chapter 3

Hydrodynamic Response of a Rope with Staggered Shells

3.1 Static Deflection Prediction

The tension and deflection along one length of ball chain subject to current and pretension was calculated based on realistic offshore wind turbine characteristics. An understanding of the maximum expected tension is necessary for selecting and sizing the rope, the roller supports, and the motor that moves the rollers. Furthermore, the resulting shape of the rope under current forces is necessary to ensure that the nets do not twist, tangle, collide, or otherwise foul with nearby structures and vessels. There is a tradeoff, however, in that increasing the rope pretension decreases the static deformation of the rope, which subsequently increases the tension throughout the rope and the reaction forces on the roller supports.

3.1.1 Model Setup

The shape of a partially submerged ball-chain subject to current forces depends on turbine dimensions, adsorbent requirements, ball-chain dimensions, and design current conditions. To get a realistic sense of the tension in the full-scale uranium extraction system, a represen-
tative floating offshore wind turbine model and proposed wind farm site were selected. The National Renewable Energy Laboratory created a model utility-scale 5MW baseline offshore wind turbine to investigate potential floating support structure designs [42]. The model was based on “Hywind,” a spar buoy developed in Norway by Statoil, which was also adopted by the European Upwind research program as a reference model because of its simplicity and promising potential for commercialization (see fig. 3-1). The model has a platform with a diameter of 6.5 m located 10 m above the still water level. It has a draft of 120 m and a diameter of 9.4 m at the base. The uranium extraction device has 2 m diameter rollers on the platform and the base, which gives the boundary conditions for the top and bottom ends of the rope. The “Symbiotic Machine for Ocean uRanium Extraction” design tool was used to determine the number of shells required on each ball-chain length [23]. Static deflection was calculated for one half of one length of adsorbent ball-chain. Design parameters determined by the wind turbine geometry and location are listed in the first column of Table 3.1, and design parameters chosen to satisfy adsorbent needs are listed in the second column. These variables were used to numerically solve for the forces on the ball-chain and its position at
Wind Turbine Characteristics | Ball-Chain Characteristics
---|---
Radius to top roller=3.25 m | Number of shells=400
Radius to bottom roller=4.70 m | Shell outer diameter=0.25 m
Height of top roller above sea level=10 m | Shell inner diameter=0.24 m
Depth of bottom roller below sea level=120 m | Shell surface porosity=20%
Roller diameter=2 m | Shell density=970 kg/m³
Current velocity at surface=2 m/s | Rope diameter=0.025 m
Current velocity at bottom roller=1 m/s | Rope density=1380 kg/m³
Rope tensile strength=39,200 lbs

Table 3.1: Design parameters determined by the wind turbine characteristics are listed in the first column, and design parameters chosen to satisfy adsorbent requirements are listed in the second column.

discrete points, which gave the resultant tension and deformed shape.

The radius from the center of the spar to the top and bottom rollers were based on the wind turbine geometry. The uranium extraction device characteristics determined the size of the rollers and subsequently the length of each adsorbent ball-chain. The uranium extraction system required 45,436 kg of adsorbent, which was divided between 40 ball-chains lengths each containing 400 shells. A shell diameter of 0.25 m, thickness of 5 mm, and porosity of 20%, or 20% reduction of material due to holes, were selected. The rope used was 1 inch diameter Novablue High Performance Double Braided Rope, found at [http://www.novabraid.com/rope/novablue/](http://www.novabraid.com/rope/novablue/), which has an approximate tensile strength of 174,370 N. Figure 3-2 illustrates the adsorbent ball-chain loop between the top and bottom rollers of the uranium extraction device.

The true weight in air per unit length of the ball chain, given by equation 3.1, was found by summing the weight of the adsorbent, shell, and rope, then dividing by the length of the ball-chain.

\[
w = \frac{[(m_{ads} + m_{shell}) g N_{shells} + g \rho_{rope} L_{rope} A_{rope}]}{L_{rope}}
\]

The buoyant force per unit length, given by equation 3.2, was found by summing the weight
Figure 3-2: Illustration of an adsorbent ball-chain looped around two rollers extending from a floating wind turbine. The ball-chain experiences a tension that varies along the length resulting from self weight, buoyancy, and current-induced drag.

The third force that contributes to the tension and deformation of the ball-chain is drag, which is induced by current. The drag force is given by equation 3.3, and it depends on the coefficient of drag, $C_d$, diameter, and velocity. The coefficient of drag for a smooth cylinder, typically in the range of 0.6 to 1.0, was taken to be 0.7. The coefficient of drag for a porous shell was taken to be that found experimentally for a wiffle shell, about 0.75.

$$f(s) = 0.5 \rho_{seawater} C_d d(s) U(s)^2 \quad 0 \leq s \leq 120m$$  \hspace{1cm} (3.3)

The force varies along the length of the rope because part of the rope is out of the water, the diameter changes along the length, and the current changes with depth. Currents vary by location. Historical data for the location of the wind turbine can be used to estimate
realistic current velocities. Current data for the proposed wind turbine site was downloaded from the U.S. Global Ocean Data Assimilation Experiment’s Live Access Server, http://www.usgodae.org/las/getUI.do, for available years, 2006 to 2013, and available depths, 0 m to 125 m below the surface [44]. The current velocity was greatest at the surface, about 1 m/s, and decreased to nearly zero at the bottom. As a factor of safety, the calculations were done with current values between 1 and 2 m/s.

The resultant tension in the rope was found by solving force balance equations on an infinitesimally short length of rope. Figure 3-3 shows a free body diagram of a segment [45]. Tension depends on the angle of the rope, which changes along the length.

Summing the forces normal to the axis of the segment gives,

\[ F - w \delta s \cos(\theta + \delta \theta) - (F + \delta F) \cos(\delta \theta) + (T + \delta T) \sin(\delta \theta) - f(s) \delta s = 0 \]

Taking the differential, dividing by the length \( ds \), and simplifying gives,

\[ \frac{dF}{ds} + w \cos \theta - T \frac{d\theta}{ds} + f(s) = 0 \]

The shear force \( F \) is equal to \( \frac{dM}{ds} \), and the curvature \( \frac{1}{R} = \frac{M}{EI} = \frac{d\theta}{ds} \). M represents the internal moment, E is the Young’s Modulus, and I is moment of inertia of the cross section [45].
Substituting this information into the equation above,

\[
\frac{d^2}{ds^2}(EI \frac{d\theta}{ds}) - T \frac{d\theta}{ds} + w\cos\theta + f(s) = 0
\]

Assuming the stiffness \( EI \) is zero, we get an equation for \( \frac{d\theta}{ds} \),

\[
\frac{d\theta}{ds} = \frac{w\cos\theta + f(s)}{T}
\]  \( \text{(3.4)} \)

Summing the forces tangent to the axis of the segment gives,

\[
-T - w\delta s \sin\theta + (F + \delta F)\sin(\delta\theta) + (T + \delta T)\cos(\delta\theta) = 0
\]

We neglect the drag force acting tangentially. Taking the differential, dividing by the length \( ds \), making the same substitution for \( F \), and simplifying gives,

\[
\frac{dT}{ds} = ws\sin\theta
\]  \( \text{(3.5)} \)

The rope chosen for the device stretches, which must be taken into account in the equations used to find the shape and tension of the rope. The manufacturer provided a graph of the rope’s elongation as a function of tension, seen in figure 3-4. The best fit line for this region of the graph was used to determine the strain. Given the tension in a segment of the rope and the equation found for strain, the elongated length of each segment of rope was found using equation 3.6. The x- and y-coordinates for the next point on the rope were calculated from the elongated segment.

\[
ds_{elong} = ds_{initial}(1 + strain(s))
\]  \( \text{(3.6)} \)

With equations 3.4, 3.5, and 3.6, the tension \( T \) and angle \( \theta \) were calculated for discrete points along the length of the rope. The boundary conditions were given by the wind turbine.
Figure 3-4: Novablue graph showing the relationship between tension applied and rope elongation [46]

geometry. In order to satisfy the boundary conditions, the initial tension and angle at the bottom of the roller were guessed and the Forward Euler method of numerical integration was used to calculate the position of the top end of the rope. The calculated position was compared to the known boundary condition at the top end, and if they were sufficiently similar, less than $10^{-6}$ difference, the initial guesses were correct. If not, MATLAB’s nonlinear system solver, `fsolve`, based on the Trust-Region Dogleg Method, was used to iteratively find the correct initial tension and angle [47].

### 3.1.2 Representative System

In the United States, the Block Island Wind Farm, about 4 mi from Block Island, Rhode Island, is the first, and currently the only, commercial offshore wind farm [48]. Water depths are only about 23 to 28 m, which would limit the length of the adsorbent ball-chains if the uranium extraction system were to be installed on these bottom-mounted offshore wind
turbines. Current velocity data for the latitude and longitude of this site indicated that the water moved about 1 m/s near the surface and decreased to about zero at 25 m below the surface [49]. An offshore wind farm is in the planning phase for the North shore of Oahu, Hawaii where the water depths are upwards of 400 m [50]. Current velocity data for these proposed global coordinates indicated little to no current from the surface down to 125 m [49]. On the other hand, if a coupled offshore wind turbine and uranium extraction system were constructed in the vicinity of a boundary current, such as the Gulf Stream which follows the eastern coast of the U.S., the system could expect to see currents ranging from 0.5 to 1.5 m/s [51]. Based on these different current predictions, conservative current velocity values of 1 to 2 m/s were selected.

The tension and rope shape were found for six cases where each case represented a different unstretched rope length. A shorter unstretched rope length equates to increased pretension on the rope when it is looped between the rollers. Unstretched rope length varied from 120 m to 130 m by increments of 2 m. Figure 3-5 shows the deformed shape of the rope with an unstretched length of 120m. This initial length resulted in the smallest deflection of the cases tested, about 2 m, which seemed reasonable for the geometry of the wind turbine and adsorbent ball-chains. The left plot shows that the velocity varied from 1 m/s at the bottom to 2 m/s at the surface, above which it went to zero. The center plot shows the deformed shape of the rope. The right plot shows how the rope tension varies along the length. When the rope comes out of the water, there is no longer a buoyancy force acting on it, so there is a sharp change in the tension.

Solving the system of equations with different rope lengths was necessary because different amounts of pretension result in different maximum deflection. As the pretension increases, the maximum deflection decreases as can be seen in Figure 3-6. Pretension stretches and lengthens the rope. Thus, for the rope to satisfy a maximum deflection design constraint as well as the boundary conditions, the unstretched length must be shorter than the point-to-point distance between the rollers.
Figure 3-5: Current velocity, adsorbent ball-chain deformation, and tension for unstretched length of 120 m.
Figure 3-6: Comparison of the adsorbent ball-chain deformation as a function of maximum tension, indicated by the *. As tension increases, deformation decreases.
3.1.3 Rope Influence on Uranium Extraction Device

To achieve a static deformation of less than 2 m, the maximum tension in the rope would be 72,079 N, which is about 41% of the rope tensile strength. 41% is outside the range of the rope strength-strain relation given by Novablue, so a more conservative option would be to change the design. One could choose a stronger rope or a thicker diameter rope of the same material to achieve a higher tensile strength. A thicker rope, however, would result in more drag. On the other hand, smaller adsorbent shells would decrease the drag force. A less stretchy rope would result in less deformation if space was a serious concern. If more deformation can be tolerated, then the pretension can be reduced. Any of these factors could be changed, and the model could be rerun to quickly obtain updated results to satisfy the design constraints.

With regard to the current velocity the representative system would see, as of April 2017, the first floating offshore wind farm is under construction in Aberdeenshire, Scotland and scheduled to start power production later in the year [52]. Water depths in the vicinity of the wind farm are between 90 and 120 m. It would be beneficial to look into the historical current data for this site to see how it compares to the conditions estimated in the representative system. These velocities could be input to the model to determine the rope tension and static deformation.

3.2 Dynamic Response of Rope

Vortex-induced vibrations have a significant impact on the fatigue life of bluff bodies. Higher frequencies of oscillation will shorten fatigue life, while damping will improve fatigue life. The resonant response of the ball-chain will give an indication of how long it may remain in service in various currents.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Full Scale Dimensions</th>
<th>Model Dimensions</th>
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<tr>
<td>shell diameter (m)</td>
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<tr>
<td>shell spacing (m)</td>
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<td>0.123</td>
</tr>
<tr>
<td>rope diameter (m/s)</td>
<td>0.025</td>
<td>0.007</td>
</tr>
</tbody>
</table>

Table 3.2: Full-scale and model flexible ball-chain dimensions determined by geometric scaling.

3.2.1 Fabricating and Testing a Flexible Model Ball-Chain

A flexible model of the ball-chain was fabricated and mounted to the MIT Towing Tank carriage to determine the coupled in-line and cross-flow hydrodynamic response. The full-size ball-chain was scaled by 0.292 to build the model. Table 3.2 gives the full-scale and model dimensions.

The rope used in the model was a rubber gasket material with a diameter of 7 mm. Standard practice baseballs were painted black and adhered to the rope with a silicone-based epoxy. The rope (black) was painted to create alternating black and white segments between the baseball shells. The coloring scheme was important for employing an optical tracking method of measuring in-line and cross-flow rope displacements as developed by Fan et al. [53]. The finished model ball-chain was about 2 m long with 30 white nodes. GoPro Hero4 cameras recorded the motion of the rope from behind (downstream) and above. The video was processed in MATLAB to get the displacement of the rope at each white node at a frequency of 240 Hz. Figure 3-7 shows the experimental setup.

3.2.2 Displacement and Resonant Response Frequencies

The carriage was moved at velocities between 0.10 m/s and 0.50 m/s in increments of 0.05 m/s. The video data was processed to get displacement of the rope at each node in cm. Figure 3-8 is an example of the cross-flow displacement plotted over time of the rope at 0.34L. This point of the rope oscillated sinusoidally at 0.30 m/s. Figure 3-9 shows the mean of the 10% largest displacements of each node for each velocity. The rope formed a half sine wave in the cross-flow direction with increasing amplitude for 0.15-0.30 m/s. The maximum
(a) Flexible model mounted to carriage  
(b) GoPro cameras track motion

(c) Still image from camera. Only the white segments were tracked

Figure 3-7: Flexible model setup in the MIT towing tank.
displacement occurred at midspan and was equal to about 2 to 3.5 times the rope diameter, or 0.20 to 0.34 times the shell diameter. At 0.35 m/s the rope started to exhibit the first and second modes of vibration. The rope formed a full sine wave for 0.40 to 0.50 m/s. The maximum displacement occurred a quarter-span from the ends and was equal to about 2.5 to 2.9 times the rope diameter, or 0.24 to 0.27 times the shell diameter. In both modes, the amplitude of the motion relative to the rope diameter was large compared to typical VIV. Thus, it was concluded that the dominant diameter driving oscillations was the shell rather than the rope. There were no oscillations in the in-line direction, only static deflection due to drag.

A Fourier Transform was applied using MATLAB’s `fft` function, and the corresponding one-sided power spectrum was calculated and plotted [54]. Figure 3-10 is an example of the power spectrum plotted on a log-log scale where the x-axis is given in Hertz. The peak frequencies, corresponding to the frequencies of self-excited oscillations, were found from the
Figure 3-9: Maximum displacement of flexible model at velocities between 0.15 and 0.50 m/s.
Figure 3-10: Power Spectrum with a peak at 0.72 Hz corresponding to lock-in at 0.30 m/s flow velocity.

The mean 1/10 largest response amplitude was plotted as a function of reduced velocity in Figure 3-12. The reduced velocity, equal to $U/f_n D$, was calculated based on diameter and the ball-chain’s natural frequency in water. For a smooth cylinder of constant diameter, $D$ in the equation for reduced velocity would be straightforward. However, the diameter of the ball-chain varied along its length. Therefore, the reduced velocity was calculated both ways, using rope diameter and shell diameter, and compared in Figure 3-12. The natural frequency depended on the length of the rope, $L$, the tension, $T$, the mass ratio of the chain, $\mu = \frac{m_{\text{chain}}}{\rho_{\text{water}} V_{\text{chain}}}$, and the added mass coefficient, $m_a$.

$$f_n = \frac{1}{2L} \sqrt{\frac{T}{\mu + m_a}}$$
The added mass was assumed to be equal to 1, which is typical for a cylinder.

The actual added mass coefficient was not equal to 1, though. It varied with velocity (and thus Reynolds Number) because the shape differed from a smooth cylinder. Figure 3-13 shows the resonant response frequency divided by the natural frequency as a function of reduced velocity. If the added mass was equal to 1, then the frequency of response would be the same as the natural frequency, and thus their ratio would equal unity. However, the ratio of frequencies is greater than 1, so the added mass must be different.

The effective added mass coefficient, $C_a$, was calculated by substituting the experimentally determined resonant response frequency into equation 3.7. Figure 3-14 shows that added mass varied with flow velocity. Some of the values are negative, which indicates that the added mass goes in the direction of the ball-chain acceleration. This result was found to
Figure 3-12: Mean 1/10 largest response amplitude versus reduced velocity for a mass ratio $\mu = 0.8745$.

Figure 3-13: Ratio of response frequency to natural frequency, which would be equal to unity if the added mass of the rope was constant and equal to 1.
Figure 3-14: Effective added mass coefficient versus reduced velocity for a mass ratio $\mu = 0.8745$.

occur with buoyancy modules attached to risers as well [55, 56].

$$f_{response} = f_n \left[ 1 + \frac{\pi C_a}{4\mu} \right]^{-1/2} \quad (3.7)$$

3.2.3 Application to Fatigue Life

The frequency of the ball-chain resonant response jumped between velocities 0.35 and 0.40 m/s when the vibrations changed mode shape. The decrease in amplitude of motion corresponds with the change in mode shape as can be seen in Figure 3-12. Figure 3-12 also shows that the resonant response of the ball-chain was large relative to the rope diameter and slow relative to typical cylinder response frequencies for the same reduced velocity. This indicated that the shells attached to the rope dominated the ball-chain’s response and damped
the vibrations of the rope. Slower vibrations will likely extend the fatigue life of the rope compared to faster vibrations.
Biofouling has a negative impact on uranium adsorption. It adds weight, increases drag, reduces uranium uptake, and decreases the potential for reuse [57]. For a uranium extraction device to be commercially viable, there must be a strategy to mitigate biofouling. Science has not uncovered a perfect solution, but there are several techniques and mechanisms that can reduce biofouling.

4.1 Prior Investigations

Most experiments involving uranium adsorbent use seawater that has passed through filters as small as $0.35 \text{ \mu m}$, which removes biofouling organisms so that biofouling has no affect on the experimental results. A few studies, though, used unfiltered seawater, or they were deployed in the ocean to represent more realistic biofouling conditions.

**Light and Dark Flume Exposures with 150 \text{ \mu m Filtered Seawater}**  The Pacific Northwest National Laboratory (PNNL) designed and carried out two experiments to quantify the effect of biofouling on uranium adsorption [58]. In the first, they set up two identical, recirculating flumes with AI8L2R2 amidoxime-based adsorbent fibers from Oak Ridge National Laboratory spaced out along the length. One flume was covered with a black tarp so
that no light entered. The other flume was exposed to 75 W, daylight spectrum compact fluorescent lights for twelve hours on, twelve hours off. Seawater from Sequim Bay, Washington passed through a 150 μm filter to remove large particles, but most phytoplankton species associated with biofouling passed through. The experiment ran for 42 days, after which the adsorbent fibers were analyzed to determine the increase in biomass. They found that biofouling reduced uranium uptake by about 30% in the flume exposed to light [58]. There was little to no reduction in uranium uptake in the dark flume. The accumulation of biomass occurred rapidly during the second and third week then slowed considerably during the remaining time. Figure 4-1 shows PNNL’s resulting adsorbent capacity from the light and dark flumes as well as a control sample that received 0.35 μm filtered seawater and a reference sample from a previous experiment [58].

The second experiment PNNL carried out involved filtered seawater and pre-fouled adsorbent fibers [59]. AF1L2R2 amidoxime-based adsorbent fibers from Oak Ridge National Laboratory were pre-fouled with Navicula incerta, a marine benthic diatom commonly used in anti-fouling experiments. Then the fibers were packed into flow-through columns. Some
columns were covered with aluminum foil to prevent light from entering, and others were subjected to the same diurnal daylight spectrum described above. The seawater used in this experiment came from Sequim Bay and passed through a 0.45 μm filter before reaching the columns, which removed all biofouling organisms. Researchers found that after 42 days, the pre-fouled fibers in the dark condition adsorbed 15% less uranium compared to non-fouled fibers [59]. The pre-fouled fiber exposed to light and filtered seawater adsorbed about 30% less uranium.

Both experiments demonstrated that biofouling decreases uranium uptake, and exposure to sunlight enhances biofouling. Researchers recommended that the adsorbent material be deployed in the ocean below the photic zone where there is little light [58]. However, to escape light, the adsorbent must be placed at deeper depths where temperatures are lower. Lower temperatures are less favorable for uranium adsorption, therefore, neglecting other antifouling measures, there is a trade-off between decreased uranium adsorption due to lower temperatures and increased uranium adsorption due to less biofouling.
Steel, Copper, and Nylon Enclosure Comparison in Seawater Amidoxime-based adsorbent fibers were enclosed in either steel, copper, or nylon cages and deployed in seawater at 5 m and 12 m below the surface to determine the effect of the enclosure material on uranium uptake (citation). The amount of biofouling growth on the enclosures was measured by recording the weight before and after deployment. The uranium uptake was also measured. In general, after 49 days in the water, the enclosures at 5 m had more growth than the enclosures at 12 m as expected because they received more sunlight. The weight measurements were inconsistent, though, during the deployment period and there were no clear trends indicating that one material was better than the others. The amount of uranium adsorbed in each enclosure was fairly consistent at a depth of 12 m while it varied significantly at 5 m. It was hypothesized that the steel and copper enclosures may leach metallic ions that impede uranium uptake. However, more experiments need to be conducted to determine the effect of different enclosure materials on uranium uptake, especially since many commercial anti-fouling coatings make use of copper and silicon.

Moving and Stationary Uranium Extraction Devices in Seawater Researchers at MIT along with students at the Massachusetts Maritime Academy built and deployed one-tenth scale models of a stationary and continuously rotating uranium extraction devices at Taylor Point on Buzzards Bay, Massachusetts [23]. Adsorbent enclosure shells were clamped to rope to create nets of shells, some of which contained amidoxime-based adsorbent material. The nets were submerged vertically in the water for a total of 56 days, and one sat stationary while the other moved continuously in a loop. The light and temperature differences between the top and the bottom are shown in Figure 4-3 [23]. At the end of the 56-day trial, the stationary system had considerably more biofouling than the moving system. Figure 4-4 shows the difference in biofouling on the stationary, 4-4a, and continuous, 4-4b, systems. It was believed that the shells of the continuous system rubbed against the rollers, helping to prevent or remove biofouling.
Figure 4-3: Light intensity and temperature measured at the top, middle, and bottom of the uranium adsorbent net [23].

Figure 4-4: Biofouling on a stationary submerged net of adsorbent shell enclosures compared to a continuously moving submerged net [23].
4.2 Antifouling Recommendations

Both the uranium adsorbent material and the uranium extraction device need to be protected from biofouling. Previous experiments showed that lack of sunlight can help prevent biofouling on amidoxime-based adsorbent material. This finding is consistent with other studies in the literature. There may be a point where temperature, sunlight exposure, and uranium adsorption can be optimized such that biofouling is minimized while adsorption capacity remains acceptable. However, more research needs to be done to find that point of optimization and determine if it is achievable in the vicinity of offshore wind turbines. It may be more practical instead to adapt the surface texture or surface chemistry of the adsorbent material such that it favors uranium uptake while being unfavorable to organisms responsible for biofouling. Studies show, though, that there is no surface texture or chemistry that is universally effective at preventing biofouling. Specific species can be targeted, but the diversity of organisms in the ocean makes this approach impractical as well. Because it may be difficult to avoid sunlight altogether, it may be helpful to make the shell enclosures black with as few holes as feasible to shade the adsorbent material from sunlight.

Looking at the adsorbent shell enclosures instead, mechanical abrasion was found to help prevent biofouling. This method is similar to cleaning techniques employed on other submerged structures. Studies show that some combination of mechanical and chemical means of anti-fouling will likely be most effective. Thus, the most likely way to prevent biofouling on the shell enclosures using current technology may be to use some sort of non-stick surface, keep the nets moving through the water, and use light mechanical cleaning techniques to remove growth periodically. More research needs to be done to determine the effect of different enclosure or coating materials on uranium uptake. It is possible that commercially available, non-toxic foul-release coatings would be highly effective at preventing strong adhesion of fouling organisms without leaching ions that would impede uranium uptake. The uranium extraction device could be fit with brushes or abrasive material where the nets comes in contact with it. A less attractive, though effective, method would be to
clean the shells by hand as is done with ship hulls.

One factor that works in favor of system is the relatively short deployment period between elution cycles and the elution bath itself. The most current design for the coupled uranium extraction device uses a campaign length of 23 days, which is relatively short in terms of biofouling. In this time, the shells will likely accumulate a slime layer and light algae growth, but relatively few hard, macro-fouling organisms. Furthermore, the chemicals used in the elution bath will likely kill what organisms do start to grow on the adsorbent nets. Even a fresh-water rinse would kill the organisms. Then brushes would easily remove the dead growth before redeployment.

Further testing is needed to find the best solution to prevent biofouling on the adsorbent material, but current knowledge and technology is promising for the shells and the uranium extraction device itself. Reducing exposure to sunlight and maintaining movement help minimize growth as well.
Chapter 5

Conclusion

This research examined the flow through and around adsorbent shell enclosures for a uranium extraction device coupled with an offshore wind turbine using computer-based modeling and scaled experiments in the MIT Towing Tank. The results provided information for effective implementation of the uranium extraction device.

5.1 Principal Findings

Experimental drag measurements showed that the coefficient of drag on the shells was higher than that on a sphere. The shell with big holes exhibited the largest coefficient of drag. The addition of fibers to the shells further increased the drag on the shell with big holes. The coefficient of drag for the wiffle shell was slightly higher than the slotted shell, though the two values were fairly comparable.

Velocity streamline images and experimental dye trials both showed that the flow went through the shell with big holes relatively unobstructed, whereas much of the flow went around the wiffle and slotted shells. As a result, the center of the shell with big holes saw higher flow velocity, and the center of the wiffle and slotted shell saw slower moving eddies. It is possible that the shell design could be tailored to create the ideal internal flow patterns and velocities, and CFD could be used to visualize the flow.
The drag force has a significant impact on the static deflection of the ball-chain of adsorbent shell enclosures. Larger drag forces cause larger deflections, and to counter the deflection, the rope has to carry more tension. Increased rope tension requires greater reinforcement at the rollers and more power to move the ball-chains. Thus, accurate tension calculations are necessary to ensure proper design of the uranium extraction device. A script was written in MATLAB to quickly calculate the tension due to current and self-weight for any combination of device design parameters and wind turbine geometries.

The flexible ball-chain experienced vortex-induced vibrations driven by the shells over a range of reduced velocities. The fatigue life of the rope corresponds with the number of oscillations it sees during its use, so larger, slower oscillations could extend the life compared to a rope without shells. However, care must be taken to ensure than adjacent ball-chains do not collide and cause physical damage.

The best defenses against biofouling are foul-release coatings, darkness, movement, and frequent cleaning. Foul-release coatings prevent organisms from strongly adhering to the surface, and fresh-water washes combined with mechanical cleaning should remove much of the growth that accumulates. Sunlight accelerates biofouling growth, so deploying the uranium extraction device at greater depths would lessen the effect of the sunlight. Another solution might be to paint the shells black or another dark color to shield the adsorbent material from light.

5.2 Future Work

More work should be done to improve the simulation of flow through and around the shells. Qualitative results seemed reasonable, but quantitative results varied between CFD programs and did not agree well with experimental results in all cases. Several studies have looked at the influence of flow velocities between roughly 0.01 to 0.10 m/s on the adsorbent material, but these velocities could be too low compared to those seen in the ocean. Further
investigations of higher flow velocities and their impact on uranium uptake are needed.

The next step with the static ball-chain deflection model is to incorporate dynamic wave loads and vortex-induced vibrations to see how the maximum deflection changes and whether or not the ball-chain needs to be stronger. The model also needs to be extended from one ball-chain to a net of ball-chains. It would be useful to model current from different directions to see what sort of twisted shape may result.

The resonant response of the ball-chain depended on the ratio of diameters and the shell spacing along the rope. If the spacing between shells is changed or the diameter of either the rope or the shells is changed, the resonant response is likely to be different. A few different spacings should be tested to see if results are consistent. The spacing or relative diameters could be tuned to avoid or target certain current velocities if fatigue is a limiting factor or if an optimal condition for uranium uptake is found.

More work needs to be done to determine the effect of non-toxic foul-release coatings on uranium uptake as well as its effectiveness at preventing biofouling on adsorbent shell enclosures. The long-term environmental effects of these coatings is not well understood. Further testing of potential anti-fouling measures should be conducted in the ocean environment to hone in on a solution.

5.3 Perspectives

This thesis involved a narrow scope of research related to a much broader investigation into uranium extraction from seawater, involving numerous disciplines. Yet, the understanding gained supports the premise that uranium extraction from seawater is feasible and can one day provide fuel and price security for uranium while minimizing the environmental footprint of the mining process. The device designed with contributions from this research need not necessarily be installed on an offshore wind turbine. The concept could be implemented on other structures as well, broadening the applicability. Lastly, because the ocean contains a
plethora of valuable metals and minerals, this technology could potentially be used with any type of adsorbent material, creating viable reserves of other materials in high demand in the developed and developing world.
Bibliography


