Group N: Fluid Flow Testing Apparatus

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Fluid Flow Testing Apparatus

A fluid flow testing apparatus was needed to accurately test valves relative to the conditions seen in the factory of a local St. Louis brewery. After concept generation, a rotating track that toggled the valve between open and closed was decided on by the team. Construction of an initial prototype was done over 3 weeks with a total budget of 400 USD. The initial prototype satisfied almost all of the performance goals: capable of cycling 200 times without intervention, 1 paper-towel of leakage at most, and upper reservoir level consistency within 10 percent.

To improve the initial prototype, the team upgraded the upper reservoir, made the track more precise, and scaled up the entire apparatus. Final prototype construction took 3 weeks. Furthermore, stress and displacement analysis were performed on the track to ensure longevity of the component. The final prototype met all the performance goals and stayed well within budget. Meanwhile, the team of Jon Fleming, Abel Soloman, and Braden Kerr presented the progress to the MEMS 411 class and received feedback and questions. The final prototype was displayed at the Design Expo and the team was honored to be voted best design and prototype by peers.

Jonathan Fleming
Abel Soloman
Braden Kerr
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1 Introduction

St. Louis is home to breweries large and small that devote a high fraction of their time formulating new beverages to entice new customers. Often times, these new innovations push the limits of the brewing equipment that has been used since beer was first brewed in the Middle Ages [1].

The goal of this design project is to construct an effective mechanism and procedure to test new valve-head plate designs to be used in fillers during the canning process. The mechanism will give insight into cycle fatigue, estimated lifetime, and strengths and weaknesses of each valve-head plate design, among other valuable statistics. Using this mechanism, brewers in the area will have a way to quickly test valve-head plate designs in order to streamline their innovation process as well as add versatility to existing brewing equipment.

2 Problem Understanding

2.1 Existing Devices

Life-cycle testing apparatuses are used across industries. We’ll be focusing on those within the fluid mechanics discipline. Below are descriptions of three apparatuses that serve a purpose similar to that which this design project is aimed toward.
2.1.1 Existing Device #1: Butterfly Valve Type Testing Machine

Figure 1: Butterfly Valve Testing Machine (Source: Aakash Hydraulics)


Description: This apparatus, by Aakash Hydraulics, is used to test Butterfly Valves for proof of design, life cycle, and type tests. It follows the AWWA 506 standards. It stores data on a computer in graphical and analytical modes. This testing apparatus is valuable because it tests the valve in a variety of situations: leakage, differing hydrostatic pressures, and cycles, just to name a few. It is limited in that it only works for butterfly valves, so it is not as flexible as this design project’s apparatus. Also, there is no evidence that valve-head plates can be added to the butterfly valves tested in this apparatus, which is the primary goal of this design project.
2.1.2 Existing Device #2: Safety Valve Test Bench

Description: The TPU Series Safety Valve Test Bench by Shanghai Zengxin Machine Electron Technology Company is meant to test kinds of safety relief valves. Various relief valves can be tested, including: full-open, micro-open, imperial, metric, flanged, and threaded. The valves can be put under clamps of adjustable force, as well as pressures exerted by water or Nitrogen. The apparatus itself is on wheels but very heavy and not easily transported. The data recording system and physical setup (bench) allow for more customization in tests. It is operated by the Standards of pressure releasing equipment, GB-T12242-2005 and according to the Common International Test Standards API526, ANSI/API TP576, and API527.

2.1.3 Existing Device #3: Tap Valves Life Cycle Tester

![Tap Valve Life Cycle Tester](source: D&S Trading Co.)

**Figure 3: Tap Valve Life Cycle Tester**


**Description:** This Tap Valve Life Cycle Tester by D&S Trading Company is made to provide hot and cold pressured water to test life cycle of various plumbing fittings. This includes tap valves and valves with single hand controls. Physically, the apparatus is completely contained in a single, mobile station. It consists of three configurations that change the clamping system, which can test different products. It uses a Centrifugal pump to maintain water pressure, and has a tank of $> 80L$. This capacity is out of scope for this design project as we will be aiming for something much smaller in scale. A concrete advantage to this apparatus is that it can run three trials simultaneously.

2.2 Patents

2.2.1 Filling System

*(US2892472A)*

This patented work relates a filling system to a system for continuously delivering carbonated liquids from a storage tank to a filling machine while containers are being filled. This system requires a storage tank for the carbonated liquid and a filling machine with a reservoir for receiving the carbonated liquid from the storage tank for delivery to containers. Such carbonated liquids include beer. In this system, Surges and churning of the beer being flowed are prevented by flowing beer continuously from a storage tank into the reservoir of the filling machine while containers are actually being filled.
2.2.2 Automatic Shutoff Dispensing Nozzle Valve (US2582195A)

This patent is issued for an invention that relates to automatically operating flow control Valves or nozzles which are automatically closed by filling of a receptacle. The working mechanism includes a flexible diaphragm made to react to pressure on opposite sides which shuts off an automatically
operating flow control valve. The reaction prevents the flow of liquid through dispensing devices. This invention also addresses the manual opening and closing of the valve with an automatic trip based on the position of a hand lever.

Figure 5: Patent Images for the Automatic Shutoff Dispensing Nozzle Valve
2.2.3 Nozzle Tester
(US2517766A)

This patent is for a device to test various types of nozzles for their spray pattern, pressure, valve operation and has the purpose of making it easier to interchange the nozzles being tested. The device has a cradle into which the nozzle to be tested is loaded before the cradle is closed around the nozzle. There are various settings that can be used to test various parameters of the devices.

Figure 6: Patent Images for the Nozzle Testing Device
2.3 Codes & Standards

2.3.1 Beer-Approved Materials (ATF 95-1)

This TTB (Alcohol and Tobacco Tax and Trade Bureau) standard details the process to gain permission to use a new material in the production of beer. Not all materials are pre-approved, and applying for one to be added to the list is preferably avoided. The design team will keep this standard in mind when deciding what kinds of materials the beer will come in contact with in the apparatus because breweries will use this to decide which valve-head plate designs can be scaled to full-production. If any material isn’t approved, the design cannot be scaled to full-production.

2.3.2 Centrifugal Pumps for Design and Application (ANSI/HI 1.3-2009)

This standard, posted by the American National Standards Institute, outlines how to most effectively use a centrifugal pump. It has sections including details on the impellers, mechanical features, noise levels, selection criteria, and many more. It is relevant to this design project because a pump is critical to the design concept, and a centrifugal pump will be considered in the design process. Following these standards will allow the team to maximize the potential use of a centrifugal pump and inform our decisions on servicing and replacement in the future.

2.4 User Needs

2.4.1 Customer Interview

Interviewee: Unnamed Local Brewery Contact

Location: Urbauer 320, Washington University in St. Louis, Danforth Campus

Date: September 6th, 2019

Setting: The interview was conducted in the fluids lab on campus. The current designs we had brainstormed for valves were drawn on a whiteboard and the tubing we had used for preliminary tests of various basic nozzle designs. We drew ideas for a cyclic nozzle testing machine on the board and the interview lasted ~30 minutes.

Interview Notes:

What are the typical uses of the device?
- To test various nozzle plate designs for extended periods of time.
- To test if nozzles clog after repeated use over a long duration
- To determine if nozzle designs would break after extended use.

What are the current likes and dislikes of the product?
- One negative is that the current testing apparatus is very basic and doesn’t allow for extended duration testing.
- One positive is that the apparatus allows for accurate testing with regards to the pressure the nozzle would be under.
- One positive is that the current design allows for quick changing of the plate design to test various designs.
− One negative is that the design required holding the apparatus and would not be suitable for long duration testing.

2.4.2 Interpreted User Needs

After the customer interview, the team condensed the needs and the results can be seen in Table 1.

Table 1: Interpreted Customer Needs

<table>
<thead>
<tr>
<th>Need Number</th>
<th>Need</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Needs to run for long periods autonomously</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>Needs to be able to have nozzles changed out easily</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Needs to maintain proper mixing of dissolved particles in product</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>Needs to test if broken product is caught by the nozzle design</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>Portable design</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>Durable for being in a factory setting</td>
<td>3</td>
</tr>
<tr>
<td>7</td>
<td>Determine if nozzle holds or releases prime per each trial</td>
<td>5</td>
</tr>
<tr>
<td>8</td>
<td>Easy to operate</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>Replicate the rotational element of brewery filling machine</td>
<td>2</td>
</tr>
</tbody>
</table>

The interpreted needs are mainly focused on the ability of the apparatus to test various products for long periods of time to replicate long periods of use in a factory setting.

2.5 Design Metrics

5 metrics were identified as important to the success of the apparatus. Table 2 summarizes these metrics and shows their acceptable levels.

Table 2: Target Specifications

<table>
<thead>
<tr>
<th>Metric Number</th>
<th>Associated Needs</th>
<th>Metric</th>
<th>Units</th>
<th>Acceptable</th>
<th>Ideal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5, 6</td>
<td>Total weight</td>
<td>kg</td>
<td>12</td>
<td>9</td>
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<tr>
<td>2</td>
<td>5</td>
<td>Total volume</td>
<td>ft³</td>
<td>&lt; 8</td>
<td>&lt; 6</td>
</tr>
<tr>
<td>3</td>
<td>1, 3</td>
<td>Volume of liquid in system</td>
<td>Liters</td>
<td>&gt; 5</td>
<td>&gt; 10</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>Run continuously on battery power</td>
<td>days</td>
<td>&gt; 7</td>
<td>&gt; 14</td>
</tr>
<tr>
<td>5</td>
<td>6, 7</td>
<td>Ability to keep electronics dry</td>
<td>binary</td>
<td>Pass</td>
<td>Pass</td>
</tr>
</tbody>
</table>

2.6 Project Management

Project and time management is important to the development of the final prototype. The Gantt chart in Figure 7 gives an overview of the project schedule.
<table>
<thead>
<tr>
<th></th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
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<tbody>
<tr>
<td>26</td>
<td>2</td>
<td>9</td>
<td>16</td>
<td>23</td>
<td>30</td>
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<tr>
<td>7</td>
<td>14</td>
<td>21</td>
<td>28</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>18</td>
<td>25</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Design Report
- Problem Understanding
- Concept Generation
- Concept Selection
- Concept Embodiment
- Design Refinement
- Peer Report Grading

### Prototypes
- Mockup
- Proofs of Concept
- Initial Prototype
- Initial Prototype Demo
- Final Prototype
- Final Prototype Demo
- Prototype Expo

### Presentations
- Critical Design Review
- Final Presentation

Figure 7: Gantt chart for design project
3 Concept Generation

3.1 Mock-up Prototype

After beginning to build our mock-up prototype, we realized that our original idea would not be the best in terms of functionality moving forward. Having a flat backboard to mount the pump, the fill valve, tubing, and tank for the testing rig was found to be harder than anticipated because of the weight of the fill valve mechanism and necessity of having the tubing being mounted behind the valve. The entrance to the nozzle is at the back of the valve which means mounting it against the backboard would block the entrance. In addition to this issue, we determined that a more accurate model would involve the nozzle mechanism being mounted on a rotating plate to more accurately simulate factory conditions. These realizations have led us to combine the backboard design and rotating plate design detailed in the three prototype ideas in the sections below.

Figure 8: Front view of the mock-up prototype. The Styrofoams on top and right of the bucket depict a fill valve and a pump respectively.
Figure 9: Side view of the mock-up prototype. The tubing goes from the the tank (depicted by the bucket) through the pump and to the back of the fill Valve.

Figure 10: Close-up view of the mock-up prototype. The tank (depicted by the bucket) serves as a reservoir to collect liquid being dispensed from the fill valve.
Figure 11: Isometric view of the mock-up prototype.
3.2 Functional Decomposition

Figure 12: Function tree for valve-head plate testing mechanism, hand-drawn and scanned
3.3 Morphological Chart

Figure 13: Morphological Chart for valve-head plate testing mechanism
3.4 Alternative Design Concepts

3.4.1 Hand Holding Oscillator

![Figure 14: Preliminary sketches of Hand Holding Oscillator concept]
Solutions from morph chart:

1. Tank with hose to top
2. Secured, easily accessible, unobscured
3. Dynamic pressure from pump
4. Utilize internal arm mechanism
5. Battery-powered oscillation
6. Backboard with supports

Description: A motor powers an Arm on the backside of the backboard. The Arm holds the Hand of the valve that toggles the internal open/close mechanism. Fluid flows according to the Hand’s position through the valve-head into a tank underneath. The fluid is pumped from the tank to the top of the valve where the process repeats itself.

3.4.2 Rotating Circular Base

Figure 16: Preliminary sketches of Rotating Circular Base concept
Solutions from morph chart:

1. Tank with hose to top
2. Detachable lock + key
3. Dynamic pressure from pump
4. Utilize internal valve arm mechanism
5. Electrical motor rotation
6. Standing beam (vertical)

Description: An electric motor rotates a cylindrical container that has cut-outs on its surface to guide the fill valve arm to open or close position. The fill valve is mounted on a non-rotating vertical beam. A dynamic pressure from a pump pushes liquid from a tank to the fill valve via a hose mounted at the back of the valve. The tank is also used as a reservoir to collect the dispensed liquid and feed it back to the pump.
3.4.3 Backboard mounted System

Figure 18: Preliminary sketches of Backboard Mounted System concept
Figure 19: Final sketches of Backboard Mounted System concept

Solutions from morph chart:

1. Recirculatory tank and pump system
2. Nozzle mechanism that has interchangeable nozzle placements
3. Dynamic pressure from pump pressure
4. Plate valve controlled by Arduino led actuator
5. Arduino controls power supply to pump

6. Solid backing to hold up nozzle mechanism through backboard

Description: An Arduino will control the power supply to the pump, allow for a cyclic process of providing the necessary pressure head above the nozzle to emulate the factory. In addition, the Arduino will control a plate valve that will open and close to simulate the shutting of the valve. The nozzle mechanism will stay open always and the flow will be controlled by the nozzle. The pump will draw from the retaining reservoir and feed the dispensed liquid back into the system to have continuous testing.
4 Concept Selection

In design selection process, one can evaluate different design concepts in matrix form at which the different functionalities of the design are evaluated numerically. The numerical evaluation of the design concepts help to make an informed and reasonable design selection.

4.1 Selection Criteria

Six selection criteria were chosen based on the functionality and the goal of this design project. The selected criteria are the reuse of fluid being tested, ease of changing nozzle plates, pressure buildup mechanism, flow shut off mechanism, automatic cyclic operation, and strong support system to hold the filling valve. Each criterion was then evaluated using Analytical Hierarchy Process (AHP). This process is used to determine the scoring matrix weights that are to be used in the concept evaluation step to select the best design concept. Figure 1 displays the Analytical Hierarchy Process (AHP) for the six selection criteria used. The numerical ratings are defined in the following way:

Row criterion is _______ than/as column criterion

Numerical ratings: 9 -- Extremely more important
7 -- Very strongly more important
5 -- Strongly more important
3 -- Moderately more important
1 -- Equally important
1/3 -- Moderately less important
1/5 -- Strongly less important
1/7 -- Very strongly less important
1/9 -- Extremely less important

<table>
<thead>
<tr>
<th></th>
<th>Reuses fluid</th>
<th>Easy to change plates</th>
<th>Pressure gradient</th>
<th>Flow shut off</th>
<th>Automatic cyclic operation</th>
<th>Support</th>
<th>Row Total</th>
<th>Weight Value</th>
<th>Weight (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reuses fluid</td>
<td>1.00</td>
<td>0.20</td>
<td>0.14</td>
<td>0.20</td>
<td>0.20</td>
<td>0.11</td>
<td>1.85</td>
<td>0.03</td>
<td>2.87%</td>
</tr>
<tr>
<td>Easy to change plates</td>
<td>5.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.33</td>
<td>0.33</td>
<td>0.33</td>
<td>8.00</td>
<td>0.12</td>
<td>12.40%</td>
</tr>
<tr>
<td>Pressure gradient</td>
<td>7.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>3.00</td>
<td>1.00</td>
<td>14.00</td>
<td>0.22</td>
<td>21.70%</td>
</tr>
<tr>
<td>Flow shut off</td>
<td>5.00</td>
<td>3.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>12.00</td>
<td>0.19</td>
<td>18.60%</td>
</tr>
<tr>
<td>Automatic cyclic operation</td>
<td>5.00</td>
<td>3.00</td>
<td>0.33</td>
<td>1.00</td>
<td>1.00</td>
<td>0.33</td>
<td>10.67</td>
<td>0.17</td>
<td>16.53%</td>
</tr>
<tr>
<td>Support</td>
<td>9.00</td>
<td>3.00</td>
<td>1.00</td>
<td>1.00</td>
<td>3.00</td>
<td>1.00</td>
<td>18.00</td>
<td>0.28</td>
<td>27.90%</td>
</tr>
</tbody>
</table>

Column Total: 64.52 1.00 100%

Figure 20: Analytic Hierarchy Process (AHP) to determine scoring matrix weights.
4.2 Concept Evaluation

The concept evaluation was done based on the scoring matrix weights obtained from the Analytic Hierarchy Process (AHP). Each alternative design concept developed during the concept generation stage is then evaluated based on the Weighted Scoring Matrix (WSM). Here, each design concept was rated on a scale of 1 to 5, 1 being the worst and 5 being the best, based on how the design satisfies each criterion.

![Figure 21: Weighted Scoring Matrix (WSM) for choosing between alternative concepts](image)

<table>
<thead>
<tr>
<th>Alternative Design Concepts</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Selection Criterion</td>
<td>Weight (%)</td>
<td>Rating</td>
<td>Weighted</td>
<td>Rating</td>
</tr>
<tr>
<td>Reuses fluid</td>
<td>2.87</td>
<td>3</td>
<td>0.99</td>
<td>3</td>
</tr>
<tr>
<td>Easy to change plates</td>
<td>12.4</td>
<td>3</td>
<td>0.37</td>
<td>3</td>
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<tr>
<td>Pressure gradient</td>
<td>21.7</td>
<td>3</td>
<td>0.65</td>
<td>3</td>
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<tr>
<td>Flow shut off</td>
<td>18.6</td>
<td>3</td>
<td>0.56</td>
<td>4</td>
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<tr>
<td>Automatic cyclic operation</td>
<td>16.53</td>
<td>3</td>
<td>0.50</td>
<td>5</td>
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<tr>
<td>Support</td>
<td>27.9</td>
<td>3</td>
<td>0.84</td>
<td>4</td>
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<table>
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<th>3.000</th>
<th>3.796</th>
<th>2.297</th>
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<tr>
<td>Rank</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

4.3 Evaluation Results

The results from the concept evaluation are used to select the best design concept. The Weighted Scoring Matrix (WSM) ranks the design concepts based on their total score. The total score is calculated by adding the weighted values, which is the multiplication of the the scoring matrix weights by the ratings, for each criterion. Based on our analysis, the rotating circular base model is going to be the best for meeting all of our desired criterion. The design itself allows for the easiest method by which to replicate the motion of the dispensing nozzle mechanism while allowing easy switching of plates. Furthermore, the central pillar provides good support for the very heavy dispensing system as it stands. Also, by mounting the pump right behind the valve we can more accurate control the flow and pressure upon the nozzle itself, allowing for the most accurate recreation of the factory environment.

4.4 Engineering Models/Relationships

4.4.1 Engineering Relationship 1: Young Laplace Equation

An integral element of our project is to maintain liquid within the nozzle. In order to do so, surface tension is the governing principle which is being used to determine if a plate design will
allow for the surface tension of the fluid to form droplets that span the open slots of the design. Therefore, the relationship between surface tension and the pressure differential between an interface. Professor Richard Fitzpatrick of the University of Texas defines it as, "the equilibrium pressure difference sustained across the interface between two static fluids, such as water and air, due to the phenomenon of surface tension." [2]

In the diagram above, the term $\Delta P$ represents the internal pressure relative to outside, which in our case is atmospheric pressure. The $\gamma$ represents the surface energy. Since surface tension acts along the surface of the bubble, it is distributed evenly around the circumference, which in the diagram is represented by the downward arrows. Thus surface tension multiplied by the circumference, $\gamma \times 2\pi r$ reflects that force. Comparatively, the internal pressure acts on the cross section in the positive x-direction, meaning the force is $\Delta P \times 2\pi r$. When set equal, terms on each side cancel to give the final simplified Young Laplace equation of $\Delta P = \frac{2\gamma}{r}$. This relationship can be used by our group to relate the pressure and the surface tension to determine the size of the radius of droplets that will maintain their form while spanning gaps in the plate. [3]

4.4.2 Engineering Relationship 2: Hydrostatic Pressure

Another important factor in determining the plate design for our project is determined by the actual pressure that the liquid at the surface of the plate is under. This pressure, which is also used in the Young-Laplace equation above, comes form the the principle of hydrostatic pressure. Hydrostatic pressure is determined by the density of a fluid and the depth at which you want to determine the pressure.
Hydrostatic pressure, \( P \), is calculated from two simple measurements. In the diagram above, they are represented by \( h \) and \( \gamma \). The first, \( h \), represents the height of the liquid that sits above the point of interest. In our case this value would be the vertical distance from the shut off valve to the level of the plate. The second variable, \( \gamma \) represents the specific weight of a fluid. It should be noted that this \( \gamma \) differs from the one above in the Young-Laplace equation. The specific weight of a common fluids can be found in tables in Fluid Mechanics textbooks or online. For a non-standard fluid, \( \gamma = g \cdot \rho \) where \( g \) is gravity and \( \rho \) is the density of the fluid. [43, 4]

For our project, we can find the density through simple volumetric experimentation which can thus be used to find the value of the specific weight. This equation is vital in determining the pressure that acts upon the plate.

4.4.3 Engineering Relationship 3: Net Suction Pump Head

Finally, the third engineering principle that will come into play for our experiment has to do with the pump itself. Pumps generate suction through pulling liquid through them and thus having negative pressure on the downstream side which draws more liquid into the pump and moves the fluid in the desired direction. However, an important issue to consider is cavitation. Cavitation is the process by which the suction of the pump pulling a liquid through it reduces the pressure on that liquid to below the vapor pressure of the liquid [124, 4]. At this point, spontaneous boiling occurs, causing rapid changes in pressure within the casing that can damage the impeller of the pump. Therefore, to prevent cavitation from occurring, there must be a certain pressure at the entrance of the pump, known as the net positive suction head, NPSH (units of meters, m). The value of the NPSH can be found based on the fluid properties and pump head through the relationship below

\[
NPSH = \frac{p_s}{\gamma} + \frac{(V_s^2)}{2g} - \frac{p_v}{\gamma} \quad [682, 4]
\]

Where \( p_s \) is the pressure at suction inlet, \( p_v \) is the vapor pressure of the fluid, \( \gamma \) is the specific weight, \( g \) is gravity and \( v_s \) is the velocity of the fluid through the pump. This relation gives the minimum pressure head required to keep the pressure head at the suction entrance from falling
below the vapor pressure head. When considering the importance of this for influencing our project
design, the location of the pump and the pressure in the system will be dictated by the minimum
pressures required to avoid cavitation as determined by the above formula. Specifically, it should
be noted that the height of the pump above the tank will determine the type of pump we need to
purchase for our project. Additionally, the pressure of the pump will influence the velocity at which
fluid can be pulled from the tank during the process. Hence, based on our requirements for testing
the nozzle at a certain exit velocity, the pump will have to function within that velocity range for
the specific distance above the tank that it is located.

5 Concept Embodiment

5.1 Initial Embodiment

The following three figures represent a CAD embodiment of our initial prototype. All screws
were excluded, but holes were placed in the places they would be installed. The motor and filler are
both simplified, but the pump is represented with an accurate pump model. Figure 24 shows top,
side, front, and iso views. All materials and parts can be found in the BOM in Figure 25. Finally,
Figure 26 shows an exploded view with bubble callouts referencing the BOM.
Figure 24: Assembled projected views with overall dimensions
<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART NUMBER</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Base plate</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Top circle</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Support pillar</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Bottom circle</td>
<td>1</td>
</tr>
<tr>
<td>5</td>
<td>3D-printed gear</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Motor</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>Filler</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>Upper reservoir</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>Bottom reservoir</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>Pump</td>
<td>1</td>
</tr>
<tr>
<td>11</td>
<td>Upper tubing</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>Secondary tubing</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td>Track pillar</td>
<td>6</td>
</tr>
<tr>
<td>14</td>
<td>1/4-20 x 3</td>
<td>22</td>
</tr>
</tbody>
</table>
Figure 26: Exploded view with callout to BOM
5.2 Model-Based Design Decisions

The team made many design decisions based on the engineering relationships described in section 4. First, to address the topic of hydrostatic pressure, the team decided to leave the upper reservoir open to the atmosphere so that the height of the liquid can be easily read and used to calculate hydrostatic pressure. With regards to the specific value that is going to be used for the final design, the height of the reservoir will be dictated by the pressure that the factory has fluid leave the nozzle at, a value which we have yet to be informed about. Therefore, for the purposes of this report, we will use the assumed value of 2psi as the exit pressure for the nozzle. Thus, the following calculations can be applied.

\[
\gamma h = 2 \text{ psi} \\
\gamma = 62.43 \frac{lb}{ft^3} \\
h = \frac{2 \text{ psi}}{62.43 \frac{lb}{ft^3}} = 4.61 \text{ ft}
\]

Figure 27: Analytic Hierarchy Process (AHP) to determine scoring matrix weights.

Furthermore, if the fluid was kept in an air-tight vessel, the team would have to add a pressure gauge to the equation. The only risk keeping the container open presents is spillage, which would occur if the pump/reservoir equilibrium wasn’t reached and the liquid overflowed from the upper reservoir.

Secondly, the use of NPSH to calculate the type of pump had to be adjusted to account for design changes of the prototype. In order to handle the large mass of the nozzle head, the nozzle head is now stationary which means the lower reservoir is stationary and thus the pump can be placed in the lower reservoir itself. By doing this, the pump does not need to rotate and thus a pond pump that pumps from the basin upwards can be used instead of one that would draw the fluid up from a pump mounted at the top. Thus, the design has to accommodate for the maximum head that the pump can provide, which is dictated by the power of pump itself and not by a NPSH calculation.
The pump that we purchased for use in the prototype has a maximum height of 5 feet. This value works within the height limit dictated by hydrostatic pressure.

Finally, the team decided that the rotating circular track, as shown in Figure 29, is much easier than trying to rotate the heavy filler. Rotating the heavy filler makes sense on a large scale such as a macro-brewery, but for this small scale, the small motor we selected wouldn’t be able to rotate the filler. After the team decided rotating the track was ideal, measurements were taken to ensure that the track perfectly toggled the filler between the open and closed positions. Moving forward, more precise measurements will be taken and the track will be permanently secured so the team doesn’t have to reset and re-measure after each working session.

5.3 Performance goals

The three main performance goals for our prototype demo were

1. Pump maintains minimum height of upper reservoir within $+/- 10\%$ (height).

2. Apparatus can run for at least 200 testing cycles without intervention/maintenance.

3. During test in Goal 2, less than one paper towel of liquid is leaked.

5.4 Proofs-of-Concept

A proof of concept was constructed. Figure 28 shows the assembly during testing.

![Figure 28: Fully assembled prototype arrangement](image)
Figure 29 show different components of this initial prototype.

(a) Gear Assembly  (b) Track Assembly  (c) Upper Reservoir Assembly

Figure 29: A close up look of the main parts of the prototype build-

In our prototype, the upper reservoir was filling in a much faster rate than anticipated. After initial testings of the prototype, the need for bigger upper reservoir became apparent. Thus, for our final design, we will be using a bigger upper reservoir that can carry the liquid being pumped to it from the bottom reservoir without overflow. This also means we need to change the dimensions of the standing beam to house a bigger reservoir while maintaining the needed height from the inlet of the filling valve. In our new model, adjustments were made to address the issues mentioned above.

The prototype was for the most part built according to the initial design of the selected design (rotating circular base). The main difference is that the prototype didn’t include the full cylindrical housing with the track running in full circle to move the valve arm in the open and close position as presented in the preliminary sketch. After careful analysis of the opening and closing mechanism of the valve, it became clear that there is no need to move the valve arm up and down continuously. Instead, a cyclic opening and closing mechanism was found to be beneficial as it will allow undisturbed flow of the fluid for few seconds. To facilitate this cyclic movement, a total of six vertical bars were used as a support system to the tracks that force the valve arm in the open and close position. Three of the vertical bars were used to support the track arrangement that has an upward slope in the direction of the rotation to guide the valve to the open position. The other three bars, which are built about 100° apart from the previous support, were used to support the track used for the valve closing mechanism.

When considering the influence that the Proof-of-concept had upon the prototype design and changes to the design itself, certain design changes were made regarding the positioning of the pump, basin and the overall system controlling the motor. First, we recognized that turning the base had to be done repeatedly and thus an outside voltage control system would function best instead of a code that would have to be run through a Arduino or other system. Additionally, to prevent any tangling of the pump the basin is now mounted to the main post itself. During the design process we discovered this would also take weight off the rotating apparatus and stress the motor less over time. Finally, the basin up top will have to be much larger as the pump moves the
liquid up to the top very fast, necessitating that the upper reservoir holds more so that it can fill as the nozzle opens and closes.

The proof of concept further influenced the importance of having the opening and closing track be different than initially planned. Instead of having the arm move a longer distance and thus requiring more track, different arm positions were chosen that still function to represent open and close, however necessitate less track to move the arm each time. Therefore, the tracks could be closer together and more time could be used watching the nozzle exit for the dripping of the fluid when it shouldn’t be occurring. Finally, the prototype changed slightly regarding how the motor was mounted. Initially we wanted to run a perpendicular gear system but determined the torque from moving the mass of the plate would be too high. Therefore, the motor had to be countersunk into the lower plate so that the gear turning the track could be parallel to the pinion track. This meant that the basin would have to be moved closer to the nozzle exit but also that the pump would have a shorter distance to pump the liquid up and thus is a double benefit in the long run.

6 Working Prototypes

6.1 Overview

The initial prototype was upgraded and many of the components were exchanged. Overall, the apparatus was scaled up, as seen in Figures 30 and 31. To make the transition from open to close more exact, the track was upgraded with spacers to keep it exactly where it needed to be.

The upper reservoir was replaced with one that didn’t need intervention and would not overflow. Increasing the size of the upper reservoir helped the team meet the performance goal of maintaining the upper reservoir’s level within 10 percent of its initial height. Also, counterweights were set on the upper wooden circle to assist the motor and create a more even rotational speed.
6.2 Initial Prototype

Figure 30: Fully assembled initial prototype arrangement
6.3 Final Prototype

Figure 31: Fully assembled final prototype arrangement

7 Design Refinement

After creating the prototype and seeing how the apparatus behaves in real life, some refinements were necessary to enhance its performance. In addition to these refinements, this section will analyze stress and deflection, safety, manufacturability, and ways the team can redesign the apparatus to improve usability.

7.1 FEM Stress/Deflection Analysis

Static-stress FEA was performed on the portion of the track that comes in contact with the filler arm. This piece of the apparatus will be put under cyclical stress as the arm runs over it and presses against it. To measure the stress and displacement the track will experience, a SolidWorks model was created. The model can be seen in Figure 32 below. The material used is PVC, which is the closest material available in the SolidWorks library to the rigid plastic the team is using currently.
The model was prepared for the static study by applying supports in the holes which represent the three screws that attach the track to the track supports. This is a fairly accurate representation since the screws will create a fixed geometry. Next, a force of 5N was placed on the top face of the track, representing the force of the arm moving across the track. This force across the entire face at the same time is not perfectly representative of the force that the track will experience. In fact, the distributed force across the entire track is more than what would occur, since the arm will only be in contact with one point on the track at a time as it moves across it. This study therefore is overestimating the stresses and displacements that the track will experience. The final step in preparation was to create a mesh. The team allowed SolidWorks to create the mesh halfway in between 'coarse' and 'fine' to reduce run-time while maintaining accuracy. The mesh and loads can be seen below in Figure 33.

The results can be seen below. Figure 34 shows the Von Mises stress results and legend, and
Figure 35 shows the displacement results and legend.

Figure 34: Von Mises stress results

The maximum Von Mises stress is reported as 16.45 kPa and it located in the two outside screw supports.

Figure 35: Displacement results

The maximum displacement is reported as 2.25e-3 mm and is located at the extremes of the track. The factor of safety (FOS) is calculated by dividing the maximum allowable stress (yield stress) by the maximum stress the part is expected to experience. In this case, the Von Mises stress reported above is used. The yield stress of PVC is 53 MPa [5]. Therefore, the FOS is 3222. This value is well above the acceptable range.

The predicted displacement is very small and acceptable. For the displacement to cause a problem, it would have to reach approximately 1”. If the deflection is this great and the screw supports are
still in place, the movement of the arm would turn from a smooth open/close to a wavy and unsteady open/close that would create a pattern not representative of factory conditions.

7.2 Design for Safety

Keeping the user safe is always a priority in prototype design. This apparatus is no exception. Below, several potential risks are acknowledged and mitigating steps are discussed.

7.2.1 Risk #1: Serious Liquid Leak

**Description:** Leakage of fluid all over the surroundings or possibly user could cause damage to materials, other items in the area, or discomfort to the user. Potential to occur if upper reservoir spills/overfills or becomes unsecured. **Severity:** Marginal severity. No serious harm could come from getting wet, and the relatively low volume of fluid is unlikely to ruin any nearby equipment. **Probability:** Seldom probability. The pump/reservoir system will reach an equilibrium so that the levels of both reservoirs become constant. Also, the upper reservoir is well-secured in two locations. **Mitigating Steps:** Increasing the size of the upper reservoir will decrease the likelihood of it overfilling or spilling. To make it more secure, a third connection should be put in place.

7.2.2 Risk #2: Finger in Gear

**Description:** A rack and pinion system is used on the underside of one of the wooden disks. This system drives the rotation of the track and is essential to the function of the apparatus. However, it’s exposed enough for a user to potentially get his or her finger caught in the gear and run over by the pinion. This could occur if the apparatus started abruptly while the user was inspecting the apparatus. **Severity:** Critical severity. Serious injury to the finger is possible since the pinion is driven by a motor and the rack/pinion connection is very tight. **Probability:** Unlikely probability. The area, although technically exposed, would be hard to reach in normal use. The pillar and motor-holder obstruct the rack for the most part, so reaching fingers into the gear system would be difficult. **Mitigating Steps:** The team suggests adding a guard of some sort to completely block off the area from user interference. Alternatively, plexiglass or a clear plastic could be used to create a housing for the entire apparatus.

7.2.3 Risk #3: Structure Failure

**Description:** Structure failure could occur in two major places: the connections holding the filler, or the pillar integrity. If the filler was to become loose, it could fall and damage the apparatus and put the user in danger. The filler weighs roughly 10lbs and is secured more than a foot from the ground. The pillar, which holds the filler, could fall over or break in which case the users in a 3ft radius could be hit. **Severity:** Marginal severity. The filler could only fall onto the apparatus - users would have to be working on the apparatus to be in danger, which isn’t likely to be the case since user intervention isn’t necessary. Pillar failure is also marginal since the signs of failure would show well before the failure occurred - cracks, sounds, bending, etc. would tell the user failure was near. **Probability:** Unlikely probability. The filler is secured with 4 heavy-duty bolts and the pillar is a sturdy 2x5” held by a base-plate made up of 3x3” and locked in place. **Mitigating Steps:** Advising the users to stand 5ft back during use would mitigate both risks. The team could add stencil warnings to the wood parts or create a warning sheet/booklet that gives the same warning and advice.
7.2.4 Risk #4: Electrocution

**Description:** Electrocution is a risk anytime electronics are used near fluid. In this case, the motor is connected to a power generator. The connection is underneath the bottom wooden disk and is not water-proofed in any way. If serious leakage occurred, it could reach this area and potentially electrocute the user if he or she is also in contact with the fluid. **Severity:** Critical severity. Electrocution can cause burns of any severity. More serious effects include cardiac arrest. **Probability:** Seldom probability. The leakage would have to be severe and reach a very specific location on the apparatus. A puddle of fluid would have to be present in order for the electricity to reach the user. **Mitigating Steps:** Again, adding a warning for the user to maintain a 5ft radius from the apparatus would mitigate the chance of electrocution. Also, adding a housing around the electrical connection could ensure fluid couldn’t reach it.

7.2.5 Risk #5: Exceeding Pressure Limit

**Description:** If the filler was to get stuck in the closed position, the pump would continue to pump into the upper reservoir. In the event that it fills, or something obstructs the piping, the pump would continue to build pressure. If the pressure becomes too great, the pipes could fail and spew fluid all over the area. **Severity:** Marginal severity. The worst case scenario is the pipe becoming unsecured and flailing fluid around like a fire-hose for a minimal amount of time until the pressure goes down. This wouldn’t result in serious injury, but could frighten the user and of course get him or her wet. **Probability:** Seldom probability. Because our upper reservoir is exposed to the atmosphere, the reservoir would leak and overfill before the pump is backed-up. However, if a fluid with particles is used, buildup in the pipe would be possible. **Mitigating Steps:** Keeping the pump on the lowest setting will decrease the likelihood of it pumping too much fluid to the upper reservoir.

7.2.6 Heat Map of Risks

Ranking the above risks on severity and probability lead to the following Heat Map broken into red, yellow, and green sections.
7.2.7 Priorities

Fortunately, no risks fall into the red section of the heat map. Electrocution is the only risk that falls into the yellow category so it should be the team’s top priority. To mitigate this risk, the team plans on adding an advisory to stand 5ft back from the apparatus while it’s in use. This advisory is a great idea because it also mitigates the risk of structural failure and exceeding the pressure limit. Once these three risks are decreased or completely removed, the risk heat map would only show risks in the green section. The team is comfortable with this and is confident the user will be able to safely use the apparatus.

7.3 Design for Manufacturing

Designing a part with manufacturing in mind will prevent obstacles and costs down the line in terms of complex manufacturing methods and time to market. Making sure the apparatus is easily manufacturable is important to its longevity and reproducibility.

7.3.1 Drafting of Simple Part

The upper reservoir was chosen to go through draft analysis in SolidWorks. Before any drafting was executed, all of the walls and faces were deemed as “Requires draft”. To accommodate this, the team drafted all the exterior and interior walls by 3 degrees. This changed their status to either positive or negative draft. The hole in the bottom of the reservoir was drafted by 2 degrees and was marked as “Negative draft” instead of “Requires draft”, as it had previously been. Refer to Figure 37 for a before-and-after photo of the upper reservoir.
As described, the part went from mostly requiring drafting to being completely drafted and ready for manufacturing.

### 7.3.2 DFM Analysis

The top wooden plate with the rack system used to rotate the apparatus was chosen as a complex piece to undergo DFM analysis in SolidWorks. Two trials were done, the first of which being for Milling/Drilling and is shown in Figure 38.

Secondly, injection molding analysis was ran. Figure 39 shows the results of the run.
DFM analysis investigates if the chosen process is feasible with the chosen part. For example, the milling run showed many errors because the holes had perfectly flat bottoms - a feature very hard to mill or drill. In the injection molding analysis, it was apparent that the walls were too thick and would present problems in cooling and solidification if injection molding were to be used to manufacture the part. The amount of errors in both analyses show more design modifications would need to be made in order for the part to be suitable for milling/drilling or injection molding.

### 7.4 Design for Usability

Some users may have disabilities or impairments that could affect their use of the apparatus. To accommodate some potential issues, the team has gathered design refinements to solve some potential problems.

1. **Vision Impairment**

   Some types of severe vision impairment would prevent the user from using the apparatus for what it is meant for: monitor flow stopping and starting. If the user was blind, he or she wouldn’t be able to see the flow stop or begin based on the arm’s location. To make the arm’s location more detectable for someone with blindness, we could add an audible cue to go on when the arm is in the open position and switch to off when the arm is in the closed position.

2. **Hearing Impairment**

   One of the biggest cues to the apparatus working well is the sound of the pump working in the bottom reservoir. Not being able to hear the pump wouldn’t be detrimental because the user could still look carefully and see fluid exiting the pipe, but if for some reason this view is obstructed, it would be nice to have another way of knowing the pump is working as it should. Replacing the opaque tubing currently in use with clear tubing would enhance the
view of the flow of fluid enough to accommodate hearing-impaired users. Furthermore, dye or another indicator of fluid movement could be used anywhere along the pipe.

3. Physical Impairment

Luckily, one of the most important aspects of the apparatus is that it can operate intervention-free. So, during the actual use of the apparatus, physical impairments don’t present any pressing issues. However, while setting up and taking down the apparatus, dexterity and strength have to be used to place the pump in the correct location within the bottom reservoir. Another example during set up is placing the two wooden disks (one with the track, one without) in the correct orientation. We could accommodate potential dexterity and strength issues by standardizing the pump power and minimizing our parts or changing their material. Minimizing our parts would lessen the amount of connections the user has to make before use, and choosing a material lighter than wood would easily lower the strength requirement.

4. Control Impairment

Control impairments don’t present any pressing issues for the use of this apparatus. However, if the apparatus is being used for extended periods of time, as designed, a trouble focusing or staying awake could present an obstacle to observing the effectiveness of the valve-head that’s being tested. To make this more accessible at the user’s leisure, the team suggests installing a video recording device, like a GoPro, onto the pillar in the center of the apparatus facing the bucket and valve-head. This would give a view of the fluid flow the user could view at their discretion.

8 Discussion

8.1 Project Development and Evolution

Does the final project result align with its initial project description?

– The final prototype meets the performance goals that the team outlined at the beginning of the project. We’re all very satisfied with the functionality of the apparatus and believe it to be one-of-a-kind.

Was the project more or less difficult than expected?

– The details of the construction were more complicated than expected. It was easy to sketch and come up with elaborate ways to toggle an arm between open and closed, but in reality, it was difficult to bring those ideas to life.

On which part(s) of the design process should your group have spent more time? Which parts required less time?

– The ‘backboard’ and mounting system took a lot of our focus early on, and differentiated the ideas coming into the first round of brainstorms. In reality, it was relatively unimportant, and we should have spent more time focusing on the track and the spinning geometry.

Was there a component of the prototype that was significantly easier or harder to make/assemble than expected?
The track was very difficult to build because the geometry of the arm changes as it goes from open to closed to open again. What the team realized is that the arm’s distance from the edge of the apparatus depended on which position it was in, so moving it between positions meant a track that moved in and out from the edge as well.

In hindsight, was there another design concept that might have been more successful than the chosen concept?

No, the design that the team decided on was indeed the best of those brainstormed. Now, if the team were to sit down and re-brainstorm with everything now known, some more simplistic track designs might come to the surface.

8.2 Design Resources

How did your group decide which codes and standards were most relevant? Did they influence your design concepts?

The codes and standards we chose focus on the type of materials approved for the particular project we were working on and on the use of centrifugal pumps. The first standard is critical as not all materials are pre-approved to come in contact with beer. The second standard was important as we needed the right pump for our design. Overall, the codes and standards considered were critical for the project and made sure we were basing our design in accordance with the legal requirements.

Was your group missing any critical information when it generated and evaluated concepts?

We were mainly focused on making the rotation mechanism as robust as possible. Most of the design concepts generated and evaluated answer the critical requirements we want to achieve. Apart from not having specific filling condition such as flow rate and filling speed, we believe we have covered all the critical information need for the design.

Were there additional engineering analyses that could have helped guide your design?

Due to lack of detail information of the industrial set-up, we were not able to recreate the exact scenario used in industries for our design. If we were given all the conditions for instance the filling pressure and flow rate, we would improve our design to match the actual condition used in industries.

If you were able to redo the course, what would you have done differently the second time around?

As mentioned above, we didn’t have the exact industrial conditions used during can filling process. Thus, if we were to redo the course, we would like to incorporate and set our testing machine to match the conditions used in industrial set-ups.

Given more time and money, what upgrades could be made to the working prototype?

The team had considered adding a flywheel or a stabilizing mechanism to make the rotation more consistent. Also, to make the apparatus lighter and resistant to water damage, a material other than would should be invested in.
8.3 Team Organization

Were team members’ skills complementary? Are there additional skills that would have benefited this project?

- Yes, each member of the team seemed to be proficient in a special area. Between construction, writing, CAD, and designing, all the team members contributed in a way nobody else could.

Does this design experience inspire your group to attempt other design projects? If so, what type of projects?

- This project relates significantly to a secondary project the team has been working on. This project will enhance the second in many ways, so yes, it inspired more designing.
Bibliography


