Project Proposal Feasibility Study
Team 21

Pan Fermenti:
From Bakeries
To Breweries
EXECUTIVE SUMMARY

U.S. Department of Agriculture Secretary Tom Vilsack gave an estimate that 133 billion pounds of food is wasted each year. That food waste, according the Bloomberg Business Journal, cost the U.S approximately $180 billion; out of that total, $11.2 billion of is wasted bread. This project evaluates the feasibility of establishing a green, industrial-scale process to minimize food waste by using, otherwise discarded bread, in the production of beer. The production of beer requires large amounts of resources, including grains for the fermentation process. The bread recovered from food waste could be used in the brewing process; this could combat food waste and aid in the EPA’s goal for the U.S. to reduce food waste by 50% by year 2030.

Some factors the team will be considering include: bread recovery methods, waste and water management, ways to maintain sanitary conditions through-out brewing process, biosynthesis of ethanol, different enzymes to promote the right reaction and compensate for insufficient fermentable sugars, bread mixtures that will result in marketable beer, mechanical design of the industrial plant, maintaining temperature control through the whole process, potential structural design changes to accommodate process changes, investigations focused on analytical techniques, most importantly, the bread to grain ratio. This project will have a large focus, but the scope will be local. The team will be partnering with local businesses to establish a client base as well as garner mentorship from those familiar with both the brewing process and the impact of food waste in Grand Rapids. The goal is to substitute up to 30% by volume of current brewing solution with a recycled bread mixture.

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1. INTRODUCTION

1.1 Calvin College Engineering

Calvin College Engineering program is that offers an ABET accredited Bachelor of Science in engineering degree in four concentrations: Chemical, Electrical and Computer, Civil and Environmental, and Mechanical Engineering. As a capstone project the students are required to complete a year-long project that pushes the students to focus on integrating design processes with a reformed Christian worldview.

1.2 Team

The group is composed of four engineering students from different concentrations; 2 mechanical engineers, one civil engineer, and one chemical engineer. The members of the team can be seen in Figure 1.1. As part of the requirements to graduate with a Bachelors in Engineering from Calvin College, seniors are required to complete a capstone project, referred to as “Senior Design Project.” The team came together because of each individual’s interest in serving others, and caring for God’s creation. The team struggled with finding a project that would fulfil each member’s interests as well as create the opportunity to showcase our education here at Calvin thus far, and each member’s innovative capabilities. Brewing beer from food waste, specifically bread, is exactly what the team needed.

Figure 1.1 Team members (left to right) - Hanfei Niu (ME), Michael Schur(ChE), Ayo Ayoola (ME), and Jerome Navarro (CE) Image credit: Kwesi Asare
1.2.1 Ayooluwa Ayoola
Ayo Ayoola is a senior Engineering Student with a mechanical concentration. Ayo loves discovering ways Engineering can be used to serve a community locally, nationally and internationally. Along with her Engineering studies Ayo studied several health-related classes at Calvin College, with the hope of discovering ways Engineering can be used to improve the way healthcare is administered. Beyond the classroom setting, Ayo loves travelling and learning about the diverse culture around her. She also enjoys participating on the Calvin College track and field team as a jumper, and losing herself in good novel.

1.2.2 Jerome Navarro
Jerome Navarro is a senior Civil and Environmental Engineering student with a passion for sustainability. Growing up in Grand Rapids, he has been keenly interested in giving back to the community. Specializing in water resources, Jerome contributes to the CAD designing of the brewing process as well as constructing the structure that will house the project design. Besides this project, he has pursued other avenues to protect the environment and pursue sustainability. Through Calvin College, he has conducted research on creating inexpensive water filters for developing countries. Jerome also serves as the Local Project Coordinator for Calvin’s Engineering Unlimited student club, which aims to provide service projects both locally and abroad. Additionally, Jerome has extensive cross-cultural experience from his travels to Germany, Kenya, and Ecuador for both schooling and work.

1.2.3 Hanfei Niu
Hanfei is a senior Engineering Student with a Mechanical Engineering focus at Calvin College. Hanfei was born and raised in China, and was drawn to the prospect of exploring the world around her when she came to the United States. One of the things that drew Hanfei to Engineering was the prospect of using the concepts thought to tackle agricultural and environmental challenges. Hanfei loves to care for the environment and discover new sustainable technology.

1.2.4 Michael Schur
Michael received an Associate’s degree in Mathematics and Science from SUNY Rockland Honors College. Originally from Tarrytown, NY, Michael is currently a senior at Calvin College in Grand Rapids, MI, pursuing a B.S.E. in Chemical Engineering with a dual major in Chemistry and a focus in Optics. He has a passion for chemistry education and nonprofit organizations. In the past few years he has interned at Soundoff Signal, Amphenol, and Magna Mirrors. Upon graduation, Michael plans to pursue a Master's degree in Optical Engineering with a medical/chemical emphasis, with a view to starting his own engineering consultant firm.
1.3 Project
This project offers several possibilities while challenging the team. By taking bread that would otherwise be disposed of and making it into something marketable, this project combats food waste. In this way the project provides an avenue by which the team can care for God’s creation. This project has the potential of making a business impact. Grand Rapids has a plethora of breweries and bakeries. This creates the opportunity to implement the process locally, thus allowing the team to evaluate the impact this would make to food waste.

1.3.1 Problem
Beyond the billion dollars’ worth of food that is lost as food waste, money is also lost to maintaining the landfills that hold these wastes. According to an article published on NPR, National Public Radio, Ashley Zanolli from the EPA said "Forty to 50 percent of food waste comes from consumers, and 50 to 60 percent from businesses”\(^3\). In an effort to accommodate consumers, grocery stores, restaurants, and bakeries end up disposing good food. This could be because a lot of the food is used for display or to serve the best and freshest baked goods that have sitting out for an extended period of time is no longer marketable. Along with food waste, there is also the challenge the brewers face of cost driven by sales price of the grains used in the brewing.

1.3.2 Objectives
The team will design a recipe that replaces at least 30 percent mass of the grains used in brewing with stale bread. The designed recipe, which will be prototyped for a 1 gallon batch, will be scaled up for local craft breweries, 315 gallon batch sizes. Along with the recipe the team will identify process changes that will be necessary to accommodate the change in the recipe. This will include adding bread grinders, and bread drying to the process.

Pan Fermenti will also be designing an automated brewer for the use of testing the recipe. The automated brewing machine would reduce the amount of external labor the team would do throughout the brewing process. Along with this, the team will design temperature control devices for the fermenter the team will be using.

1.3.3 Design Norms
Pan Fermenti is made up of group passionate about serving the local community in a way that helps rather than hurts the community. This means from the brainstorming process to the implementation of the project the team will be consciously trying to incorporate several design norms. The team longs to design a project that is representative of the character of the team members. So throughout the process the team will have these values on the forefront: trust, stewardship and transparency.

1.3.3.1 Trust
One of the drivers for growth and success for local businesses is trust between the consumers and the producers. Especially for bakeries and breweries, were the goods are being ingested. When the bakeries advertise freshly baked goods it is to ascertain that the consumer gets the best tasting

goods. When breweries market craft beer, the goal is to offer quality product that is authentic to
the brewing company’s values and stewardship principles, with a taste that appeals to the target
market. With this in mind Pan Fermenti will be making efforts to make the recipe trustworthy.
This will require ensuring that the product is consistent. In addition, during the prototype process
the team will ensure a thoroughly sanitized process eliminating the introduction of foreign particles
to the process.

1.3.3.2 Stewardship
The Earth is our home. It is our responsibility to preserve its resources, the beauty it has, and
reduce its degradation rate. This sometimes looks like recycling, or using renewable resources. For
Pan Fermenti this means not just reducing waste, but also reusing resources. The team will make
efforts to reduce the waste production throughout the beer production process. It will also include
a bread recovery process that will reduce the food waste bakeries contribute to the landfill annually.

1.3.3.3 Transparency
To build credibility and trust bakeries and breweries share nutrition facts, or ingredients used in
the marketed good. Likewise, Pan Fermenti will be open with both its customer and the public
about the intended brewing process, the ingredients used in the new recipe and the methods used
to arrive at a reliable recipe.

1.3.4 Local Affiliations and Background
One of the factors that drew Pan Fermenti to this project is the opportunity to work with local
businesses, to observe the impact this project would make in Grand Rapids, Michigan. To ensure
the success of the project the team partnered with Hall and Wealthy Street Bakeries for a source
of bread that will be used throughout the design process. The team will also be partnered with
Grand Rapids Brewing Company to garner a better understanding of the brewing process and what
it means to be a craft brewery.

1.3.4.1 Hall and Wealthy Street Bakery
Hall Street Bakery is a local bakery partnered with Wealthy Street Bakery that creates a place for
the people in the neighborhood to meet and get to know each other better. David and Melissa
LaGrand invested in Hall Street with the hope of bringing new life to a neighborhood where
businesses were moving out. The Bakery is designed to resemble a European café, with its outdoor
seating area and alcohol on tap⁴. It showcases a “pastry counter, wood stone pizza oven, bread
display, espresso bar and several tap handles pouring Michigan beer”⁵. The bakery also features a
gluten-free kitchen catering to its ever-growing, gluten-intolerant customers. Hall Street Bakery
along with Wealthy Street Bakery have a strong regard for the community.

November 2015.
1.3.4.2 Grand Rapids Brewing Company

Grand Rapids Brewing Company’s story begins on the first of January in 1893, with the merger of six local breweries\(^6\). After the company’s start it thrived for 20 years before the prohibition in the 1920’s disrupted its success story. In 2012, the brewery was revitalized in downtown Grand Rapids once again. The brewing company holds sustainability as one of its core values. This is seen first in the way the brewery was built, with its floor made of repurposed wood, the arts and furniture designed by local artisans. It is then seen in the efforts the company makes to recycle and compost their waste, this reduces the waste that goes to the landfill by 90 percent. The company’s history and the way it values sustainability, makes it a perfect target customer for the process the team is designing.

1.3.5 Challenges

The biggest challenge to this project is the low alcohol content with current bread brewing recipes. The team is aiming for 5-7% alcohol content with 30% bread substitute in the brewing process of final project. Another challenge the team will face is keeping the test brewing process sanitized to eliminate the introduction of foreign particles in the brew and thus affect the fermentation process and the taste of the beer. The team will also have to work with possibility of introducing additional enzymes to the brew recipe, which might not align with the desire to keep the recipe authentic to the brewery’s values and principles.

2. PROJECT MANAGEMENT

2.1 Operational

Installing the design into existing breweries would require capital investment, though this would be offset by both financial savings and branding of environmental stewardship. In the future, the acts of stewardship may lead to certification to both bakeries and breweries that designate environmentally-friendly business practices. Once the project is implemented, breweries will be able to both conserve water and grains in their brewing process.

2.1.2 Marketing

The team will evaluate the design based on sustainability: the effects on the environment, on business, and on clients. The nature of the project lends to an extremely local focus. The sustainability of waste bread is defeated if the transportation is too extensive. Within a city, the coordination between bakeries and breweries would have a comparably small effect. The project is thus geared towards locations with an avid brewery and bakery population, since the coordination of the two is integral to the design. This transportation may be mitigated by the scale of both bakery and brewery, with those having a large industrial process having a decreasing effect on transportation costs.

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2.1.3 Storage
The design will require structural changes to existing breweries. Due to the additional supply of bread for the brewing process, additional storage space is required. Loaves of bread must be kept in freezer conditions for preservation. Lump sum of bread will be obtained from bakeries, understanding there is limit to the amount of waste bread bakeries produce. Additional filtering equipment of bread starches will be amended onto existing equipment. The current brewing space at Grand Rapids Brewing Co. also has limited room for expansion, with the wort boiler and fermenter tanks shown in Figure 2.1.

![Wort boiler (left) and Two Fermenter Tanks (right) From Grand Rapids Brewing Co. Image Credit: Jerome Navarro](image)

2.2 Financial
The current cost of grains is set at $1.09/lb of grain, as set by the team’s industrial mentor. This sets a standard for the implementation of the design, assuming no cost for the acquisition of wasted bread. Any additional equipment necessary will have a calculated return on investment based on the savings in supply cost.

2.2.1 Production cost
The majority of cost for the design stems from additional equipment required. Filtration is necessary for a homogenous project. The cost of equipment is dependent on the design specification chosen.

2.2.2 Food Savings
The reduction of food waste is the fundamental goal to the design. The process established will mitigate the amount of bread thrown away by bakeries. Additionally, the reliance on foreign import of grains will be replaced by locally sourced suppliers. This results in both a reduction of grains harvested for brewing and effects on the environment for transporting the grains.
3. PROJECT OVERVIEW

3.1 Research

3.1.1 Bread and Yeast

Roughly thirty-eight percent of all baked goods are thrown away\(^7\). Some bakeries will turn the goods to compost to reduce the waste that goes to the landfill, while some bakeries try to give these goods to local food banks or even encourage dumpster diving by packaging the disposed goods well to preserve the content. Food waste disposal is at the discretion of the bakeries based on values and principles. Hall Street Bakery, gives away about 30 to 40lb of bread weekly in an effort to combat food waste.

Bread itself is a commodity that has a history tracing as far back as 30,000 years ago\(^8\). However, when bread was first made it was baked on stones and unleavened. Addition of leavenings like yeast to bread recipe began in Ancient Egypt in 300 BC. The yeast would consume the sugars present in the dough and excrete carbon dioxide, CO\(_2\), thus creating the bubbles and giving the bread the light fluffy texture found in bread today.

For this process, we are using brewer's yeast: a species of *Saccharomyces cerevisiae*, an aerobic eukaryotic microorganism. Through the complex biochemical pathways within the yeast cell, ethanol is produced along with CO\(_2\). This process starts with the consumption of glucose, seen in **Figure 3.1**. For a method to keep the yeast healthy and promote longer life span, research will be conducted to determine optimal conditions. For yeast to grow and reproduce successfully, an adequate supply of nutrients fermentable sugar (carbohydrate source), nitrogen source, vitamins, and trace elements within solution are needed.

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\(^7\) National Resources Defense Council, U.N. Food and Agriculture Organization


During the lag phase, or Phase I, the yeast cells adjust to their new environment, producing enzymes and gathering nutrients needed for reproduction. The length of lag phase is entirely dependent on the growth medium in this case, bread wort. During Phase II, growth phase, exponential growth occurs. This growth is directly proportional to cell concentration. In this phase, it is assumed that 100% of the cell’s pathways are being utilized, and the cells utilize initial nutrients efficiently. The third phase, stationary phase, tells us that the cells have reached a minimum space and are over populated. In this phase, cell growth is also inhibited by toxicity levels of its products (ethanol). The final death phase, or Phase IV, occurs when the nutrient supply (glucose) decreases and the toxic by-products (ethanol, and CO₂) increases. Understanding how the yeast cells respond to the bread-beer batch compared to a normal batch will determine whether we will need to replace the yeast. If yeast health/concentration does not reflect a pattern shown in Figure 3.2 then a new yeast will need to be used, or certain conditions like temperature, initial nutrients will have to be changed.

![Figure 3.2 Phases of bacteria cell growth](image)

3.2 Waste Management and Recycling

Once the recipe is established, the team will implement practices to recover the water expended during brewing and the spent grains after the mash process is complete. Methods applied across the country would be incorporated into the design. These common water conservation practices will be modeled after the guidelines of the 2014 Water & Wastewater Sustainability Manual published by Brewers Association¹¹.

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3.2.1 On-Site Wastewater Treatment
This process will be modeled on current wastewater treatment practices. The treatment will involve controls of pH and removal of solids in the wort, but will not currently focus on tertiary water treatment of bacterial and viral sanitation.

3.2.1.1 pH Neutralization
The addition of bread will cause the wort to naturally sour. To avoid this flavor, the acidic pH of the wort will be neutralized. A mix and trim tank configuration for pH control is shown in Figure 3.3. This requires proper configuration of controls and continual mixing for a consistent pH throughout the batch. Research will be conducted to obtain a safe and natural method of reducing acidity while still following the guidelines of organic brewing.

![Figure 3.3 Configuration layout for pH control](image)

3.2.1.2 Solids Removal
Current practices involve the use of passive, physical filtration. Screening and flocculation methods would be employed to obtain sufficient quality water for heat exchangers. Higher level treatment methods, such as UV cleansing, would only be employed for water intended for wort production. Once the separation of starches and grains from the wort are complete, the leftover material will be repurposed. Further research will be conducted for the caloric value of the material, as well as the nutritional value of use as fertilizer or as livestock feed. For breweries with extensive property space available, the addition of bio-digesters can greatly improve water treatment.

The team’s industrial mentor has mentioned that after the primary fermentation of the wort, the batch can be placed in cold storage to encourage the settling out of solids. This has been investigated in the initial prototype batch. There was a significant reduction of suspended solids in the batch, but was not enough to completely eliminate the suspended solids.

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3.2.1.3 Reduction of Usage

Standard reduction practices include the maintenance of water pumping and piping, shifting the process to be less water intensive with filtration, and recycling water. Part of the team’s consultation services will involve creating a water balance sheet that shows how water is used throughout the brewing process and the total effective cost of water that factors in wastewater treatment, municipal purchase costs, and associated labor costs. These reduction methods would be developed following lean management and Pareto principles to continually improve the system. This entails focusing on the most water intensive parts of the process for the greatest reduction of water usage, and then progressing on to less intensive parts. For the brewing process, focus would be on the heat exchangers and wastewater from sanitation.

The introduction of these methods would involve incentivizing of the employees in the existing business, which can be done in the form of education or a rewards program.

3.3.3 Water Conservation

By nature, Brewing is a very water-intensive process. Currently, standard brewing practices result in a water usage ratio of 10 gallons of water to 1 gallon of beer produced. Several steps can be taken to minimize the impact of water during the process. The knockout phase of beer production is notably water intensive, while the use of water to filter out starch particles can also be lessened. With the team’s primary client, Grand Rapids Brewing Co., a problem was outlined: the majority of water expended was during the cooling of the wort during the heat exchanger process.

3.3.3.1 Water Knockout Recovery System

The cooling down of wort during the brewing process is integral to preserving the yeast for fermentation. The wort is prepared by boiling the batch; this temperature range would detrimentally harm yeast strains. The wort is thus chilled by the circulation of water in a heat exchange system. To cool down the 450 gallon wort requires a tremendous amount of circulation. Water is used as a coolant and makes a single pass through the wort. The water is then placed into a 600 gallon hot-liquor tank for later use. However, any excess amount of water after 600 gallons is displaced into the sewer. Another cold tank liquor has also been permanently repurposed as an excessive water container, limiting production potential for the tank. These tanks are shown in Figure 3.4.
3.3.3.2 Starch Filtration

In an industrial-scale process, the grain bed used for the wort is repurposed as a filter to self-strain the batch. The liquid from the wort is recirculated multiple times through the grain bed to strain out suspended solids. After the initial batch of bread-based beer, the team found the resultant starch in the wort to be extremely high. This excess in starch is due to the large volume produced by the bread during the wort process. The design process will be amended to accommodate this constraint in the preparation of the wort and its post-boiling filtration. The initial batch involved the bread being crumbled to maximize surface area for sugars to ferment. Future batches will instead cube the bread to minimize excessive starch in suspension while still allowing for adequate surface area for boiling.

The team’s industrial mentor suggested the usage of cloth and felt bags during the boiling process to physically separate the grains from the boiling water during the entire process. This would involve either scaling up existing inexpensive grain socks or by manufacturing large scale felt bags. A demonstration of the grain sock technique is shown in Figure 3.5.
There are also several industrial methods will be explored for the straining of starch after boiling. The use of a solid liquid separator is common in the potato starch industry. The machine operates by rotating the starch solution in a centrifuge to separate the suspended materials. An alternative design involves the use of semi-permeable membranes. This can either be maximized for ease of implementation by the addition of a felt strainer inside the wort boiler or for water efficiency with a Meura mash filter, shown in Figure 3.6. However, this would be cost ineffective as the Meura filters sell from $3,000 for small-scale breweries to over $60,000 for a factory-scale, while also taking a large amount of floor space. These methods will be evaluated based on their cost and utility. Overall, beer membrane filtration has grown in popularity amongst large industrial-scale breweries. These filters have a pore space of 0.5 μm and a diameter of 1.5 mm to screen and recapture as much water as possible from spent grains. Furthermore, the typical service life of these membrane filters run up to 400 run-cycles, which translates to 1.6 billion gallons of beer filtered per year.

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3.3 Industrial Application

One of the goals of this project is to take the designed recipe and scale it up for local craft breweries. To meet the brewing industry standards, the team will be designing a recipe for a 315 gallon batch. This requires mastering the ratios for each component at a small-scale level.

The team will also evaluating changes to the process current breweries would have to make to accommodate the changes to the new recipe would require, such as a grinder for the loaves of bread.

3.3.1 Pilot Plant Prototype: Microbrewery

Pan Fermenti will be designing an automated microbrewery that will used to prove the designed brewery process with the new recipe. The automated brewer will be brew one gallon batches. The brewer will be designed to reduce the tasks the brewer has to perform.

3.3.1.1 Temperature Control

One of the factors that affect taste and alcohol content is temperature. From the mashing to the fermentation, maintaining good temperature range is important to control the taste of the final product. In the mashing process, the temperature would affect the enzymatic activities of the enzymes present in either the grains or the bread, thus affecting the breakdown of sugars. Similarly during fermentation, the temperature affects the yeast’s metabolic activity. High temperatures could introduce undesired flavors to the brew because of the effect the heat has on the metabolic activity of the yeast. Temperature of the wort is critical when the yeast is pitched, added to the

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wort, and if the wort is still warm. There is an increase in the concentration of diacetyl in the final brew\textsuperscript{16}.

To eliminate these additional flavors and products, the team will be designing an insulated space for fermentation as well as a temperature control device to monitor temperature and maintain constant temperature throughout fermentation. The temperature sensor would later be extended to mashing process as well to increase temperature control in the process.

For the design specification of the design controller, the amount of heat that needs to be moved for each phase and the rate the heat needs to move either into the brew or out of the brew was calculated. All calculations were done using EES, Engineering Equation Solver. These calculations and key assumptions made can be found in the appendix. **Equation 3.1** is the primary equation used. In this equation, \( m_{\text{fluid}} \) is the mass of fluid at a specific stage in the brewing process, \( C_{p,\text{fluid}} \) is the heat capacity of the fluid, \( \Delta T_{\text{fluid}} \) the change in temperature of fluid. Where the heat transfer is directly correlated to the change in temperature.

\[
Q_{\text{fluid}} = m_{\text{fluid}} C_{p,\text{fluid}} \Delta T_{\text{fluid}}
\]

**Equation 3.1**

During the mashing process, the batch temperature is raised about 76 degrees Celsius, so about 2,400 kJ of heat has to be added to the mash to get to the desired temperature. The team is planning on using a turkey fryer to control the heat added and to maintain the temperature at the desired temperature over a period of 45 minutes to an hour.

The brew is then cooled back to room temperature or cooler, which is another temperature drop of about 76 to 80 degrees Celsius. So approximately 1,744 kJ of heat will have to be removed to cool the wort down to pitching temperature, about 21 degrees Celsius. The team plans on running cold water through copper tube to cool the wort to pitching temperature. The cold water will be from the faucet, which on average in Michigan is about 10 degrees Celsius. **Equation 3.2\textsuperscript{17}** was used to calculate the cool time. Where \( T_{c,in} \) is the cold inlet temperature, \( T_{h,f} \) is the final temperature of the wort, the temperature at time = 0 second, \( \dot{m}_c \) is the rate water is flowing through the copper tube, \( m_{\text{wort}} \) is the mass of the wort, \( C_c \) is the heat capacity of the water, \( C_{\text{wort}} \) is the heat capacity of the wort. K is a constant solved for using equations found in the appendix, and \( t \) is the cool time in seconds. The cool time was calculated to approximately 30 minutes, based on the current geometry of the cooper tube the team has. To reduce the cool time to the recommend 15 minutes team will have to either increase the outer diameter of the tube to about 2.5 cm.

\[
\frac{T_{c,in} - T_{h,f}}{T_{c,in} - T_h} = \exp\left(\frac{\dot{m}_c C_c (1-K)}{m_{\text{wort}} C_{\text{wort}}} t\right)
\]

**Equation 3.2**

During the fermentation process about 32.62 kJ to 125.8 kJ of heat can be generated depending on the initial pitch temperature and the type of wort being brewed. This means there is an expected

temperature change of 2 to 8 degrees Celsius. The amount of heat generated during fermentation will have to be removed to maintain constant temperature, and keep the yeast population alive. The team will be designing a temperature controller that can remove the generated heat within 1 to 3 minutes. The cooling source would be a fan that can move the air at a minimum rate of 0.085 kg/s, 0.0713 m^3/s, for only 32.62 kJ heat generated and the fermenter cooled within 3 minutes. The necessary maximum rate of air flow is 0.25 kg/s, 0.2182 m^3/s, for 125.8 kJ of heat generated cooled within on minute. Fans are rated by airflow rate using the units cubic feet per minute, CFM. For the purpose of the fermenter, the fan should have airflow rate ranging from 152 CFM to 462 CFM. On average a ceiling fan would have a CFM of about 5640 CFM, for the purpose of the fermenter the team will be using a significantly smaller fan. The current target is a 120 x 38mm high-speed 12 volt fan. As the airflow rate of the fan goes so does cost of the fan. So for the purpose of this fermenter, a fan with a 190.5 CFM will suffice. It will take 2.42 minutes to cool the fermenter back to desired temperature. This decision may change as the team evaluates cost effective alternatives, such as increasing the cooling time.

The fermentation temperature will range between 20 to 22 degrees Celsius. To maintain the surrounding temperature for the carboy being used for fermentation at the set fermentation temperature an insulated chamber will be constructed. The insulated space will be a Styrofoam box large enough to hold the one-gallon carboys during fermentation. Different materials were considered for the construction of the insulated space. Table 3.1 displays the alternatives evaluated. The selected material could change after further investigation to include more materials. The biggest decision factor was the thermal conductivity of the material. The thermal conductivity of the material describes how well it can conduct heat. In the case of an insulator the team wants a material that acts as a poor conductor with a low thermal conductivity. Another factor evaluated was the cost of the materials; the cost presented in the table is per unit the material would be purchased. A unit for the plywood is about 7/16 in x 4 ft. x 8ft, for the Styrofoam it is for on 32-quart container, for the cork material a unit is a 1/4 in x 4 ft. x 8ft sheet.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (W/m(^2)-K)(^18)</th>
<th>Cost ($/unit)</th>
<th>Box Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plywood</td>
<td>0.13</td>
<td>8.85(^19)</td>
<td>Yes</td>
</tr>
<tr>
<td>Styrofoam</td>
<td>0.033</td>
<td>5(^20)</td>
<td>No</td>
</tr>
<tr>
<td>Cork</td>
<td>0.07</td>
<td>40(^21)</td>
<td>Yes</td>
</tr>
</tbody>
</table>

To maintain a constant temperature, Pan Fermenti will have to incorporate a feedback control system, which will adjust for changes in temperature in the control volume, the insulated box. Figure 3.7 illustrates the block diagram of the system that will be used for the insulator. The team evaluated different controller options that would successfully achieve a stable system that will adjust for the error between the actual box temperature and the desired box temperature.

**Figure 3.7 Closed Loop Feedback Control System for Temperature Control**

For the temperature controller several options were considered. The controller would have to take the information from the sensor as an input and convert that to an output, while making the appropriate adjustments. One of the decision factors identified is cost. Table A-1 and Table A-2, in the appendix, show the team’s budget and expense thus far, respectively. To be cost effective the team will be going with the Arduino sensors. The Arduino offers the most flexibility for the cost. It allows for data recording, which would allow for improvement on current heat transfer calculations, it also provides the option of two outputs, for either heating or cooling. In Table 3.2, wiring refers to connecting jumper cables, or similar product from the controller to other components, including the temperature sensor, heating and/or cooling source. While DIY, refers to a “do-it-yourself” setup, requiring assembling from scratch. The cost in this table does not include the heating or cooling source.
Table 3.2 Alternative Process Controller for Temperature Control

<table>
<thead>
<tr>
<th>Temperature Controller</th>
<th>Supplier</th>
<th>Cost ($)</th>
<th>Function</th>
<th>Data Recording</th>
<th>Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature Controller</td>
<td>Omega</td>
<td>95</td>
<td>Heating and cooling</td>
<td>Potentially</td>
<td>Some wiring</td>
</tr>
<tr>
<td>Brew pi</td>
<td>Brewpi</td>
<td>112</td>
<td>Heating and cooling</td>
<td>Yes</td>
<td>Some wiring</td>
</tr>
<tr>
<td>Thermostat</td>
<td>Jet.com</td>
<td>20.99</td>
<td>Cooling or Heating</td>
<td>No</td>
<td>Some wiring</td>
</tr>
<tr>
<td>Fermenting heater</td>
<td>Midwest supplies</td>
<td>29.99</td>
<td>Heating only</td>
<td>No</td>
<td>No wiring</td>
</tr>
<tr>
<td>The Brew Belt</td>
<td>Home brew Supply</td>
<td>23.95</td>
<td>Heating only</td>
<td>No</td>
<td>No wiring</td>
</tr>
<tr>
<td>STC-1000</td>
<td>Amazon</td>
<td>39.52</td>
<td>Heating and cooling</td>
<td>No</td>
<td>DIY</td>
</tr>
<tr>
<td>Arduino</td>
<td>Multiple Suppliers</td>
<td>31.51</td>
<td>Heating and cooling</td>
<td>Yes</td>
<td>DIY</td>
</tr>
<tr>
<td>Son of a fermentation chiller\textsuperscript{22}</td>
<td>Multiple Suppliers</td>
<td>70</td>
<td>Cooling</td>
<td>No</td>
<td>DIY</td>
</tr>
</tbody>
</table>

3.3.1.2 Arduino Sensors

Based solely cost building a temperature controller using Arduino would be the option the team would use. This would give the team experience working with coding, as well as a PID controller. PID controllers are a type of microcontroller.

For building a temperature controller, Table 3.3 shows the parts the team will need, the cost and what role they play in building the controller. Further cost analysis will be done to validate the decision to build the controller as a team, or introduce the possibility buying cheaper and easier to install temperature controllers. For the purpose of the project the team will have the option of two outputs, one for a cooling source, a fan, and another for a heating source, an incandescent bulb. However, guidance provided by the team’s industrial mentor, Jake Brenner, informed that time is well-spent focused on a cooling source. It is most likely that the process had generated heat instead of heat loss during the fermentation process.

\textsuperscript{22} "Son of a Fermentation Chiller." Innovative Homebrew Solutions, n.d. Web.
### Table 3.3 Parts List for Team Built Controller

<table>
<thead>
<tr>
<th>Parts</th>
<th>Cost ($)</th>
<th>Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arduino UNO</td>
<td>9.88</td>
<td>Sense temperature via an input and control the surrounding via an output</td>
</tr>
<tr>
<td>White Breadboard</td>
<td>7.48</td>
<td>Platform to connect all appropriate parts to one another</td>
</tr>
<tr>
<td>LM35/TMP36 Temperature Sensor</td>
<td>5.95</td>
<td>Sense the surrounding temperature</td>
</tr>
<tr>
<td>Relay Module</td>
<td>5.99</td>
<td>acts as an electrical switch in the case when the</td>
</tr>
<tr>
<td>9V battery</td>
<td>7.99</td>
<td>Power the fan and the bulb</td>
</tr>
<tr>
<td>DC fan (9V/12V)</td>
<td>5.00</td>
<td>Cooling source</td>
</tr>
<tr>
<td>Some jumper wires</td>
<td>Included in breadboard</td>
<td>For prototype wiring, to connect all necessary parts</td>
</tr>
<tr>
<td>16 x 2 LCD (Optional)</td>
<td>2.70</td>
<td>To display temperature</td>
</tr>
<tr>
<td>Incandescent bulb</td>
<td>7.99</td>
<td>Heating source</td>
</tr>
</tbody>
</table>

#### 3.3.2 Scaling up the Design

Once the recipe has been fine-tuned, the industrial mentor will coordinate with the team in scaling the design to an industrial level. Jake Brenner, the head brewer at Grand Rapids Brewing Co., has extensive experience working in breweries and experimenting with beer recipes. Under his mentorship, the team will design a process that can be scaled to other breweries.

#### 3.4 Structural Design

The working facility will require addition joists for the implementation of a filter for the bread starches. Additionally, storage space is necessary for the bread in the wort due to the comparably large volume to compensate for the replaced sugars in beer production. Catchments made for filtration will also need to be regularly sanitized and cleared. The joist protrusion that supports a filter for the mash will be designed for ease of detachment and cleaning of the filter in place. A supportive mesh will also be necessary for the structural integrity of the mash filter while allowing clearance for the liquid.
3.5 Challenges Encountered
The existing space for brewing at Grand Rapids Brewing Co. is limited. The dimensions of the room where the fermentation takes place is roughly 20’ x 60”; this leaves little room for additional equipment. Thus, the project will be designed to function alongside existing equipment.

The breakdown of sugars present in bread will also be problematic. Since the available sugars have been subjected to baking, it may require additional catalytic enzymes to break down the sugars present in the bread mash.

3.6 Chemical Process
3.6.1 Chemistry
The chemical process of this experiment revolves around the biochemical pathways of yeast, specifically the species *Saccharomyces cerevisiae*. The team will observe the yeast cell as an isolated system where the input is a simple sugar (glucose, fructose, maltose, and maltotriose) and the product is two moles of carbon dioxide and ethanol per mole of sugar, the expression is shown in Equation 3.3,

\[
C_6H_{12}O_6 \xrightarrow{glycoysis} 2CO_2 + 2C_4H_6O
\]

As a basis for this experimental process, it is assumed that 100% of the sugars in solution are fermentable and that total conversion occurs for this system (this same assumption is used in most brewing software). Further analysis will be done to determine actual amount of fermentable sugars. The first experiment the team conducted was boiling the bread post mashing. This further complicated the process as both the sugars broke and the starches broke down. The sizes of these starch molecules can range from 2 microns to 100 microns, which created a filtration problem.

Upon asking for recommendations from The Beer Project, the team was directed to not boil the bread, but to process the bread back into powder “flour,” use rice husk in the lauter process to help congeal the starches, and do all this in combination with grain processing. The team will also determine the best type of yeast strain to use. Initial brewing and modeling of sugar breakdown will use the yeast that Grand Rapids Brewing uses for their wheat-based beer. In addition, the team will develop a standardized method to determine what outputs needed to achieve.

A ‘library’ of analytic data will be made of different wheat-based beers from Grand Rapids Brewing Co. The high pressure liquid chromatography (HPLC) will be used to analyze bitter acids in the hops and beer. Gas chromatography will be used to determine the volatile compounds in the solution. This includes alcohol and aldehydes. Upon assessing the beers the process is trying to mimic, the process and design will be altered to best reach the concentrations and components of the final product.

To measure rate of reaction and course of reaction, these equations were plugged into an ODE solver, *Polymath*. The sample results can also be found in the appendix. These sample showed expected results once the design specifications are entered into the equations. Upon solving for the
initial cell concentration and initial substrate concentration (glucose), the final concentrations of glucose and ethanol can be predicted. Knowing this will allow the process to extract as much fermentable sugars from the bread to be optimized. This will also indicate whether or not more sugar or malt extract (adding malt extract is undesired) should be added prior to fermentation.

3.6.2 Final Product Testing

3.6.2.1 Bitterness:
Humlene is a monocyclic sesquiterpene originally found in the essential oils of humulus lupulus (hops); it is the main aromatic that influences the IBU’s of beer. The more alpha-acid extracted from the hops, the higher the IBU number. The Glenn Tinseth formula shown in Equation 3.4 calculates the percentage of alpha acids (Humlene) to predict bitterness in beer by assuming that alpha acid isomerization is a first order reaction, or a pseudo first order chemical reaction.23

\[
IBU = (1.65 \times 0.000125 G_{gravity}^{-1})(1 - e^{-0.04t_{min}})\left(\frac{\alpha\%}{100}\frac{W_{oz}}{V_{gallons}}\right)
\]

Equation 3.4: Glenn Tinseth’s equation

Where \(G_{gravity}\) is the boil wort gravity (specific gravity), \(t_{min}\) is the time hops were boiled (minutes), \(W_{oz}\) is the mass of hops added (ounces), \(\alpha\%\) is the alpha acid rating and \(V_{gallons}\) is the final beer volume (gallons). This equation along with proposed process conditions such as hops boiling time, initial hops weight, and initial volume will help predict final IBUs. Here, the results can then compare the bread beer to the beer the design is aiming to mimic, and it can also get similar IBU values from this equation.

3.6.2.2 Specific Gravity (alcohol content) - hydrometer
Sugar content will raise the specific gravity of wort and beer, and a hydrometer is used to measure the specific gravity to obtain alcohol content. Equation 3.5 was used to convert specific gravity, FG, and original gravity, OG, to alcohol content, ABV. These values were visually measured using a hydrometer, seen in Figure 3.8.

\[
ABV = \frac{105}{0.79} \frac{(OG - FG)}{FG}
\]

Equation 3.5

---

Figure 3.8 Alcoholmeter Testing with Hydrometer\textsuperscript{25}

3.6.3 Chemical Kinetics

3.6.3.1 Mass Balance

Using \textbf{Equations 7-77, 7-79, 7-80} in Fogler\textsuperscript{26}, a mass balance can describe the system,

Cells:

\[ V \frac{dC_c}{dt} = (r_g - r_d)V \] \hspace{1cm} \text{Equation 7-77 (Fogler)}

where \( C_c \) is the concentration of cells, \( V \) is the volume of the reactor, \( t \) is time, \( r_g \) is the cell growth rate derived from the Monod equation or Tessier equation, and \( r_d \) is the cell death rate.

Substrate (bread wort):

\[ V \frac{dC_s}{dt} = Y_{s/c}(-r_g)V - r_{sm}V \] \hspace{1cm} \text{Equation 7-79 (Fogler)}

where \( C_s \) is the concentration of substrate, \( Y_{s/c} \) is the substrate and cell yield coefficient, and \( r_{sm} \) is the rate of substrate consumption (independent from cell growth).

Product (ethanol):

\[ V \frac{dC_p}{dt} = Y_{p/c}(r_g)V \] \hspace{1cm} \text{Equation 7-77 (Fogler)}

---


where $C_p$ is the concentration of product (ethanol), and $Y_{p/c}$ is the stoichiometric yield coefficient that relates the amount of product formed per mass of substrate consumed. Upon writing the overall mass balance of the process, each rate law has to be expressed.

### 3.6.3.2 Rate Law

The rate laws explained in the mass balance above are expressed in Equations 3.6-8 as,

$$r_g = \mu_{max} \left( 1 - \frac{C_p}{C_p^*} \right)^{0.52} \frac{C_c C_s}{K_s + C_s} \quad \text{Equation 3.6}$$

$$r_d = k_d C_c \quad \text{Equation 3.7}$$

$$r_{sm} = m C_c \quad \text{Equation 3.8}$$

where $\mu_{max}$ is the maximum specific growth rate, $C_p^*$ is the product (ethanol) concentration at which all metabolism ceases, $K_s$ is the Monod constant, $k_d$ is the specific rate constant with respect to cell death, and $m$ is the consumption rate (g of substrate over gram of cell hour) of substrate per cell per hour. The values for these constants can be found in the appendix. The initial values of the constants can be viewed on the Polymath computation sheet.

### 3.6.3.3 Stoichiometry

This is described in Equation 3.9, where $r_p$ is the corresponding rate of product formed.

$$r_p = \frac{Y_p}{c} r_g \quad \text{Equation 3.9}$$

Combining previous equations results in Equations 3.10-12. The results of these equations over time are shown in Figures 3.9-11.

$$\frac{dC_c}{dt} = \mu_{max} \left( 1 - \frac{C_p}{C_p^*} \right)^{0.52} \frac{C_c C_s}{K_s + C_s} - k_d C_c \quad \text{Equation 3.10}$$

$$\frac{dC_s}{dt} = \mu_{max} \left( 1 - \frac{C_p}{C_p^*} \right)^{0.52} \frac{C_c C_s}{K_s + C_s} - m C_c \quad \text{Equation 3.11}$$

$$\frac{dC_p}{dt} = \frac{Y_p}{c} r_g \quad \text{Equation 3.12}$$
Figure 3.9 Concentration of product and substrate over time, where $C_s =$ concentration of substrate (glucose) and $C_p =$ concentration of product (ethanol)

Figure 3.10 Concentration of Yeast Cells
Figure 3.12 Rate function as a function of time, where \( rd = \text{rate of cell death}, \ \text{rg} = \text{rate of cell growth}, \ \text{and rsm} = \text{rate of substrate consumption.} \)

4. PRODUCT ANALYSIS

4.1 Existing Competitors

Brewing with bread is a new practice in local Grand Rapids area, so there is no company around here is producing consultant’s beer recipe/brewing method with bread. Thus, there are no competitors.

4.2 Production Feasibility

The project is inspired by a Belgium brewing company, called Brussels Beer Project. In their project, about 500 kilograms of the uneaten bread can were processed using yeast, US- or UK-sourced hops, and a 4,000-liter batch of the beer, a 7-percent amber called Babylone. The goal of the project is to increase the amount of bread that can be put into brewing process.

4.3 Marketing Strategies

4.3.1 Target market

Breweries that are considering their environmental impact will be interested in Pan Fermenti. By reducing bread waste and conserving water, Pan Fermenti offers environmentally conscious consultation backed with economic feasibility. More specifically, head brew-masters will be interested by the savings in their variable cost: the reduction of grains necessary for their wort. Mid-size breweries would work best with Pan Fermenti’s designs due to the size necessary for additional equipment while also incorporating ease of implementation in existing facilities.
4.3.2 Customers' motivation to buy

Thus far, only Brewery Vivant and Grand Rapids Brewing Co. lead the campaign of sustainable brewing in Michigan. Being the only LEED certified craft brewery, the motivations of Brewery Vivant and Pan Fermenti lie in tandem. With Grand Rapids Brewing Co., the material costs of grain and water intensiveness of the brewing process is well known. These breweries are symbolic of the larger problems that breweries are addressing: how to reduce material cost and water waste. Pan Fermenti would persuade clients with a design that caters to these problems in a way that is sustainable. The image of sustainability would also act as a marketing point that these breweries could promote after the implementation of the design.

5. DELIVERABLES

Once the project is complete the team will have prototypes to prove designed process, along the way the team will present different documents, presentations, and complete different actions as milestones and ways to present the research and design process throughout the process. Table 5.1 shows some of the deliverables and the dates they will be available.
Table 5.1 Items the Team will have Available on the Project

<table>
<thead>
<tr>
<th>Item</th>
<th>Date</th>
<th>What</th>
<th>Format</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oral Presentation I</td>
<td>26 October 2016</td>
<td>Presentation to class on the project and status thus far</td>
<td>.ppt</td>
</tr>
<tr>
<td>Team Poster</td>
<td>6 November 2016</td>
<td>Visual representation of the team and the project</td>
<td>.pdf</td>
</tr>
<tr>
<td>Website</td>
<td>12 November 2016</td>
<td>Communicates as much info about the project to the public</td>
<td>.html</td>
</tr>
<tr>
<td>Oral Presentation II</td>
<td>2 December 2016</td>
<td>Presentation to class on the project and status thus far</td>
<td>.ppt</td>
</tr>
<tr>
<td>PPFS</td>
<td>11 December 2016</td>
<td>Project Proposal and Feasibility Study presents the idea and plan for the project throughout the year</td>
<td>.pdf</td>
</tr>
<tr>
<td>Business Plan</td>
<td>11 December 2015</td>
<td>Document communicating the plans to start a business around the product</td>
<td>.pdf</td>
</tr>
<tr>
<td>Oral Presentation III</td>
<td>TBD</td>
<td>Presentation to class on the project and status thus far</td>
<td>.ppt</td>
</tr>
<tr>
<td>Oral Presentation IV</td>
<td>TBD</td>
<td>Presentation to class on the project and status thus far</td>
<td>.ppt</td>
</tr>
<tr>
<td>Recipe</td>
<td>May 7 2015</td>
<td></td>
<td>.pdf</td>
</tr>
<tr>
<td>Automated Brewer Prototype</td>
<td>May 7 2015</td>
<td></td>
<td>Visual display</td>
</tr>
<tr>
<td>Final Report</td>
<td>TBD</td>
<td>Document relaying information about the project</td>
<td>.pdf</td>
</tr>
<tr>
<td>Final Presentation</td>
<td>May 7, 2015</td>
<td>Senior Design Banquet</td>
<td>N/A</td>
</tr>
</tbody>
</table>
APPENDIX

Budget .......................................................................................................................... A-1
Heat Transfer Calculations .......................................................................................... A-2 – A-5
Conversion Kinetics Calculations .............................................................................. A-6 – A-7
Sources ......................................................................................................................... A-8
Acknowledgements ...................................................................................................... A-9
## Budget

**Table A-1 Budget**

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit Cost</th>
<th>Count</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Budget</td>
<td>500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turkey Fryer</td>
<td>60</td>
<td>1</td>
<td>60</td>
</tr>
<tr>
<td>Brewing Grains</td>
<td>1.09</td>
<td>15</td>
<td>16.35</td>
</tr>
<tr>
<td>Bread</td>
<td>0</td>
<td>30</td>
<td>0</td>
</tr>
<tr>
<td>Startup Kit</td>
<td>94</td>
<td>1</td>
<td>94</td>
</tr>
<tr>
<td>Arduino Sensor</td>
<td>31.51</td>
<td>1</td>
<td>31.51</td>
</tr>
<tr>
<td>12 V Fan - 192 CFM</td>
<td>30</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>Priming Sugar</td>
<td>0.96</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sanitizer</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1- gallon kit</td>
<td>34</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Recipe book</td>
<td>20</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total cost</strong></td>
<td><strong>268.14</strong></td>
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<td><strong>231.86</strong></td>
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</tbody>
</table>

*Table A-2 Sunk cost as of 11 December 2015*

<table>
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<tr>
<th>Team Name</th>
<th>Pan Fermenti</th>
</tr>
</thead>
<tbody>
<tr>
<td>Team #</td>
<td>21</td>
</tr>
<tr>
<td>Senior Design</td>
<td></td>
</tr>
<tr>
<td>Advisor:</td>
<td>Prof. VanAntwerp</td>
</tr>
</tbody>
</table>

Name of student submitting THIS budget and request for reimbursement:

<table>
<thead>
<tr>
<th>Date</th>
<th>Team member</th>
<th>Description</th>
<th>Debit</th>
<th>Credit</th>
<th>Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/1/15</td>
<td>Michael Schur</td>
<td>Brewing Starting up Kit</td>
<td>94.00</td>
<td></td>
<td>$406.00</td>
</tr>
<tr>
<td>11/11/15</td>
<td>Jerome Navarro</td>
<td>Turkey Fryer</td>
<td>60.00</td>
<td></td>
<td>$346.00</td>
</tr>
</tbody>
</table>
Heat Transfer Calculations

"Assumptions"
"surrounding conditions"
T_mash = convettemp(C, K, 25)
P_mash = 101.325 [kPa]
T_chiller = convettemp(C, K, 100)
P_chiller = 101.325 [kPa]
T_wort = convettemp(C, K, 65)
P_wort = 101.325 [kPa]

"Volume of liquid"
Vol_mash = 2 * convert(gallon, m^3)
Vol_chiller = 1.5 * convert(gallon, m^3)
Vol_wort = 1 * convert(gallon, m^3)

"Physical properties of fluid"
\[ \rho_{\text{mash}} = \text{Density(Water, } T=T_{\text{mash}}, P=P_{\text{mash}}) \]
\[ C_{p_{\text{mash}}} = \text{cp(Water, } T=T_{\text{mash}}, P=P_{\text{mash}}) \]
\[ \rho_{\text{chiller}} = \text{Density(Water, } T=T_{\text{chiller}}, P=P_{\text{chiller}}) \]
\[ C_{p_{\text{chiller}}} = \text{cp(Water, } T=T_{\text{chiller}}, P=P_{\text{chiller}}) \]
\[ \rho_{\text{wort}} = \text{Density(Water, } T=T_{\text{wort}}, P=P_{\text{wort}}) \]
\[ C_{p_{\text{wort}}} = \text{cp(Water, } T=T_{\text{wort}}, P=P_{\text{wort}}) \]

"Mass"
\[ m_{\text{mash}} = \rho_{\text{mash}} \times \text{Vol}_{\text{mash}} \]
\[ m_{\text{chiller}} = \rho_{\text{chiller}} \times \text{Vol}_{\text{chiller}} \]
\[ m_{\text{wort}} = \rho_{\text{wort}} \times \text{Vol}_{\text{wort}} \]

"Temperature change"
\[ \Delta T_{\text{wort}} = T_{\text{final}} - T_{\text{init}} \]
\[ T_{\text{init}} = \text{convettemp}(C, K, 17.7) \]
\[ T_{\text{final}} = \text{convettemp}(C, K, 25.8) \]
\[ \Delta T_{\text{mash}} = T_{\text{final}} - T_{\text{init}} \]
\[ T_{\text{final}} = \text{convettemp}(C, K, 101) \]
\[ T_{\text{init}} = \text{convettemp}(C, K, 25) \]
\[ \Delta T_{\text{chiller}} = T_{\text{final}} - T_{\text{init}} \]
\[ T_{\text{final}} = \text{convettemp}(C, K, 25) \]
\[ T_{\text{init}} = \text{convettemp}(C, K, 101) \]

"Heat Transfer"
"Fermenter"
\[ Q_{\text{fermenter}} = m_{\text{wort}} \times C_{p_{\text{wort}}} \times \Delta T_{\text{wort}} \]

"Mashtun"
\[ Q_{\text{mashtun}} = m_{\text{mash}} \times C_{p_{\text{mash}}} \times \Delta T_{\text{mash}} \]
"chiller"
Q_chiller = m_chiller * C_p_chiller * DELTAT_chiller

"Heat Transfer rate"
"Fermenter"
Q_dot_fermenter = Q_fermenter/t_cool_fermenter

"mashtun"
Q_dot_mashtun = Q_mashtun/t_cool_mashtun

"chiller"
Q_dot_chiller = Q_chiller/t_cool_chiller

"fan"
Q_dot_fan = m_dot_air * C_p_air * (T_final - T_init)
Q_dot_fan = Q_dot_fermenter
C_p_air = cp_air(T = T_final)
rho_air = density(air, T = T_final, P = P_wort)
v_dot_air = m_dot_air/rho_air
v_dot_air_E = v_dot_air * convert(m^3/s, ft^3/min)

"for chosen fan specs"
v_dot = 190.5*convert( ft^3/min, m^3/s)
m_dot = v_dot*rho_air
m_dot_fan = 0.1062
Q_dot_fan_a = m_dot_fan * C_p_air * (T_final - T_init)
t_new = Q_fermenter/Q_dot_fan_a

"copper tube"
"physical constraints"
s = 0.005 [m]
ID = 0.024 [m]
OD = 0.025 [m]
L = 1.5 [m]
r_od = OD/2
r_id = ID/2
A_o = 2*pi*r_od*L
A_i = 2*pi*r_id*L
A_LM = 2*pi*L* (r_od - r_id)/(ln(r_od/r_id))
D = ID
m_dot_c = 9.46352946e-5 [m^3/s] * rho_chiller "source: http://www.allianceforwaterefficiency.org/Faucet_Fixtures_Introduction.aspx"
C_c = C_p(Water, T = T_c_in, P = P_surr)
P_surr = 101.325 [kPa]
P = P_chiller

"thermodynamic properties"
k = 0.401[kW/m-K]
h_o = x_o *convert(W/m^2-K, kW/m^2-K)
h_i = x_i *convert(W/m^2-K, kW/m^2-K)
Call FC_horizontal_cylinder('water', T_s_o, T_infinity, P, D : x_o, Nusselt, Ra)
Call FC_horizontal_cylinder('water', T_s_i, T_infinity, P, D : x_i, Nusselt_i, Ra_i)

"Temperature"
T_c_in = converttemp(F, K, 49.9) \{source: http://www.gixtechnology.com/WaterTemp.pdf\}
T_h = T_init_chiller
T_h_f = T_final_chiller
T_c_out = T_h + K_o*(T_c_in - T_h)
T_s_o = converttemp(C, K, 100)
T_infinity = converttemp(C, K, 40)
T_s_i = T_c_in

DELTA_T_lm = ((T_c_in - T_h_f) - (T_c_out - T_h_f)) / (ln((T_c_in - T_h_f)/(T_c_out - T_h_f)))

"Constant"
K_o = exp(-U_Lm*A_Lm/(m_dot_c * C_c))

"Resistance"
U_o = (A_o/(h_i * A_i)) + (k*A_o/(s*A_LM))(-1) + 1/(h_o))(-1)
U_i = (1/(h_i)) + (k*A_i/(s*A_LM))(-1) + A_i/(h_o*A_o))(-1)
U_Lm = (U_o - U_i)/(ln(U_o/U_i))

"Heat transfer rate"
Q_dot = U_Lm * A_Lm * DELTA_T_lm

(T_c_in - T_h_f)/(T_c_in - T_h) = exp(-m_dot_c * C_c * (1 - K_o)/(m_chiller*C_p_chiller) * t)
time = t * convert(sec, min)

‖cool time‖
t_cool_fermenter = 1 * convert(min, sec)
t_cool_mashhtun = 20 * convert(min, sec)
t_cool_chiller = 15 * convert(min, sec)

SOLUTION
Unit Settings: SI K kPa kJ mass deg
A_Lm = 0.1154 [m^2]
A_m = 0.1131 [m^2]
A_c = 4.188 [kJ/Kg-K]
C_p = 4.183 [kJ/kg-K]
C_v = 1.005 [kJ/kg-K]

\( L_m = 8.1 \) [K]
\( \Delta T_m = 76 \) [K]
\( \Delta T_{vort} = 76 \) [K]
\( h_i = 0.867 \) [kW/m^2-K]
\( h_o = 0.872 \) [kW/m^2-K]
\( h_{wall} = 5.442 \) [kg]
\( \dot{m}_{water} = 0.2577 \) [kg/s]
\( \dot{m}_{water} = 0.1052 \) [kg/s]
\( \dot{m}_{water} = 7.549 \) [kg]
\( \dot{m}_{water} = 3.712 \) [kg]
\( \dot{m}_{water} = 26.51 \)
\( \dot{m}_{water} = 101.3 \) [kPa]
\( \dot{m}_{water} = 101.3 \) [kPa]
\( \dot{m}_{water} = 101.3 \) [kPa]
\begin{align*}
Q_{\text{total}} &= -1.744 \text{ [kJ]} \\
Q_{\text{out}} &= -1.538 \text{ [kJ/s]} \\
Q_{\text{in}} &= 0.8942 \text{ [kJ/s]} \\
Q_{\text{temper}} &= 2 \text{ [kJ/s]} \\
Q_{\text{storage}} &= 2.400 \text{ [kJ]} \\
Ra &= 8.287\times10^6 \\
\rho_{\text{p}} &= 958.4 \text{ [kg/m}^3]\text{]} \\
\rho_{\text{water}} &= 58.6 \text{ [kg/m}^3]\text{]} \\
f_{\text{water}} &= 0.0125 \text{ [m]} \\
t &= 849.6 \text{ [s]} \\
T_{\text{total}} &= 373.2 \text{ [K]} \\
T_{\text{coolant}} &= 60 \text{ [sec]} \\
T_{\text{in}} &= 283.1 \text{ [K]} \\
T_{\text{inlet}} &= 299 \text{ [K]} \\
T_{\text{outlet}} &= 374.2 \text{ [K]} \\
T_{\text{out}} &= 298.2 \text{ [K]} \\
\text{time} &= 14.18 \text{ [min]} \\
\text{feed flow} &= 900 \text{ [sec]} \\
\text{feed mass} &= 1.200 \text{ [sec]} \\
T_{\text{coolant}} &= 264.7 \text{ [K]} \\
T_{\text{water}} &= 298.2 \text{ [K]} \\
T_{\text{inlet}} &= 283.1 \text{ [K]} \\
T_{\text{outlet}} &= 374.2 \text{ [K]} \\
\text{time} &= 14.18 \text{ [min]} \\
U &= 0.4598 \text{ [kW/m}^2\text{-K}] \\
U_0 &= 0.4416 \text{ [kW/m}^2\text{-K}] \\
V_{\text{water}} &= 0.007571 \text{ [m}^3\text{]} \\
V_0 &= 0.08901 \text{ [m}^3\text{]} \\
V_{\text{air}} &= 462.3 \text{ [ft}^3\text{/min]} \\
V_0 &= 1.500 \text{ [W/m}^2\text{-K]} \\
\text{No unit problems were detected.}
\end{align*}

**KEY VARIABLES**

**Heat transfer at different stages**

\begin{align*}
Q_{\text{storage}} &= 2.400 \text{ [kJ]} \\
Q_{\text{total}} &= -1.744 \text{ [kJ]} \\
Q_{\text{temper}} &= 125.8 \text{ [kJ]} \\
\text{time} &= 14.16 \text{ [min]} \\
\Delta T_{\text{cool}} &= 8.1 \text{ [K]} \\
\dot{m}_{\text{air}} &= 0.2577 \text{ [kg/s]} \\
\end{align*}

**Cool Time**

**Expected maximum temperature change during fermentation**

**Maximum airflow rate**
Conversion Kinetics Calculations

**POLYMATH Report**

Sample calculation and results

Ordinary Differential Equations

15-Nov-2015

<table>
<thead>
<tr>
<th>Table A.3 Calculated values of DEQ variables</th>
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<tbody>
<tr>
<td>Variable</td>
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<tr>
<td>1 Cc (g/dm^3)</td>
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<td>2 Cp (g/dm^3)</td>
</tr>
<tr>
<td>3 Cs (g/dm^3)</td>
</tr>
<tr>
<td>4 kobs (g/dm^3)</td>
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<tr>
<td>5 ks (g/dm^3)</td>
</tr>
<tr>
<td>6 m (g substrate/g cells/hr)</td>
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<tr>
<td>7 rd (g/dm^3*s)</td>
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<td>8 rg (g/dm^3*s)</td>
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<td>9 rsm (g/dm^3*s)</td>
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<tr>
<td>10 t (hr)</td>
</tr>
<tr>
<td>11 umax (1/hr)</td>
</tr>
<tr>
<td>12 Ypc (g/g)</td>
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<tr>
<td>13 Ysc (g/g)</td>
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</table>

**Differential equations**

1. \( \frac{d(Cc)}{dt} = rg - rd \)
2. \( \frac{d(Cs)}{dt} = Ysc(-rg)-rsm \)
3. \( \frac{d(Cp)}{dt} = rg*ypc \)
Explicit equations

1. \( r_d = cc \cdot 0.01 \)
2. \( y_{sc} = 1/0.08 \)
3. \( y_{pc} = 5.6 \)
4. \( k_s = 1.7 \)
5. \( m = 0.03 \)
6. \( u_{max} = 0.33 \)
7. \( r_{sm} = m \cdot cc \)
8. \( k_{obs} = \left( u_{max} \cdot (1 - cp/93)^{0.52} \right) \)
9. \( r_g = k_{obs} \cdot cc \cdot cs / (k_s + cs) \)

### Table A-4 General Information

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Bibliography


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