USE OF REVERSE OSMOSIS TO INCREASE THE BRIX CONTENT OF SWEET SORGHUM SUGAR SOLUTION

By

Taylor Jay Ahrensdorf

Jacob Michael Hodeaux

John David Hottenstein

A Thesis Submitted to The Honors College

In Partial Fulfillment of the Bachelors degree
With Honors in

Biosystems Engineering

THE UNIVERSITY OF ARIZONA

MAY 2014

Approved by:

____

Dr. Peter Livingston
Department of Agricultural and Biosystems Engineering

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Bachelor of Science in Engineering

Honors area (eg Molecular and Cellular Biology, English, Studio Art):

Biosystems Engineering

Date thesis submitted to Honors College:

May 7th, 2014

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Abstract

The goal of this engineering project is to increase the concentration of sugar, as measured by percentage sugar by weight or brix, in sweet sorghum solution. The team decided to utilize reverse osmosis to remove water from the solution to increase sugar concentration. The final goal of the project was to reach between 15% and 22% brix. Subsequent design goals for the project included reducing the suspended solids in the solution and ensuring the process could be scaled to handle a load of 1 acre/hour.

After two semesters of experimentation and design, the team constructed a pilot scale model which included two pumps, a bag filter, a screen filter, four reverse osmosis membranes, and a needle valve. Additionally, the system is designed so that is can function throughout the harvest season with minimal supervision, maintenance, and membrane replacement.

With this design, the team was able to increase the brix to a maximum of 9%, reduce the turbidity from 770 NTU to 170 NTU. The economic savings from choosing dehydration over boiling are 26 times more. With a larger budget and higher pressure membranes, the team expects a reverse osmosis system to be able to obtain 15% brix concentrate.

Team Member Roles

Each team member contributed equally in the design and construction of this project. Jacob was the lead when it came to implementation and placing the pieces of the system together. John was in charge of the economic analysis and scaling the system. Taylor was in charge of purchasing and ensuring that system parts were up to specifications, as well as scheduling and logistics. During the design phase of the project, all team members were present and contributed unique viewpoints to the engineering analysis. This includes the development of the reverse osmosis process, as well as the filtration component of the overall design. All team members were also physically present when experiments were conducted to determine process parameters. In addition, all team members were present for the final assembly of the physical components within the reverse osmosis system. Each team member contributed discrete components to the final design report that were then assembled and compiled together. Finally, each team member reviewed and edited the report individually before submission of the report.

Using Reverse Osmosis to Increase the Brix Content of Sweet Sorghum Sugar Solution

May 7th, 2014

Team Members:
Taylor Ahrensdorf
Kristen Currier
Jacob Hodeaux
John Hottenstein

Advisors:
Peter Livingston
Donald Slack

1200 E South Campus
Tucson, AZ 85721

May 7th, 2014

Sweet Ethanol LLC.
2000 N Kimberlee Rd
Tucson, Arizona 85749

Dear Dr. Livingston and Dr. Slack:

Enclosed is our report for the design of the pilot scale reverse osmosis system for processing of sweet sorghum juice obtained from diffusion extraction.

Throughout the 2013-2014 year, our team has been designing and testing elements for the pilot scale reverse osmosis system for the Agricultural and Biosystems Engineering (ABE) Department at the University of Arizona. This project works in conjunction with a former ABE senior design project, the diffusion extraction system for sweet sorghum, to process and separate the extracted sugar through reverse osmosis and obtain a final solution of increased sugar concentration.

Reverse osmosis is the process in which pressure is applied to a fluid across a semi-permeable membrane in excess of the osmotic pressure in attempt to increase the diffusion of water across the membrane. Compared to heating, evaporation, and standard osmosis, reverse osmosis reduces cost and required power inputs.

In the maple syrup industry, reverse osmosis has yielded overall water removal rates of over 80%. The goal of this project is to remove sufficient water to make the final sorghum solution competitive in ethanol production with other crops, such as sugar cane and corn, which are processed with other methods including roller mills and screw presses.

The enclosed reverse osmosis system is designed to process sorghum solution directly from the diffusion extractor. The pilot scale constructed model is designed to process 12 gallons/hour of sorghum solution. The reverse osmosis system will include pre-filters to remove suspended solids and decrease turbidity prior to entry into the reverse osmosis membrane. The series of reverse osmosis membranes will then increase the brix. Additionally, the system is designed to function throughout the harvest season with minimal supervision, maintenance, and membrane replacement.

Overall, the system was designed to maintain low construction and processing costs and require minimal power input and therefore become an efficient means of increasing the sugar concentration of sorghum juice obtained from diffusion extraction.

Sincerely,
Reverse Osmosis Senior Design Team

Executive Summary

Over the course of the semester, the team worked to create a pilot scale reverse osmosis system to process juice from the University of Arizona's sweet sorghum diffusion extraction unit. The current system is scaled down to 12 gallons / hour, where the full scale reverse osmosis system processes sorghum at a rate of one acre per hour. The ultimate goal of the project is to increase the low brix obtained from diffusion extraction, approximately 8%, to 22%. Brix is a ratio of the weights of sugar to liquid solution and is commonly used in the wine, sugar, and fruit juice industries to determine sugar content, Maximum ethanol processing efficiency is achieved at 22% brix and therefore increasing the sugar concentration further is unnecessary.

The entire process was broken down into two main components. The first component is a filtration unit designed to clean the sorghum solution to increase the reverse osmosis membranes lifespan and decrease overall system maintenance. This step is necessary as the sweet sorghum solution coming off the diffusion extraction unit has high turbidity measurements and contains ground up sorghum stalk. A screen filter removes large solids from the solution and is followed by a 1 micron bag filter to further remove smaller suspended solids from the solution. The bag filter was successful at decreasing overall turbidity from an incoming 770 NTU to an effluent of 170 NTU.

Experiments were conducted to ensure the bag filter was the best filtration method. These tests determined the efficiency of various filters in reducing turbidity and their effect on brix. The other pre-filtration methods included two types of carbon filters, a sand filter, single layer filters (i.e. coffee, felt, and fabric filters), and protein skimmers. Results showed that the bag filter was the best choice to meet design criteria such as ease of installation, cost, and the ability to be maintained and operated efficiently.

The reverse osmosis membranes make up the second component of the overall designed process. Final measurements showed that the four membranes in series are capable of increasing brix to a maximum of 8.5% to 9%. With the chosen components and operating pressure utilized in our design there appears to be minimal improvement beyond the 9% brix we have obtained. This is a result of the 110 psi operating pressure that our current pump provides and the rated pressure of the reverse osmosis membranes.

Other researchers have found that higher brix values are able to be obtained; however, they will require membranes and pumps used for seawater desalination and may become cost prohibitive. In addition, the team researched methods of increasing brix besides reverse osmosis including evaporation. Reverse osmosis is the most economical method of the two and further efforts to refine our design process with seawater membranes would be recommended.

Reverse osmosis proves to be an effective means for increasing brix content of sorghum juice, the team has designed a low cost means of producing an increased brix sorghum solution capable of being refined into ethanol. Furthermore, the team has reduced the overall water input of the University's diffusion extraction system by recycling water into the diffusion extraction system.

Acknowledgements

Thank you to the following people who have helped with the project:

Peter Livingston
Donald Slack
Charlie DeFer

And thank you to the following project sponsors:

Sweet Ethanol
University of Arizona

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Purpose and Overview of Project

The purpose of this project was to develop an effective means of solving the problem of the low sugar concentration obtained after using a diffusion extraction system to extract sugar from sweet sorghum. The proposed system to remove water used reverse osmosis. The designed system will work to filter out solids, increase the brix concentration, and return the extracted freshwater to the diffusion extraction system for reuse.

A typical reverse osmosis system includes several pre-filters, the reverse osmosis membrane, a post filter, a drain, and a storage tank. Our team spent the year designing and testing various pre-filtration methods and the reverse osmosis membrane itself. Based on the results, the team then created the final reverse osmosis system design.

Introduction

Statement of Problem

The term reverse osmosis is typically used for water purification and desalination and refers to the process by which water is forced through a semipermeable membrane at high pressure between 45 to 100 psi for residential water filtration to between 700 - 1200 psi in a large desalination plant. In desalination, the salts stay within the membrane system and become reject water, while the desalinated water is collected and distributed as freshwater. Additionally, reverse osmosis has been implemented by the maple sugar industry, at pressures between 100 - 250 psi, to remove water and increase sugar content in maple syrup. Reverse osmosis allows up to 75% to 92% water to be removed from the sap. However, this value is dependent upon the incoming brix concentration and varies per batch. The reverse osmosis process reduces the energy consumption and exposure of the syrup to high temperatures during the final evaporation process.

In the case of sweet sorghum, sugar is extracted using diffusion extraction as a result of hot water percolating through ground up sorghum stalks. The hot water then diffuses sugar from the ground up sorghum stalks resulting in a diluted sorghum sugar solution exiting the diffusion extraction system. This low sugar concentration sorghum solution can then have water removed to increase sugar concentration. Currently, evaporation of water through boiling is a popular method to increase the brix concentration. This higher sugar concentration creates a higher value product to eventually deliver for fermentation into ethanol. Additionally, the sweet sorghum juice must be well filtered and free of microbial contamination in order to avoid spoiling before fermentation. Also, the degradation of the filter and reverse osmosis membranes has to be monitored to ensure optimal extraction.

The specific goal of the project is to create a reverse osmosis system capable of processing 12 gallons per hour while increasing the brix of the output solution to between 18% to 22% while minimizing cost and power input.

In addition to the goal of increasing the brix to at least 18%, the team should attempt to return the pure water extracted to the sweet sorghum diffusion extraction system to reduce the water use of the entire sorghum juice extraction process.

Client goals include:

- Create a bench scale design able to process 12 gallons per hour
- Remove about 85% of water for a final brix of 22%
- Reduce power requirements to increase overall ethanol processing efficiency
- Budget a max of $1,500 dollars for final bench scale system
- Place pressure gages in system
- Strive to reuse and regenerate membranes between multiple harvests.

Background

Normal sweet sorghum stalks have a brix of between 12% and 20%. The process of diffusion extraction uses water to extract sugar from sorghum stalks. Water is added to the overall solution, thus decreasing brix. The University of Arizona's new diffusion extraction system was recently tested and obtained a brix between 5-8%. This suggests an almost complete sugar extraction from the crop. Process requirements remain to make the solution ready for fermentation. Brix must be increased to a maximum of 22% to maximize yeast fermentation of the sorghum solution into ethanol. A final brix of 22% would make sorghum competitive with other crops like sugar cane and corn, as well as other methods including roller mills and screw presses. The high brix level would also ensure maximum yeast efficiency in the actual process of converting the sugar solution to ethanol.

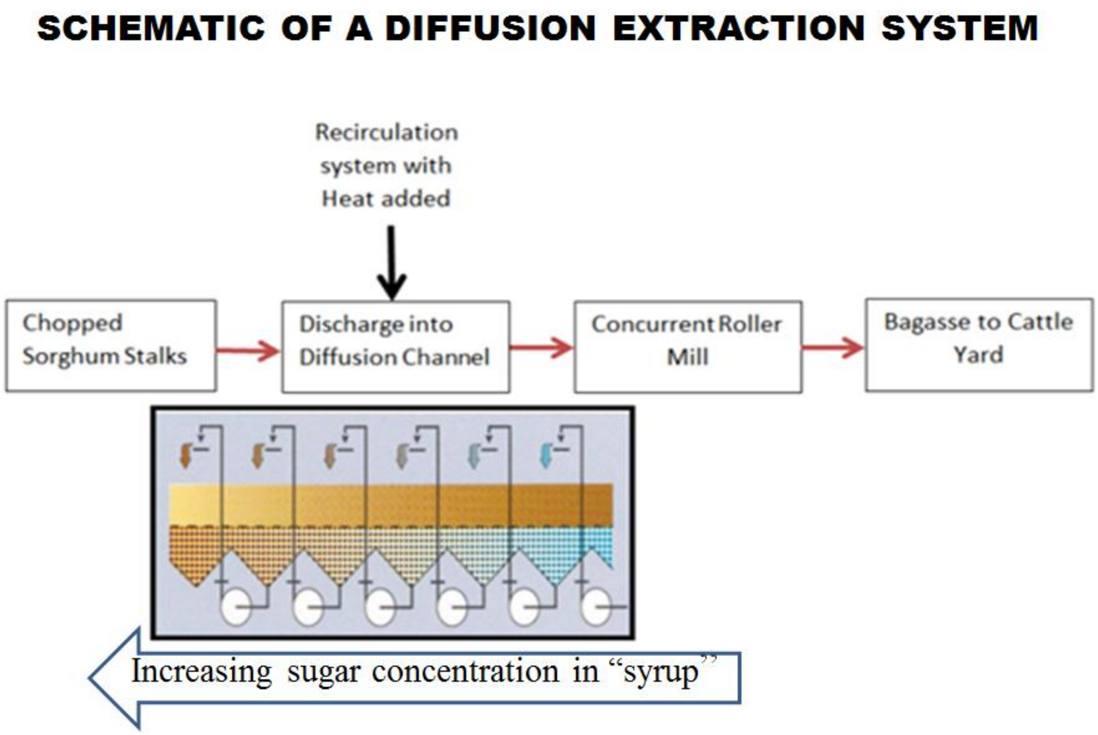

Figure 1. Diffusion Extraction Schematic

In making sorghum a competitive crop for biofuel production, the overall cost of the system must be considered. The goal is to sell the sorghum juice to an ethanol processing plant. Any increase in initial costs, reduces the profit of the overall process. Similarly, the power input is the second design constraint. The goal of the diffusion extraction and reverse osmosis systems is to create a new viable source of biomass for biofuel production in Arizona. Any increase in the initial power output, reduces the net power output of sweet sorghum as a biofuel. The sorghum solution used in this project was obtained from diffusion extraction.

The main variables that needed to be accounted for in the design process of the sorghum solution coming off the diffusion extraction unit were the dissolved solids measured as a function of the turbidity of the solution and the initial brix of the incoming solution. The performance of the reverse osmosis process is affected by the type and amount of dissolved solids and starting solute concentration. These design variables were then handled separately in two stages. The filtration system lowered dissolved solids and turbidity, while the second reverse osmosis stage increased brix concentration.

Pre-Filtration System

As mentioned above, the type and amount of dissolved solids also affects the efficiency of reverse osmosis membranes. The dissolved solids in the solution can be measured in two ways, using the silt density index (SDI) or it can be approximated through turbidity measurements. First, the SDI measures the "fouling capacity" of water in a reverse osmosis system. More specifically, it measures the rate that a 0.45 micrometer filter will become clogged with under a pressure of 30 psi or the percent decrease in the flow rate of water through a filter per minute over measured time period. Turbidity, on the other hand, is the amount of the suspended solids in a fluid. Decreases in turbidity show a reduction in the amount of suspended solids. The turbidity of the sorghum solution must be significantly decreased prior to entry into the reverse osmosis membranes to prevent clogging of the expensive components.

Several methods of filtration were explored as potential options including sand filters, carbon filters, protein skimmers and bag filters.

In essence, sand filters are containers filled with variable amounts of gravel and sand, which contaminated water flows through. The sand limits the flow of larger particles and pathogens, allowing only fine particles and water to flow through to the output. Sand filters are often used in water pretreatment, as in this design. There are several types of sand filters including slow sand filters, rapid sand filters, pressure filters, and diatomaceous earth filters. Slow and rapid sand filters have lower input costs than the pressure filter and diatomaceous earth filters because the pressure filter requires a power input to obtain the pressure and the diatomaceous earth is more expensive than the readily available, inexpensive sand. In terms of the less expensive options, they both use gravity for water flow and are frequently used for water systems. The rapid sand filter has a more desirable flow rate than the slow sand filter and is both smaller and more compact when compared to the slow sand filter which requires a large land area for processing.

Carbon filters are often used in water filtration and have been used for the purification of sugar cane. They use activated carbon to remove impurities by chemical adsorption. Adsorption is when atoms, ions, and molecules adhere to a surface. Activated carbon has many small pores increasing the surface area and therefore chemical reactivity and adsorption by providing increased sites for contaminants to adhere to. In addition to porosity, the flow rate affects the filtration ability of the activated carbon filters. When water moves slowly thorough a membrane there is increased reaction between the carbon and the contaminants and therefore a cleaner output. Considering this, the team must optimize the amount of activated carbon used to achieve both the desired flow rate of 12 gallons per minute and have maximum adsorption through multiple layers of carbon.

Protein skimmers are often used in municipal water treatment and aquariums. They are used to remove organic matter, such as proteins and amino acids. Protein skimmers work by creating small bubbles in the water and creating a large air to water interface. Due to the polarity of the molecules, they are either repelled or attracted by the air/water interface. Thus, hydrophobic molecules interact with the bubbles and rise to the surface where they are removed from the solution. In typical protein systems, not only proteins are removed in this process but fats, fatty acids, carbohydrates, metals, and trace elements can also be removed. The team decided to test protein skimming as a way to decrease turbidity without affecting the brix and to remove organic molecules. Testing proved that the method does reduce turbidity without affecting brix thus the team considered it as an option to the final design.

Bag filters (or fabric filters) are semi porous fabrics which allow only certain particles to flow through. Unlike the gravity powered filtration systems, bag filters are required to be pressurized. When the solution is pressurized, the suspended solids are then trapped in the filter. The fabric (or in this case, bag filter) can be rated anywhere from 100 micron to 1 micron depending on how fine the filtration process needs to be. One variable to be aware of when using bag filters is the reduction in flow rate with high rated filters. At the same operating pressure, the bag filter output will be less with a 1 micron filter than a 100 micron filter, as the pump has to work much harder to push the solution through the fabric. After consulting with an aquaculture specialist, we were assured that this method would not affect the brix, while significantly reducing the turbidity. Based off of this recommendation and our analysis the team decided to use a bag filter in the final design of the system. The 1 micron filter effectively reduced the turbidity, while pressurizing the filter allowed it to be placed in-line, resulting in smoother operation.

Reverse Osmosis Membranes

Reverse osmosis membranes typically have a dense polymer matrix layer which is woven to ensure the desired separation. In the case of sorghum juice, only water should flow out of the membrane to the permeate storage tank, while the concentrated sugar solution should be rejected to the alternate storage tank. These matrices have different configurations including spiral membranes, tubular membranes, and hollow fiber membranes. Spiral membranes, shown below, are said to be robust, energy efficient, and economical with a high packing area compared to other configurations. These membranes are most commonly used in water treatment including desalination and reclamation. Tubular membranes on the other hand are particularly useful in the case of high suspended solids and can concentrate the input solution without significant clogging. Tubular membranes are often used for waste water. Finally, hollow fiber membranes are well suited for large input volumes.

This information suggests that spiral membranes would be best for the reverse osmosis system, as they are energy efficient and have a high surface area to prevent clogging by the sorghum solution. However, the team should consider changing to tubular hollow fiber membranes when scaling up to a quarter million gallons per hour as these membranes are better suited for high volume flows. If the design calls for multiple membranes in series, then the team can potentially test how these different membranes work together (i.e. a spiral membrane followed by hollow fiber membrane).

When considering the overall efficiency of the membranes, the operating pressure is a crucial variable. The pressure required for reverse osmosis depends on both the original and desired concentrations of a solution. Increased pressure is needed when encouraging water to work against steeper concentration gradients. The pressure is applied to the solution side to “push” the water across the membrane and either capture the pure water or remove the water from the solution thus increasing the solute concentration. The typical pressure required for fresh water is between 30 and 250 psi. Reverse osmosis membranes in the maple syrup industry typically range from 100 to 220 psi. Note that all membranes are rated by both operating pressure and flow rate.

Methods and Design Approach

As a continuation of the University's sweet sorghum diffusion extractor project, the goal for this project is to create a reverse osmosis system that will take the juice from the diffusion extractor and removing water from it, both increasing the brix of the final sweet sorghum solution to be sent to the ethanol production plant and providing pure water to be recycled back to the diffusion extractor to reduce the overall water use of the sorghum project.

After determining the problem statement and main constraints the team began research, the essence of which can be found in the background, and began with initial ideas and an introductory process diagram. At the beginning the team thought to only include a sand filter, a typical five micron filter used as a prefilter in home reverse osmosis systems, and then the reverse osmosis membrane.

Filtration Component

Filtration methods researched included carbon filters, sand filters, protein skimmers and bag filters. First, the team experimented to test the efficacy of a protein skimmer and carbon filters. To perform these experiments the team created an artificial sugar solution to mimic the sorghum solution for experimenting. The team created two solutions, one of 5% brix and one of 10% brix. The 5% brix solution contained, one cup of honey, two cups of sugar, four teaspoons of vanilla extract, 15 drops of red food dye, 15 drops of yellow food dye, 5 drops of green food dye, 5 drops of blue food dye, 2 cups of soil, and 3.5 gallons of water. To increase the brix to 10%, the team added a second cup of honey and two more cups of sugar.

Then to determine the flow behavior with different pipe diameters and amounts of sand and gravel the team set up two experiments. The first experiment involved measuring the time it took for the water level in a pipe to decrease across various distances with varying sand amounts. In the second experiment, the team measured the time it took for the water level in a pipe to decrease across various distances with varying pipe diameters. Next, the team needed to determine the effect that varying levels of sand on the turbidity and brix of the solution in order to optimize the final sand filter dimensions. The team thus measured the turbidity and brix of a control solution at various time intervals.

Additionally, other types of water filters were researched. The team tested the change in brix of the sorghum solution after being run through a new Brita filter (filled with activated carbon and ion exchange resin), a new generic filter (activated carbon, silver, and a mesh layer), and an old generic filter. The results showed that new older filters were best at reducing turbidity (with an average of 81.3% turbidity reduction) without significantly affecting the brix (average reduction of 10.7%), but that they had the slowest flow rate. Comparatively, the new Brita filter decreased the turbidity by an average of 54.5% and had the fastest flow rate but decreased the brix by 25%. The new generic filter reduced turbidity by an average of 51.6%, was slower than the new Brita filter, and decreased the brix an average of 37.1%.

The team then experimented with the protein skimmer for six hours. The protein skimmer immediately began to bubble suspended solids out of the sugar solution, however, it took over an hour for the turbidity to measurably decrease. In the six hour experiment, the turbidity decreased by 0.9%, 6.6%, 30.3%, 6.0%, 9.6% and 5.48% each hour respectively. In total, over six hours, the turbidity decreased by 59.0%. Over the entire experiment the brix remained 5.3%. Thus the protein skimmer shows promise as a pre-filter, though the team would like to perform repeat experiments and test the reduction in microbial content with use of the filter.

After performing experiments the team created a second design matrix below to demonstrate the strengths and weaknesses of each pre-filtration method.

Filtering Method	Relative Brix Decrease	Turbidity Decrease	Energy Consumption	Required Time of Operation	Relative Cost
Carbon Filter	Medium	High	None	Low	Low
Sand Filter	Medium	Medium	None	Medium	Low
Protein Skimmer	None	Medium	Medium	High	High
1 Micron Bag Filter	None	High	Medium	Low	Medium

Table 1. Filtration Methods Comparison

Carbon filtration is excellent at reducing turbidity but has a variable effect on brix. Older membranes have little effect on the brix and a large effect on the overall turbidity, while newer filters have less effect on turbidity and a greater effect on brix. This suggests that the filters saturate with sugar at a point. To ensure maximum turbidity reduction and as little decrease in brix as possible, the system could reuse filters throughout multiple harvests. In addition to effectively reducing turbidity, carbon filtration does not require energy filtration and has a low overall cost; activated carbon costs as little as $16 dollars a kilogram.

Sand filtration is extremely effective at removing large particles from the sorghum solution, such as parts of shredded stocks, dirt, and rocks. On the other hand, the effect the sand filter has on turbidity depends on the cap at the bottom of the filter. If the pore filter cover is placed over the sand filter, some sand may by-pass through the sand filter and into the solution, increasing the turbidity. Assuming sand cannot pass through the filter cover however, then the process has a moderate effect decreasing the turbidity. Advantageously, sand filters are easy to create, have extremely low costs, and require no energy, making them an ideal first pre-filter.

Protein skimmers effectively decrease turbidity over time and particularly work to remove organic matter and the amount of microbes in the solution unlike the other pre-filters. The cons of the protein skimmer include long operation time required for significant reduction in turbidity and the need for a power source. While industry protein skimmers can cost thousands of dollars, homemade system can be inexpensive. The team plans on building an inexpensive system with a higher flow rate to hopefully reduce the overall processing time.

The team questioned whether they should use sand or diatomaceous earth, but ultimately decided on sand because the long time required for filtration lead to the need to increase the sediment surface area and thus the amount of sediment used. Sand is significantly cheaper and more available than diatomaceous earth thus making it the selected alternative. With time and further research, the team expanded the idea to first include a sand filter, followed by a carbon filter, followed by a protein skimmer, before a pump would feed the solution into the reverse osmosis membranes where the sorghum juice would be divided into the concentrate and permeate.

Finally, a one micron bag filter was tested for its effect on decreasing turbidity of the sorghum solution. It performed the best overall with a decrease of turbidity from an incoming turbidity of 770 NTU to 170 NTU leaving the bag filter, a 78% reduction in turbidity. This method of filtration was chosen as the final filtration system because of its ease of installation into our reverse osmosis process as well as the quick ability to clean and maintain the bag filter during operation. The only drawback to this method is a modest power input requirement due to a pump necessary to force the water through the bag filter.

Sweet Sorghum Solution Dehydration Component

Additionally, in order to ensure reverse osmosis was the best way of extracting water and increasing brix of the sorghum solution, the team explored other ways to achieve these goals. The team explored two competing ideas to reverse osmosis: evaporation and freezing. These methods are briefly explained in the introduction. The team used the information they collected and created a design matrix below to make the final decision.

Dehydration Method	Maintenance and Reliability	Energy Consumption	Required Time of Operation	Relative Cost
Evaporation	Low	High	Medium	High
Freezing	High	High	High	High
Reverse Osmosis	Medium	Medium	Low	Low

Table 2. Comparison of Dehydration Methods

Evaporation and freezing are cost prohibitive to becoming viable ways to remove water due to the intense energy demands required with either process. Additionally, both require significant time of operation making them hard to scale up. Diffusion extraction requires almost no energy input, however, it has a high required time of operation. Moreover, the addition of salt to the chamber across from the sugar solution which the water flows into, makes water unusable in the diffusion extractor and thus increases the overall cost and input requirements of sorghum processing. Hence, reverse osmosis, is the best method available to achieve the client goals. It has a relatively low cost and requires little overall energy input. Further, the system does not require significant maintenance and is a reliable method. The team therefore concluded that reverse osmosis was indeed the method to pursue.

Using freezing as a method of increasing brix, would entail taking the entire sorghum solution obtained from diffusion extraction and freezing it. The sorghum solution would then be placed in a freezer and after a certain time the less concentrated water would begin to freeze. After partial melting, the remaining frozen cube would be collected and stored for later use. The sorghum juice that did not freeze at the same time would be at a higher brix than before freezing. The process could be repeated until the desired brix concentration is reached. The removed ice cubes would then be completely melted in a different chamber, and run back through the diffusion extractor to reduce the required water input.

The evaporator would work by using a heat source, such as natural gas, to increase the temperature of the sorghum solution past boiling. The pure water would boil out of the solution first and be collected, leaving only the higher concentration sugar solution left. The collected boiled off water would then be recycled into the diffusion extraction system. Although evaporation and freezing do increase the brix of the final solution, both require significant power inputs; this reduces the overall viability of sweet sorghum as a source of biomass crop. Additionally, heating and freezing the sorghum juice could have adverse effects on the sugar structure and quality. One process which does not require a high energy input is passive diffusion or standard osmosis.

The team has experimented with the reverse osmosis membranes, and has found that they increase the brix while reducing the turbidity. The team improved upon unsuccessful models by using a more powerful pump capable of pressures above 100 psi and membranes rated to deal with that pressure. Further, the team has been in contact with a maple syrup producer using a similar reverse osmosis system for suggestions.

Results

Technical Description of Reverse Osmosis System

The system will begin with two screen filters leading into a holding container, followed by a booster pump to push the solution through the in-line one micron bag filter. Once pre-filtration is complete, the sorghum solution will pass through a high pressure pump and through four reverse osmosis membranes in series. A needle valve must be included on the concentrate line in order to establish back pressure in the system. Pressure gauges are used to monitor operating pressure throughout the system.

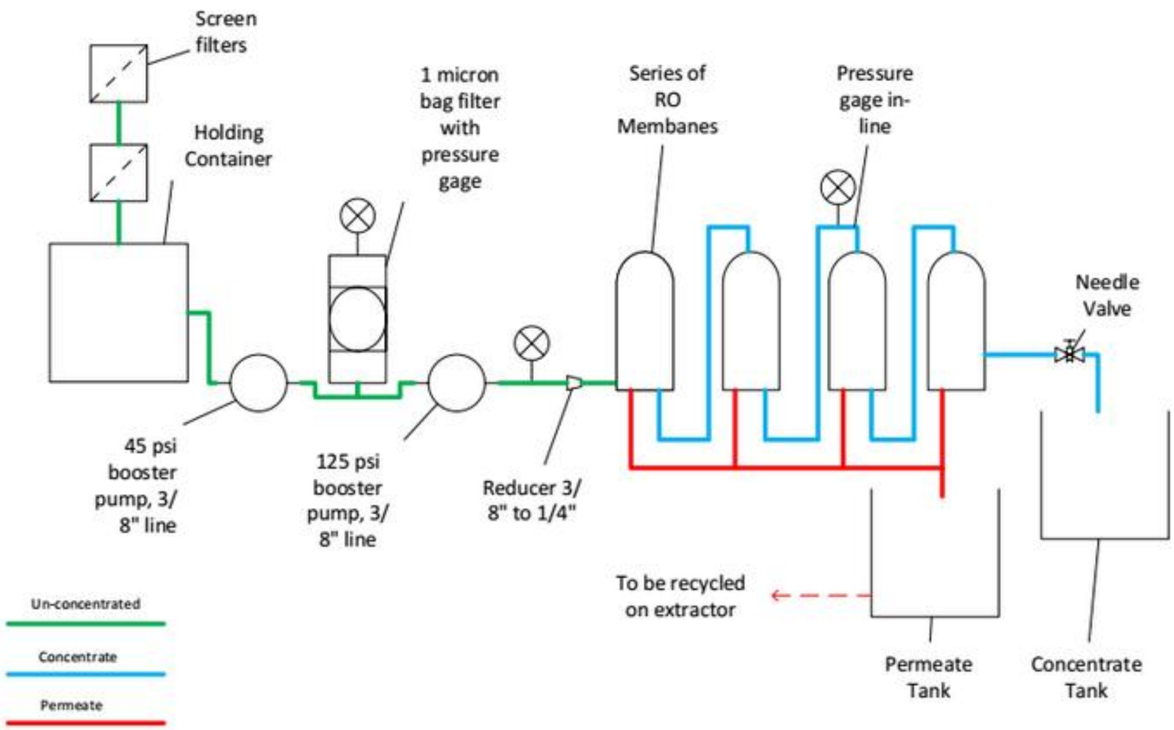

Figure 2. Reverse Osmosis Process Diagram

Specifications

- Initial storage tank
  - The initial storage tank is where a portion of the sorghum from the diffusion extraction process is stored until processing by the reverse osmosis system.

  Pump
  - The pump provides the pressure to the reverse osmosis system.

  Bag Filter
  - The bag filter comprises the filtration step and is responsible for removing suspended particles within the solution. This lowers the silt density index and increases the reverse osmosis membrane life span.

- Reverse osmosis membranes
    - The reverse osmosis membranes are responsible for producing clean, filtered water. As a byproduct, the membranes reject the sugar in the sorghum solution effectively increasing brix by extracting pure water.
- Permeate tank
    - The permeate tank collects the clean, filtered liquid that passes through the reverse osmosis membranes.
- Concentrate tank
    - Contrary to usual reverse osmosis use which discards the concentrate, for this project, the concentrate tank holds the concentrated sugar solution after processing.

Construction Materials

Off the shelf components were utilized to simplify construction and scale up. These include:

- Initial storage tank
    - Standard five gallon plastic bucket
- Pump
    - Aquatec 8800 Booster Pump
- Bag Filter
    - Pentek 1 micron bag filter
    - Pentek Bag Filtration System
- Reverse Osmosis
    - KX Industries PWFROMH Reverse Osmosis Membrane Housing
    - Filmtec 100 GPD Residential RO Membrane
- Permeate tank
    - Standard five gallon plastic bucket
- Concentrate tank
    - Standard five gallon plastic bucket

Operation

Operation has been simplified to ensure a relatively maintenance free and continuous life for the system. Day to day operations only require an occasional cleaning of the bag filter when the bag filter pressure gauge decreases into the labeled red area. To accomplish this, the bag filter must be removed from its housing and cleaned by backwashing with fresh water from a hose removing small particles that have attached to the cloth filter. If the water pressure across the final two membranes is not between 105 and 110 psi, the needle valve at the end of the process may be adjusted to attain this pressure across the final two membranes. If the permeate or fresh water flow rate appears to significantly decrease the reverse osmosis membranes need to be replaced with new membranes purchased from the manufacturer.

Testing and Calibration

Testing of the prototype yielded that the initial pressure at the first membrane needs to be at least 150 psi. The pressure entering the third membrane is recommended at between 105 psi and 110 psi. The testing points out the design limitations in our system that with the membranes and pressure this system operates at no brix higher than 9% brix can be obtained. This is a result of the increased osmotic pressure at 9% brix that can only be overcome at higher pressures with membranes designed to withstand high process pressures. Another positive outcome of this testing shows that all of our freshwater extracted had no sugar, allowing it to be easily reintroduced into the sorghum diffusion unit for lower water usage.

Trial	Starting Brix	Concentrate Brix	Permeate Brix	Operating PSI	Valve Ratio
1	3.5	5.0	0	105	1 : 2
2	3.5	5.0	0	115	1 : 2
3	3.5	5.4	0	135	1 : 2
4	6.8	8.0	0	150	1 : 3
5	6.8	8.5	0	162	1 : 2.5
6	6.8	9.0	0	162	1 : 1

Table 3. Experimental conditions and results of testing

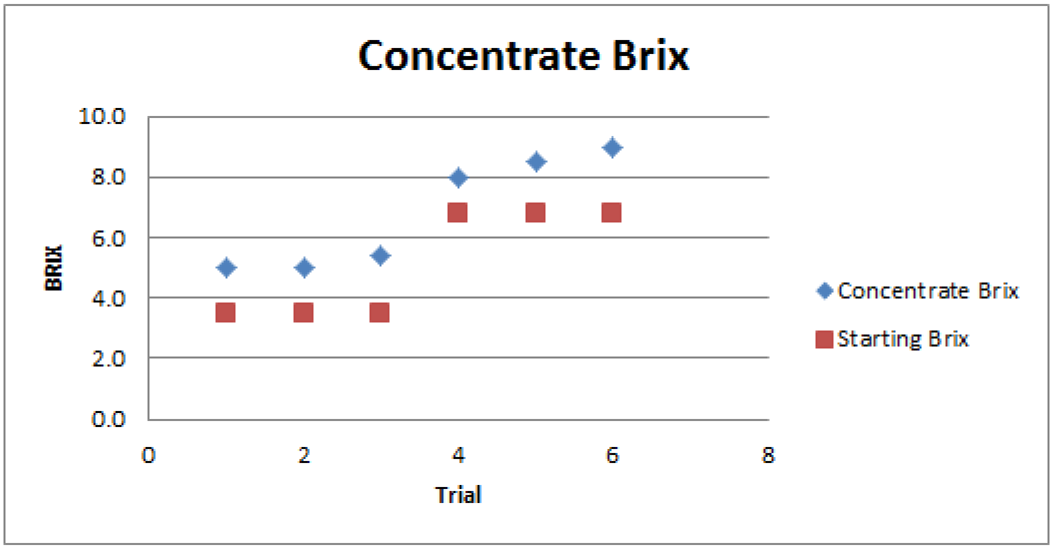

Figure 3. Initial testing of various process conditions with starting and final brix concentrations

Testing showed that four membranes in series were all contributing in the removal of pure water from the sorghum solution, thereby increasing brix.

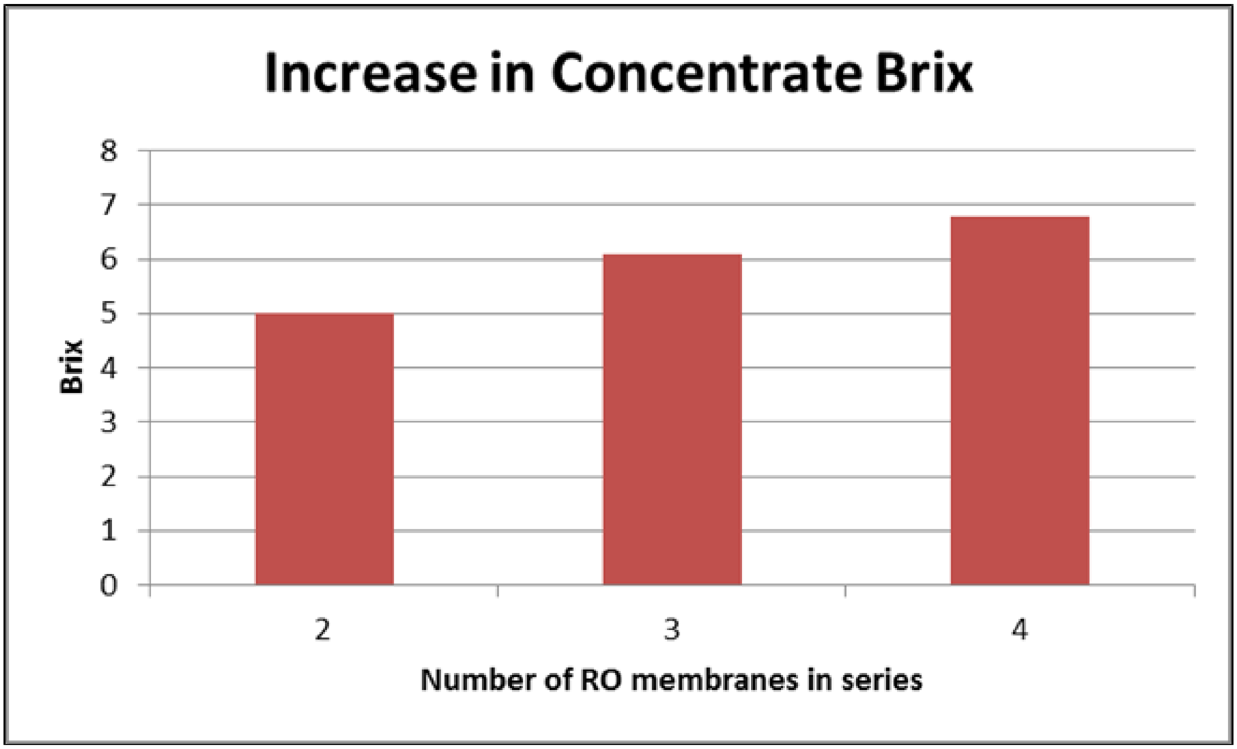

Figure 4. Ability of membranes in series to remove water from sorghum solution

External Constraints

Economic constraints: One of the main team goals is to produce the reverse osmosis system for less than $1,500 dollars. This means that the team should optimize performance while considering the final cost of all materials and that recycled and donated materials should be used where available. The system should also operate at a low cost, therefore the team should work to create a low power and energy input final design.

Environmental constraints: Arizona is a desert and the sweet sorghum will be harvested during the late summer and early fall months where the temperatures peak. This places several environmental constraints on the system in terms of the desire to increase the reuse of as much water as possible, and ensuring at all materials are resistant to UV radiation and high temperatures.

Sustainability: If pure water output from the reverse osmosis system can be maximized and the heating, pumping, and flow optimized, the project should be relatively sustainable. The device should last several years.

Manufacturability: The goal of the project is for the system to be easily produced by the ABE department in the ABE shop. The students should participate in the construction. While this reduces the manufacturing costs, it also provides constraints on the construction methods. All materials used come from off the shelf suppliers and are easy to procure.

Ethical constraints: In the diffusion extraction system, without the reverse osmosis attachment, the use of this large amount of water in a desert and without significant ethanol production could have been considered unethical by environmental advocates. With the addition of the reverse osmosis system and the reduction in the amount of water used, the ethical and environmental concern is mitigated.

Other ethical considerations include the concern that the use of biomass as a source of fuel can lead to deforestation, and that the use of sorghum for ethanol can compete with animal feed and thus, increase food prices.

Social constraints: At this point it is not anticipated that the device will be replicated or sold. Only the one diffusion extractor unit will be created with one reverse osmosis system and both will be supplied to the University of Arizona. Only department officials will interact with the product, reducing the social effects. Successful implementation of the technology however could lead to replication by other university and outside departments leading to the increased popularity and use of the technology and increases in funding and availability of using biomass as a of source energy.

Political constraints: The control of the fossil fuel industry and current political policy may lead to a reduction in wide scale alternate energy research, but should not have significant effect on the team’s small diffusion extraction system and reverse osmosis systems.

Conclusions

How well does your product actually work?

The system successfully reduces the turbidity of the sweet sorghum solution while increasing the brix. The team consistently reaches the same end product of 8.5-9% brix without any malfunctions or hiccups from the system. The system successfully meets the flow requirement for concentrate, and consistently removing around 50% of the water. The percentage of total water removed is dependent upon incoming brix concentration. Of further importance, in nearly all trials the brix concentration of the permeate is 0%, indicating that the system effectively removes all of the sugar from the sorghum solution that moves across the reverse osmosis membrane. Lastly, the system is correctly designed for the optimum operating pressures; the bag filter does not operate over its maximum psi, and the reverse osmosis membranes are held at a steady pressure (due to the booster pump and needle valve) to separate the clean water from the concentrate.

Does your product solve the problem that your company wanted to be solved?

While the product does not meet the benchmark of 22% brix, the system does provide proof of concept that reverse osmosis is a viable method for concentrating the sugars found in sweet sorghum. As the data supports, the largest brix the team was able to reach was between 8.5% and 9% given an input of 5-7% brix. The system approaches an upper limit of 9% brix and stabilizes.

With regard to the turbidity, the system is able to reduce the turbidity to 170 NTU. This is a reduction of 600 NTU or 78%, as the initial sorghum solution averages approximately 770 NTU. Again, unfortunately, this did not meet the design goal of 1-3 NTU's in the final concentrate solution. However, the decreased turbidity of the sorghum solution entering the membranes allows the membranes lifespan to be increased over unfiltered sorghum juice.

Summing up the two major design goals: the system works well to decrease the turbidity to 170 NTU and increase the brix to 8.5%

What are the weaknesses and limitations of your product?

In comparing the design to how the system actually operates, the team has noticed a few limitations. The biggest limitation is with the reverse osmosis membranes. These membranes are only rated for a certain psi and flow rate. In order to increase the brix of the concentrate, it is necessary to upgrade the reverse osmosis membranes to a much higher psi. Otherwise, at a certain point the membranes cannot pull any more water from the sorghum solution due to the osmotic pressure.

Another limitation to the system was the sorghum juice itself. Ideally, we would have liked to run a majority of our experiments with diffusion extracted sorghum juice, as this is the final operating fluid of the system. However, there was only one harvest this year, and our senior design team was only allocated an allotment of 25 gallons. To put this in perspective, an average day of testing and experimentation uses at least 5 gallons of juice. This meant that the team used sugar water to mimic the brix concentration of sweet sorghum. While it was a good substitute, we found that the system behaved notably different when running with sorghum juice compared to sugar water.

Limitations to the design also arose because the team tried to quantify the suspended solids using turbidity measurements. One of the stipulated team design goals was to reduce the turbidity of the sorghum juice. For sweet sorghum, this is not necessarily an accurate method of measuring the SDI which is the measurement that is used to determine how quickly reverse osmosis membranes deteriorate. This is because sweet sorghum has a natural dark color, and this color dyes the water in the diffusion extraction process. In effect, the bag filter in our system could be very effective in removing the suspended solids, but this success is unable to be measured with a turbidity meter as the dark color skews the reading.

What parts of the original problem were more difficult than anticipated?

The initial filtration testing also provided the team with quite a challenge, especially with the sand filtration. The first results stunned the team: sand filtration showed an increase in turbidity from the input to the output. This was because the team did not take into account that the sand must be thoroughly cleaned prior to using it in a filter. Thankfully, after cleaning the sand, turbidity did reduce; but, the entire filtration process (from input to output) required a significant amount of time. Furthermore, if there was not constant pressure, then the process would slow down even further as juice height above the sand decreased. This meant a team member had to monitor the sorghum input and the process was more difficult to be automated. When the head/ input of sorghum juice was not properly maintained (i.e. variable input flow rate), then the system could not be treated as a control volume. This created an issue when trying to measure the outflow of the sand filter, due to the rags, sand and gravel that were stuffed in the end of the filter.

Another problem the group faced stemmed from the project requirement of turbidity; near 1 NTU is recommended to increase membrane longevity. This was an extremely hard target to reach, especially considering that the raw solution comes off the diffusion extractor around 770 NTU. For reference, most drinking water companies have a standard of near .1 NTU (*Drinking water contaminants*.). Most of our filtration techniques were able to reduce the turbidity, with the bag filter being the most successful reducing the turbidity to 170 NTU's. Unfortunately, none of these experiments nor implemented filters provided results near our goal. To further complicate the issue, sometimes the reduction of turbidity was at the expense of losing brix concentration, as was the case with the commercial carbon filters.

The inclusion of in-line sensors was much more difficult than expected. At first, the team had budgeted and designed for the inclusion of multiple brix and turbidity sensors, as well as UV light sensors. Placing these sensors was deemed impractical in our pilot scale system as tubes could be easily detached to take measurements and the investment of an in-line sensor system would not be feasible. However, in a commercial system in-line sensors would be needed for quality control and assurance of the sorghum juice production. This same principle can be seen as we removed the UV light from the process since no sorghum juice was being sent to fermentation and could potentially create production problems within the ethanol facility.

What hopes for your solution didn't turn out?

The team had a few hopes which never came to fruition. The first was the inclusion of the solenoid valve before the reverse osmosis series. We were confident the system would be successful; so much so that we designed the system with a bypass solenoid valve to lower the brix in the concentrate tank. In the end, the solenoid valve was irrelevant because the membranes were only capable of reaching 8.5-9% brix.

Another hope and design component that never worked out with the project was the implementation of a gravity powered media filter. The team spent quite a bit of time experimenting with both sand filters and carbon filters, but each had too many problems. From a pre-filter standpoint, the sand filter did a decent job reducing the turbidity while not affecting the brix of the sorghum solution. The problem with the sand filter stemmed from the need for a constant head of juice and the abysmally slow flow rates. The carbon filter was much quicker from a flow rate perspective; however, the activated carbon seemed to also cling on to the sugar, as the brix would significantly decrease after passing through.

Another disappointment with the initial design stemmed from the protein skimmer. After significant research on protein skimmers and dissolved air flotation (DAF) systems, the team decided to invest in a commercial protein skimmer (for an aquarium) to test with the sorghum solution. Research and testimonials supported the hypothesis that the skimmer would dramatically decrease the turbidity of the sorghum solution. In the end, it seemed like a costly investment, as the skimmer fell short of expectations. It was difficult to adjust the airflow into the chamber, and changing the diameter of air bubbles was a non-existent option (this variable is important in increasing a protein skimmers effectiveness).

Recommendations

What recommendations do you have for your company?

The first recommendation we have for Sweet Ethanol is to not give up on this idea and project. While the team was unable to meet the main goal of reaching 22% brix, this system provides proof of concept that reverse osmosis is a viable method for concentrating sweet sorghum. Furthermore, the cost savings by using reverse osmosis make it economically feasible. As noted in previous sections of this paper, the system is limited by the flow rate and operating pressure of the reverse osmosis membranes. Levels closer to economic viability are entirely possible by designing the system to use, for example, 700 gpd membranes at an operating psi of 500-600 psi. If the company decides to pursue using higher rated pumps and membranes, the team suggests performing a more thorough economic analysis. These pumps and membranes will make for a high initial cost, and the company will want to ensure that this cost can be recovered through using reverse osmosis.

Second, the team suggests changing the turbidity measurement to total suspended solids, as well as including the silt density index. As discussed in the limitations section, suspended solids would give a better measurement of how well the bag filter trapped colloidal particles. The inclusion of the silt density index would help determine maintenance routines for backwashing and replacing the membranes. This could extend the life of the membranes, translating into greater economic savings.

Third, the team recommends a thorough case study of how viable ethanol will be in the next 10 to 20 years. While this reverse osmosis project could potentially produce an alternative system to compete in the ethanol market, the project will be useless if ethanol prices plummet, or worse, ethanol becomes non-existent in the alternative energy market. A small investment now could potentially save the company a lot of money if ethanol is irrelevant in the future.

Should they begin immediate production of the prototype?

At this time, the team does not suggest immediately reproducing this prototype. The current system simply does not economically compete with other types of ethanol production. Until there is a bench scale model which can consistently increase sugar concentration to 15%, we recommend that Sweet Ethanol remain in the prototyping phase.

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