Executive Summary

We explored the concept of adapting experimental thermal-storage cooker technology to heat a still for the distillation of fermented whey. A Fresnel lens was used to heat and melt lithium nitrate. The heated lithium nitrate was used to boil liquid and power the distillation process. Experimentation was done on a small scale to obtain system component efficiencies. These efficiencies were determined to be sub-optimal and information from experimentation was taken into account to design a 6 L prototype system. The initial system design was reviewed and adjusted. The prototype was then constructed. The constructed prototype's energy transfer properties were tested and found to inadequate for the systems intended purpose. The system was reviewed and design recommendation were made. Further research and experimentation was determined to be necessary for the development of a Fresnel lens powered distillation system. Further research concerning the use of traditional photovoltaic solar power is also recommend to examine the conversion of fermented whey to usable ethanol.

Introduction

Whey is a co-product of cheese production which is produced at approximately a 9 to 1 whey to cheese ratio. Whey can be broadly categorized into two categories into sweet and acid whey. Sweet whey is produced from rennet set cheeses such as cheddar, mozzarella and Gouda. Acid whey is produced from acid set cheeses such as cottage cheese and Greek yogurt. Sweet whey can be processed into many value added products such as protein powders and emulsifiers. Acid whey cannot be processed in this manner due to compositional differences such pH and protein interactions. The increased production of Greek yogurt has left processors in search of an economically advantageous and environmentally friendly means of processing acid whey. One solution is the fermentation of whey. The fermentation process reduces the biochemical oxygen demand (BOD) of whey due to the conversion of lactose to CO_2 and ethanol[1]. The ethanol in the fermented whey can then be distilled to use as biofuel or to produce a potable spirit. One of the challenges related to the distillation of fermented whey is the low ethanol content, typically 2.5 % alcohol by volume (ABV). A commercial grain distillery's feed stock will range from 8% ABV to upwards of 20% ABV[2,3]. Water has greater heat capacity and heat of vaporization than ethanol due its strong hydrogen bonds. While acid whey may be obtained for little to no charge the increased energy requirements for a distillation may make it a less economically advantageous than producing ethanol from a fermented corn slurry. One possible solution to this issue is the use of solar energy to provide the energy necessary to distill fermented whey. The conversion of an environmentally challenging by-product into a biofuel or potable spirit has many potentially positive economic impacts. This project aimed to determine if the technology used in a thermal-storage solar cooker conceived by David Wilson [4], an MIT professor could be adapted to distill fermented whey. This technology uses a Fresnel lens to collect light/energy hitting the back lens and concentrates the light/energy to a half an inch beam [5]. Depending upon size of the lens temperature at this half inch spot can be greater than 1000°C. This concentrated heat is then used to melt lithium nitrate which acts as an energy storage medium for cooking for several hours. We sought to determine if this technology was a viable means of powering a still which in turn could be used to distill fermented whey.

During the course of the project we collaborated with the chemical engineering department which allowed us to look at this problem from interdisciplinary approach. This collaboration proved to be useful because it increased the funds available for the project which was found to necessary and also provided engineering expertise. The initial task was material acquisition. The two major hurdles related to the acquisition of materials was determining the size of Fresnel lens needed/desired and how to obtain lithium nitrate. The increase in funding allowed for a large Fresnel lens (78.7 x 101.6 cm) to be purchased. This was chosen because surface area exposed to sun could be adjusted by covering portions of lens with fabric. This allowed us to decrease the intensity of the heat at the focal point if deemed necessary. Initial estimates for lithium nitrate were approximately $300. This was based on ranges provided by the suppliers. After contacting the suppliers we found that low end of the range was for tonnage per month. Domestic suppliers cost greatly exceeded our budget for the 25 kg of lithium nitrate. We were able to obtain the lithium nitrate from a Chinese supplier for approximately $1000. This exceeded the original budget but the additional funding allowed the project to continue without being hampered.

Experiments and Analysis

During the procurement period experiments were conducted to gain an understanding of the energy requirements for conducting a distillation and the amount of lithium nitrate needed to perform a similar distillation. A 6 L copper still fitted with thermometer was loaded with 7.4% ABV solution and was placed upon a VWR 230 V magnetic Hotplate Stirrer which was hooked a Kill-a-Watt meter. A distillation was conducted until 85% of the ethanol was recovered. This was determined using an Anton Paar Density Meter DMA 35. The Kill-a-Watt meter measured the energy usage in KWh and allowed us to determine the approximate energy requirements for a distillation. This information allowed us to approximate the amount of lithium nitrate needed for prototype development (Appendix A). Research about the properties of lithium nitrate and optical and energy transfer principles related to the Fresnel lens and distillation process was also carried out.

Once the Fresnel lens arrived a mounting system was built which allowed the lens to be easily adjusted for optimal focal point concentration. The Fresnel lens efficiency was approximated by heating an aluminum block and measuring the surface temperature. Two thermocouples were placed each side of the block with the lens's focal point was concentrated one of the thermocouples for 20 minutes. The temperature of the block increased from 35°C to 300°C (Appendix B). Energy consumption and generation was calculated using mass, heat capacity and change in temperature. The efficiency was then calculated by dividing by the energy supplied by the lens. The efficiency was between 10-30%.

Once the lithium nitrate was received, experiments were conduct to evaluate the use of lithium nitrate as a heating source. Three experiments were performed to estimate the heat transfer efficiency. Each experiment involved the heating 155-280 g of lithium nitrate to 350-400°C. Thermocouples were used to measure to temperatures of both the water and lithium nitrate. Once heated, the vessel containing heated lithium nitrate was placed into insulated container with a lid of glass or copper placed upon it. For the first two experiments an Erlenmeyer flask containing 25 ml of water was then placed upon the lid. The heat transfer efficiency was calculated and found to be between 2.1%-3.6%. To increase efficiency a water holding vessel with a wider base to increase surface area contact and insulation to decrease heat loss was used (Appendix A). This increased the heat transfer efficiency to 20%. This illustrates the necessity to insulate the vessel containing the lithium nitrate and vessel containing the feedstock. The generated and consumed power to bring water to 100°C was calculated using the mass, specific heat and temperature change. The efficiency was determined by dividing power consumed by the water and by the power supplied by the lithium nitrate. The average efficiency was determined to be 13%.

Two experiments were conducted to test the Fresnel lens ability to melt Lithium nitrate. A coated aluminum baking dish was filled with 280 g of lithium nitrate. It was placed in paved parking lot and the Fresnel lens' focal point was fixed upon the lithium nitrate in the dish. The experiment was conducted upon a partly cloudy day for an hour. The lithium nitrate did not melt completely. A second experiment was conducted on a clear day, using an insulated vessel to hold the lithium nitrate. The lithium nitrate was heated for 75 minutes and achieved a temperature of approximately 465°C (Appendix C). The vessel was covered with a copper lid and an insulated petri dish with 25 ml of water was placed on the copper and heated for 20 minutes to approximate the efficiency of the heat transfer. Unfortunately, due to a technical error with the Vernier LabQuest computer interface most of the data was not recorded.

Using the experimental data, a theoretical model was generated at several different efficiencies were generated using MATLAB. At the experimental efficiency we found that the overall system operated at approximately 7% efficiency. At this efficiency it would take 55 hours to melt 25 kg of lithium nitrate. This is not a feasible due sunlight only being available for this amount time in Oregon or most habitable areas. If the overall systems efficiency was increased to approximately 30% it would be possible to melt 25 kg of lithium nitrate. To increase efficiency of the system additional insulation and the addition of wind screens may be added to reduce convective heat loss. To address this a prototype vessel was designed to heat a 6 L still. A stainless steel pot with a depth of 17.8 cm depth and 25.4 cm diameter was used to hold the lithium nitrate and stainless steel pot with 25.4 cm depth and 33.0 cm was used to hold the insulation. The insulation was fiber glass rated up to 1200°C and was packed around the pot holding the lithium nitrate. A lid for container was designed to transfer the lens focal point energy to the lithium nitrate. The lid was flat and circular with 9 rectangular fins extending to the bottom of the container. The vessel was designed and then evaluated by Dr. Skip Rochefort, a chemical engineering professor with over 30 years of experience. The lid was then fabricated by Greyson Termini. Unfortunately, the welding process warped the lid so it did not lay flush on the vessel. The effectiveness of the lid design was tested. This tested the lids ability to transfer energy to the pot's contents. The insulated pot was filled with water and lid was placed on top of the top. The focal point of the Fresnel lens was centered upon the lid. The maximum water temperature achieved was 40°C. Two properties were examined to explain the reason for the water not exceeding 40°C. The convective heat transfer coefficient of water was determined and found to be 1823 W/m^2 K which is within the normal range for water 500—10000 W/m^2 °K [6]. The conductivity of the stainless steel lid was also examined. The stainless steel was found to have a conductivity of 15 W/m °K. The lid was initially designed to be copper which has a conductivity of 350 W/m °K.

Early experimentation indicated that copper reacted with the lithium nitrate and was deemed not suitable for the lid prototype because of this reaction.

Recommendations and Conclusions

The current system has been deemed to inadequate for the heating 25 kg of lithium nitrate to act as an energy source for the distillation of whey. Further research into the system optimization is necessary for this to become a reality. Several factors were identified to increase system viability. The use of a Fresnel lens which uses a sensor to track the sun and an automated system that adjust the angle lens to achieve the ideal angle for heating would increase the rate of solar energy accumulation. The amount of lithium nitrate used could be reduced and system adjusted for a smaller volume of liquid to be distilled. The use of possible alternatives to lithium nitrate could be explored. One possible alternative is the use of solid metal blocks of equal volume. Cast iron and copper could in principle be heated to 100°C below their melting point. These blocks could be insulated easier than lithium nitrate and can store more energy than lithium nitrate which has been heated to 500°C. These blocks would be much heavier than an equal volume of lithium nitrate. This would require extra design considerations as well as the handling of the heated blocks. The lid design would also have to be adjusted. Alternative materials with higher thermal conductivity and which are do not react with lithium nitrate should be considered for the lid construction. Further research and design experimentation would be necessary for the use of a Fresnel lens as a valid energy source for the distillation of fermented whey. Additional research into the use of traditional photovoltaic solar power to distill fermented whey should also be considered.

References

(1) Siso, M. I. G. The biotechnological utilization of cheese whey: A review. *Bioresour. Technol.* **1996**, *57* (1), 1–11.
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(3) Hughes, P.; Buxton, I. Crop-to-Cask Production of New Make Spirit. In *The Science and Commerce of Whisky*; The Royal Society of Chemistry: Cambridge, United Kingdoms, 2014; pp 90–134.
(4) Wilson, D. Development and Optimization of a Thermal Storage Solar Cooker. MIT 2013.
(5) Green Power Science -Large Spot Fresnel Lens https://www.greenpowerscience.com/55inchspotFRESNEL.php3 (accessed Nov 30, 2017).
(6) *Springer Handbook of Mechnical Engineering*; Groter, K.-H., Antonsson, E., Eds.; Springer Science and Business Media, 2009; Vol. 10.

Appendix A: Water Energy Consumption from Molten Salt

Figure A.1: Experimental setup for measuring energy consumed by water. A dish containing lithium nitrate is placed in the insulated, bottom vessel. A copper plate is then placed on top of the lithium nitrate dish. A partially-insulated petri dish with water is then placed on top of the copper lid to heat.

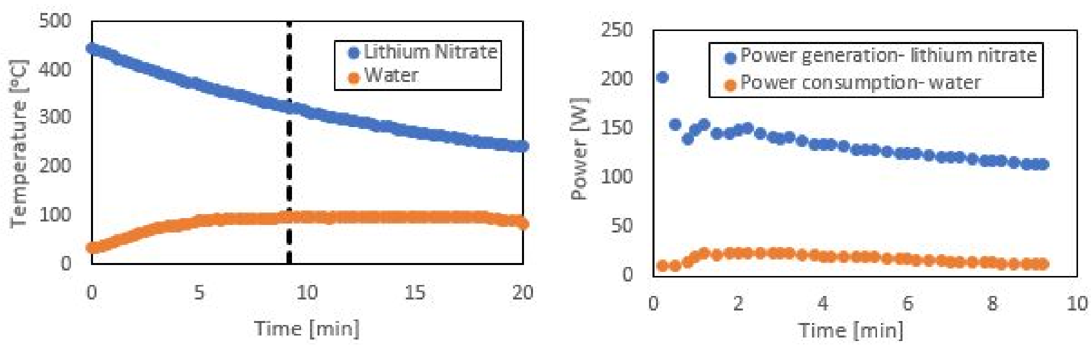

Figure A.2: Left -Temperature of lithium nitrate and water vs. time. This experiment was conducted after heating the salt with the Fresnel lens. The point at which the water boils is noted by the dashed line. Right - A plot of energy generated/consumed by lithium nitrate and water vs. time. Energies were calculated using mass, heat capacity, and change in temperature.

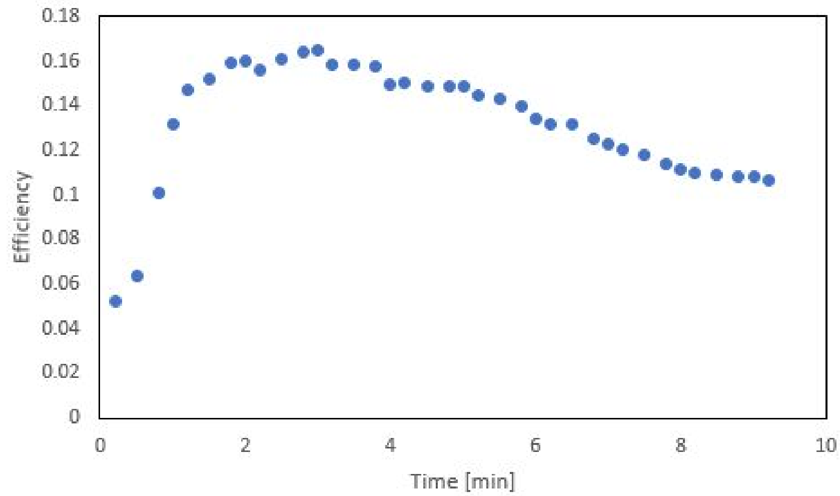

Figure A.3: A plot of the efficiency vs. time of solar-heated, molten, lithium nitrate heating water to a boil. Efficiency was found by dividing energy absorbed by water (up until the specified time) by the energy released by the molten salt for the total time. The average efficiency of this experiment is approximately 13%.

Figure A.4: Experimental setup for estimating energy required for a batch distillation. The hotplate was used to heat the still (left). Distillate travels from the still to the condenser (right).

Energy calculations for required $LiNO_3$ mass:

$$Q_{Dist} = m_{salt} * (Cp_{solid} * (T_{melt} - T_0) + \Delta H_{fusion} + Cp_{liquid} * (T_{Final} - T_{melt})) * 0.2$$
$$4212\ kJ = m_{salt} * (0.93\ \frac{kJ}{kg*K} * (528 - 293)K + 373\frac{kJ}{kg} + 1.8\frac{kJ}{kg*K} * (673 - 528)K) * 0.2$$
$$m_{salt} = 25\ kg$$

Appendix B: Lens Characterization

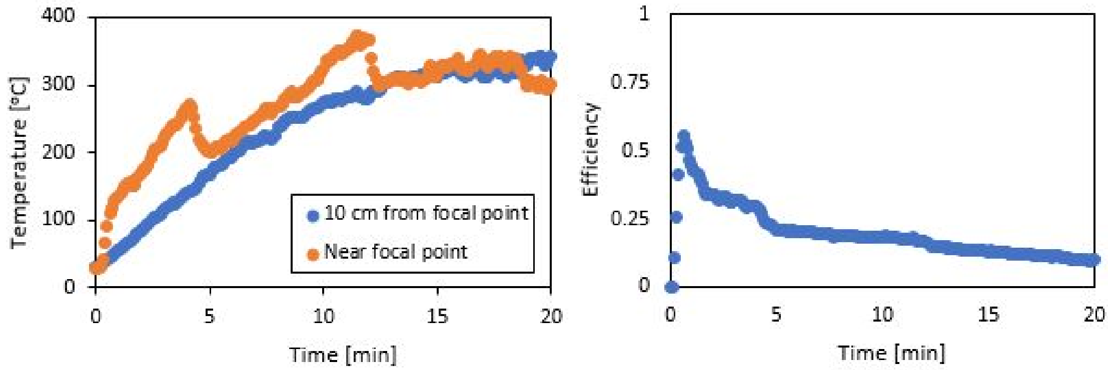

Figure B.1: Left: Temperature of the 437 g aluminum block vs. time. The different sets of data represent the two different locations of the thermocouples with respect to the focal point. Large drop-offs in the "Near focal point" data result from when the block was moved to maintain the focal point in the correct location. Right: Efficiency of the lens vs. time when heating up the aluminum block.

Figure B.2: Experimental set up for the characterization of the Fresnel lens. An aluminum block was placed at the focal point of the lens. One thermocouple was placed 10 cm away from the focal point (above) and another was placed near the focal point (below).

Appendix C: Theoretical Modeling for Solar Lithium Nitrate Melts, A Comparison to Experimental Data

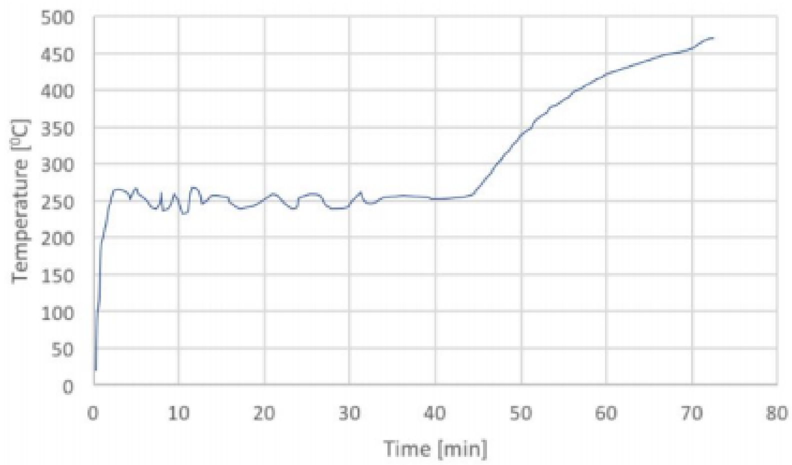

Figure C.1: A representation of lithium nitrate temperature vs. time as it was heated using the Fresnel lens and solar energy.

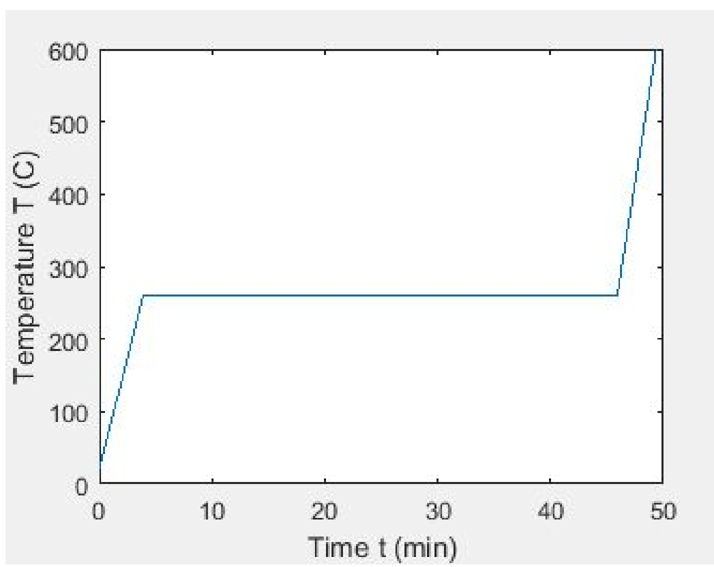

Figure C.2: A theoretical model for heating up 280 g of $LiNO_3$ salt at a 7% overall system efficiency.