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Senior Project

THERMODYNAMIC EFFICIENCY EVALUATION FOR DISTILLATION OF ETHANOL

by

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ABSTRACT

Energy will always be a consideration when distilling any product. Fog's End Distillery in Gonzales, CA is a small scale micro distillery for ethanol. For Fog's End, efficiency is key to staying competitive. In this project the efficiency of energy in vs product out will be calculated. While collecting this data the price/bottle for energy will be determined and used for an assembly cost. To determine the efficiency the fuel usage will be recorded for several distillation trials. The mash contents and product contents will all be measured and calculations will be performed to find the theoretical amount of energy required to heat up the mash and to evaporate the products collected. For sensible heat the equation $Q = mc\Delta T$ will be used, and for latent heat the equation $Q = \pm mL_v$ will be used. This project will not take into consideration many of the small factors that affect efficiency, such as burner efficiency, radiant heat loss, or energy loss from cooling water. 17 trials were conducted and it was found the average efficiency was 23.8% and the average cost/bottle for energy was $0.76. There are many small factors that affect the efficiency, with more testing the most inefficient component could be isolated and adjusted. Monetary limitations prevent acquiring a larger and more efficient still. Energy cost/bottle will help Fog's End distribute manufacturing costs properly.

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INTRODUCTION

Background

U.S. refineries throughout the United States are producing record high volumes of distillate fuels. By increasing efficiencies and fine-tuning their production mix refineries have been able to top 5 million barrels of distillate fuels in one day. (EIA – 1, 2012). The process of refining crude oil to make products such as gasoline and motor oil has helped the world exist, as we know it. Without these fuels cars would not run, trucks would not make deliveries, and airplanes would not fly. It is the process of distillation that makes many tasks possible. As of 2005 there are roughly 10 petroleum refineries in California that produce a total of 2 million barrels of fuels per day (EIA – 2, 2004). Although the number of petroleum refineries in California is low relative to other parts of the United States, distillation in California is on the rise. However, the new trend of upcoming micro distilleries is not for producing fuel for cars, but a human product for consumption, drinking alcohol.

The growth of micro distilleries in the United States is explosive. The number of craft distillers has risen from 24 in 2000, to 52 in 2005, 234 at the end of 2011, and the numbers will continue to grow (Kinstlick, 2011). California is at the frontline of this revolution with roughly 30 micro distilleries alone! The west coast makes up nearly 30 percent of all micro distilleries in the United States (Kinstlick, 2011).

Fog's End Distillery is just one of the micro distilleries in California. The owner, Craig Pakish, has been operating from Gonzales, CA, since 2007. As a small distillery operation efficiency is key to staying in business. The cost of running an ethanol still is expensive. Heating large amounts of liquid to boil for long periods of time can be costly. The amount of fuel used by Craig is one of the factors for estimating costs associated with business. He currently estimates that his fuel use is $0.23 per bottle; however, this is a rough estimate. Recently the still was upgraded with a metal jacket to help heat the still quicker and more efficiently. Craig has noticed a large difference in the startup time as well as the run time of his distillation process.

Justification

As a small distillery minor changes in efficiency can make a large difference in the overall operation. Not only will being more efficient save energy, it will save time, which is critical for a one-person operation. It took over a year before Craig added a jacket around his still to increase performance. Relatively simple additions can be the difference between hours while operating a still. Examining the process from an engineering background will help identify the areas for improvement. Recording and analyzing data can help determine the efficiencies and areas for improvement of the operation at Fog's End Distillery.

Objectives

This project will start by observing the efficiencies of operation for the distillation process at Fog's End Distillery. By measuring the fuel consumed and comparing it to theoretical values of heating and vaporizing an efficiency can be determined. From calculating the efficiency it can be determined if improvements to the distillation process at Fog's End Distillery are necessary. If cost effective improvements can be made, they will be implemented and the process will be analyzed again.

Staying efficient is the key to saving money. By implementing this project Fog's End Distillery will be able to calculate efficiencies for each run. Through testing, the unit cost of fuel per bottle for the distillation process can be determined. Finding the unit cost of fuel per bottle will help Craig distribute the operating costs through his product. If in the future changes are made to the distillation process Fog's End Distillery will be able to recalculate their energy cost.

LITERATURE REVIEW

Distillation is the process of separating materials based on differences in volatility (Berk, 2009). Volatility is the ease to vaporize a substance from a boiling solution. More volatile (lighter substances) will evaporate before heavier substances (Hengstebeck, 1966). The separation depends on factors including the concentration (in mol-fraction) of each substance present in the solution and difference in volatility of each substance (Berk, 2009).

Distillation can be performed as a continuous process or as a batch. Single stage Batch distillation is the simplest form in which a batch of material is heated and the vapors are condensed and collected. As the process is performed the batch and vapors are continuously changing as the mol-fraction of the batch material changes. (Berk, 2009).

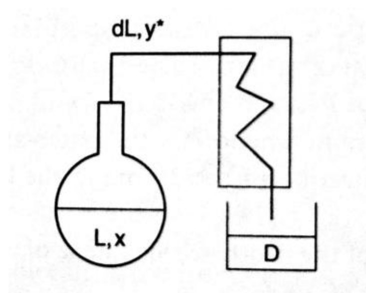

Figure 1. Diagram of batch distillation, L is the mixture with concentration x, dL is an infinitesimal amount of liquid evaporated with concentration y, and D is the distillate (Berk, 2009)

Most large-scale distillation operations will be performed on a continuous basis. A single stage continuous operation is the most simple. A liquid feed is partially vaporized and then sent to a “flash drum” to allow the vapor and liquid to separate. The separation in a single stage continuous distillation is often not sufficient, and is seldom the only separation process used. Typically multiple stages are used to acquire the level of purification necessary.

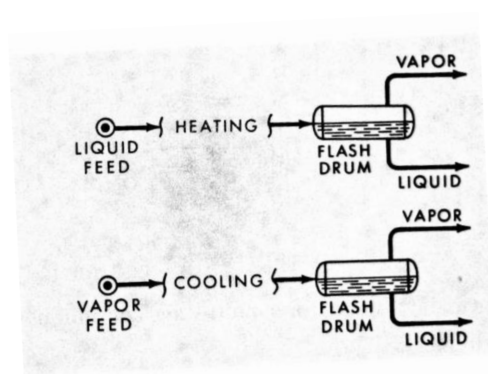

Figure 2. Diagram showing a continuous single stage distillation with a flash drum (Hengstebeck, 1966).

Multi-stage distillation processes are typically performed in columns or towers. Multi stage distillations can increase the quality of distillate by passing the vapor through a column and returning a portion of the condensate as “reflux” down the column.

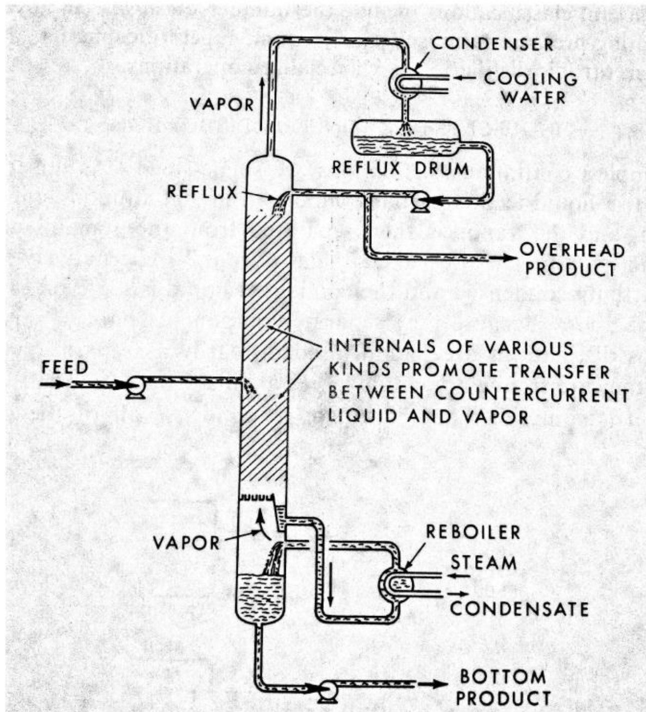

Figure 3. Multi-stage Continuous distillation (Hengstebeck, 1966).

As reflux (liquid) falls down the column it contacts rising vapors, transferring heat. The time the materials have to transfer heat is increased through the use of packing (Hengstebeck, 1966). Column plates, rings, or packing help promote heat transfer between liquid and vapor (Kirschbaum, 1948). The simplest trays consist of a flat plate with perforated holes with a weir that provides a lip. Liquid must fill up past this lip to descend to the next lower tray. A “downcomer” is used to allow the fluid to pass the tray in figure 4.

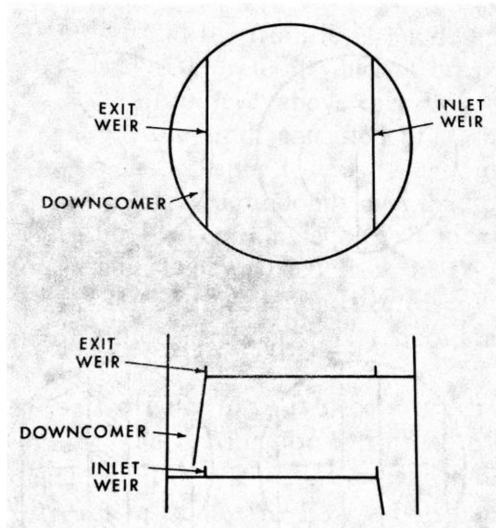

Figure 4. Weir and downcomer type plate (Hengstebeck, 1966).

The volume of liquid that this tray can hold is dependent on the pressure of the ascending vapor and the hydrostatic pressure of the liquid (Berk, 2009). When a "downcomer" is not used the tray is referred to as a shower type tray. Shower type trays create turbulence between vapor and liquid resulting in froth. The rate that froth dissipates and is created comes to equilibrium, so there is always a layer of froth.

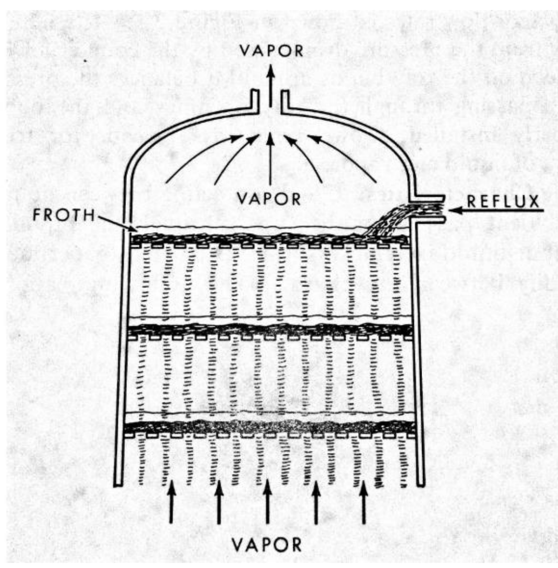

Figure 5. Shower type trays (Hengstebeck, 1966).

More efficient and expensive trays are called a bubble-cap tray (Berk, 2009). For a bubble-cap tray several holes are fitted with a riser. Over the riser is a cap that directs rising vapor down into the liquid sitting on the tray (Hengstebeck, 1966). An illustration of a bubble-cap tray can be seen in figure below.

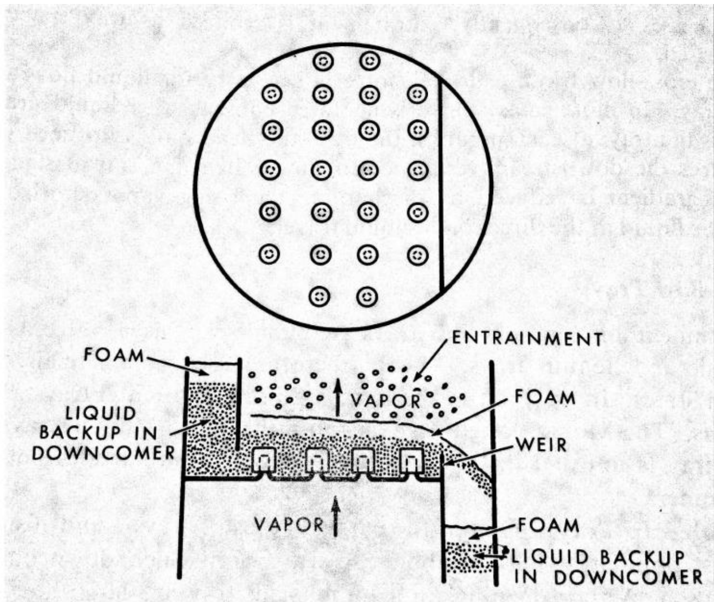

Figure 6. Bubble-cap tray (Hengstebeck, 1966).

Packing can mean a wide variety of column internals including rings, hollow balls, or woven metallic mesh. Some woven mesh are claimed to be close in efficiency as bubble caps. Packed columns are not typically used on columns larger than 12 to 18 inches (Hengsbeck, 1966).

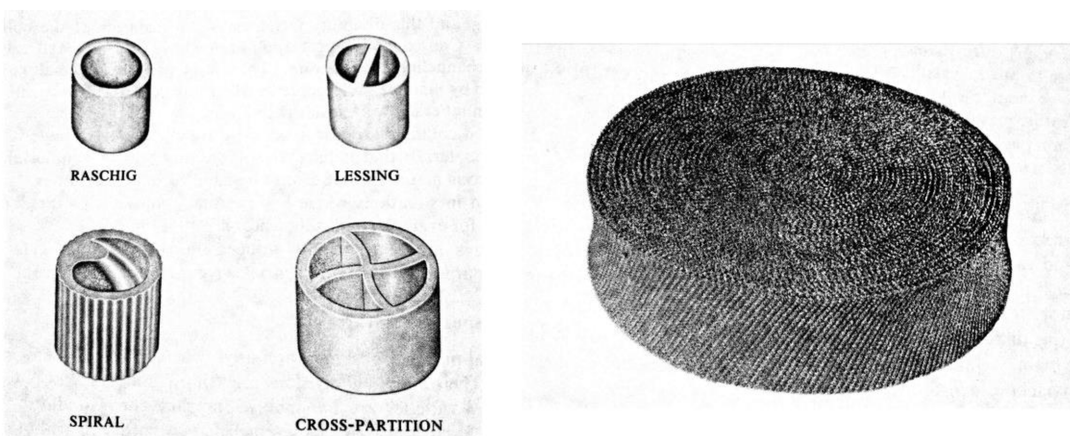

Figure 7. Typical ring type packing (Left) and Woven metal mesh packing (right) (Hengstebeck, 1966).

The temperature at the top of the column will be less than the temperature at the bottom and only the most volatile vapors will continue up the column to exit. Heavier vapors will re-condense on packing and return down the column as liquid. Substances will condense and vaporize many times before reaching the top. Each time the substance is condensed and vaporized the sample is slightly more pure than it previously was. More surface area of the packing will allow vapor more area to condense (Kirschbaum, 1948). This helps for distilling a more pure substance in the end (Stichlmair, 1998).

The amount of energy required for a distillation process is enormous. The heat required to vaporize ethanol from the water is the latent heat of vaporization. The heat of vaporization is much more than that of the specific heat that is required to bring the solution to a boil.

Ethanol has a boiling point of 78 *C and the heat of vaporization of 854 J/g. Water has a boiling point of 100 *C and the heat of vaporization is 2256 J/g (Young and Freedman, 2006). As you can see the large difference in boiling points allows for easy separation of materials through distillation.

For a solution of ethanol and water the boiling temperature will be between 78*C and 100*C. The boiling temperature of the solution is dependent on the relative amounts of each material in the solution.

The energy used to heat up a solution is called "sensible heat." An example of sensible heat would be changing the temperature of water from 32*F to 212*F as seen in purple in figure 7 below. Latent heat is the energy used for a phase change, such as ice to water or water to steam. The green boxes in figure 7 show latent heat (ThinkQuest, 2013).

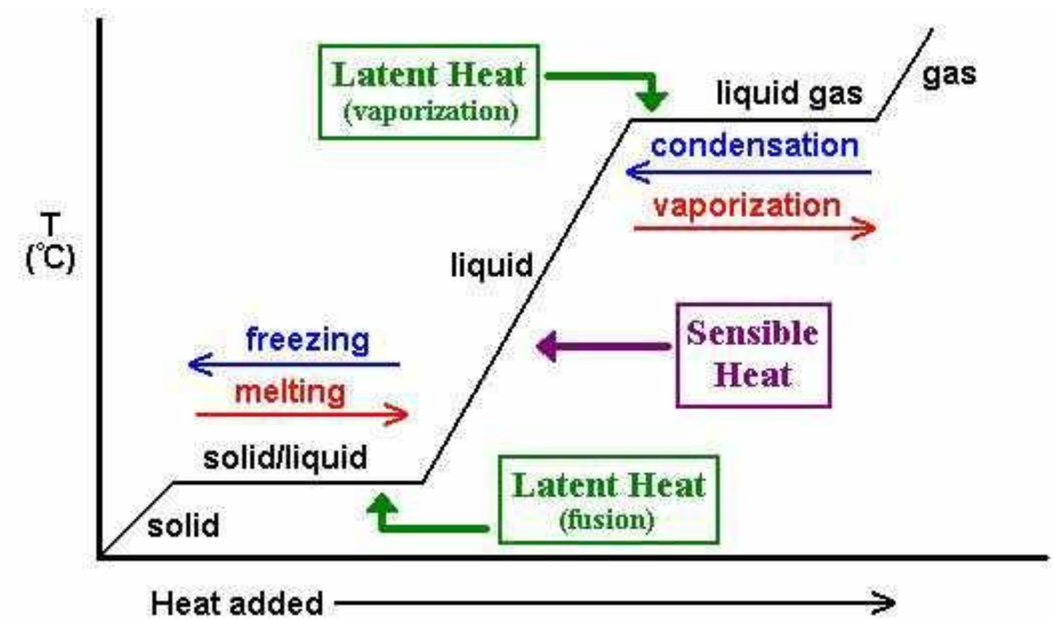

Figure 8: Sensible and Latent heat chart. Sensible heat (purple) is for a temperature change in a phase. Latent heat (green) is energy required for a phase change (ThinkQuest, 2013).

The equation for the sensible heat (theoretical amount of energy to undergo a heat change) can be given by the equation 1 below.

$$Q = mc\Delta T \tag{1}$$

Where:

$Q = Quantity\ of\ heat$
$m = Mass\ undergoing\ a\ temperature\ change$
$c = Specific\ heat\ of\ the\ material$
$\Delta T = Temperature\ final - Temperature\ initial$

This calculation only accounts for the heat required to bring the material up to boiling temperatures (Young and Freedman, 2006). The energy required for vaporization is much more than that of temperature change. The latent energy required for a phase change can be given by equation 2.

$$Q = \pm mL_v \tag{2}$$

Where:

$Q = Quantity\ of\ heat$
$m = Mass\ undergoing\ a\ phase\ change$
$L_v = Latent\ heat\ coefficient$

The plus sign is used when heat is entering the system, and minus sign for heat leaving (Young and Freedman, 2006).

The fuel used to heat a still can be measured in two ways. The higher heating value (HHV) is defined as the amount of heat released by a certain amount of fuel, and takes into account the latent heat of vaporization of water in the combustion product. The lower heating value (LHV) is the amount of heat released by combusting a specific amount of fuel, which does not account for the energy from the latent heat of vaporization. (Boundy et al. 2011).

The LHV of natural gas is 983 BTU/FT3 or 20,267 BTU/LB (47.141 MJ/kg). The HHV of Natural Gas is 1089 BTU/ft3 or 22453 BTU/ LB (52.225 MJ/kg) (Boundy et al., 2011). For this project we will assume the average to be 1000 BTU/ft3.

The combustion efficiency for natural gas is dependent on several things. The fuel and air mixture as well as the temperature difference between the burner and the room environment can vary the efficiency from 68% to 85%. Typically for natural gas the burner requires 5 to 10% excess air to combust most efficiently (TET, 2013).

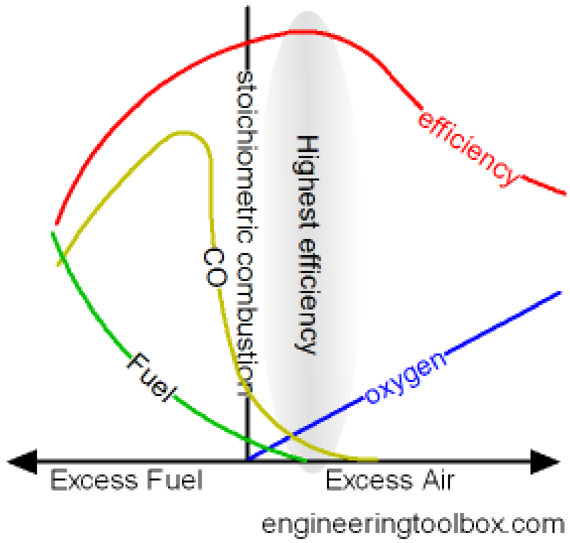

Figure 9. Relationship between fuel and oxygen for efficient burn of natural gas. When fuel and oxygen are in perfect balance the combustion is "stoichiometric." (TET, 2013).

When making a distilled product one of the most important factors is the "mash." The mash is created by adding fermentable sugars, water, and yeast. Fermentable sugars can come from a variety of sources. A common source for sugar is through grains. Although grains do not initially contain sugars, through a process of heating the grain, enzymes convert starches to sugar. After a solution of water, grain, and sugars is made yeast is added to the mixture to start the fermentation process. Many factors such as grain type, yeast strain, and temperature can have a large impact on the final product. Before the yeast is added a sample is kept to check the initial gravity of the solution. After the mash has fermented the final gravity is read in a similar manner. The difference between the initial gravity and the final gravity will indicate a percent alcohol of the mash. Specific gravity is read by using a hydrometer.

A hydrometer is a tool commonly used by brew masters and distillers. A hydrometer works on the premise of displacement (Carlton Glass, 2013). The hydrometer is calibrated based on its weight it can be calibrated to find relative densities to water. Water has a specific gravity of 1 and alcohol has a specific gravity of .876. A common hydrometer is roughly 12" long and 1" in diameter, but can vary depending on manufacturer. Some hydrometers are calibrated to float higher or lower relative to sugar content, while others are for reading percent alcohol. Both are based on specific gravities of each material (sugar and water or alcohol and water) present (Carlton Glass, 2013). In these trials it is assumed the mixture is a binomial mix of water and ethanol (although small traces of other alcohols are present). The specific gravity is relative to temperature of the liquid, and can vary depending on temperature calibration (Carlton Glass, 2013). Tables of these temperature correction values can be found in various brewing books.

Another common method of measuring alcohol is by "proof gallons" or PG. A proof gallon is equal to one liquid gallon of spirits that is 50% alcohol. One gallon of 40% alcohol would be .8PG (TBB, 2013). This is useful for comparing various amounts of liquid at different alcohol levels.

PROCEDURES AND METHODS

Equipment Used

Fuel Consumption Data. Natural gas meters are commonly used for residence houses to record fuel use for a specific location. Because the rate at which the fuel is used is not uniform the only way to accurately record the fuel use is through a meter. EKM Metering is a company in Santa Cruz, CA. that sells natural gas metering boxes for this application.

EKM's PGM.75 model gas meter was chosen for this project for many reasons. The specifications of pressures and volumes fit with the desired application. The meter will pulse once for every cubic foot of natural gas that is distributed through the meter. The pulses sent by the box can be read remotely on a pulse counter by wiring the pulse counter through the existing wires provided.

The natural gas burner used at Fogs End has a maximum BTU rating of 125,000 BTU/Hr. Assuming there is 1000 BTU/Ft^3 of natural gas the meter will pulse 125 times/hour at high fire. This precision over a typical 8 hour distillation period would allow for accurate readings of natural gas used. The inlet and outlet are ¾" fittings which fit the existing gas line. More advanced meters can offer higher accuracy in reading but come at a much higher cost.

Figure 10: EKM meter (Model PGM .75) installed behind the stove unit outside at Fog's End Distillery.

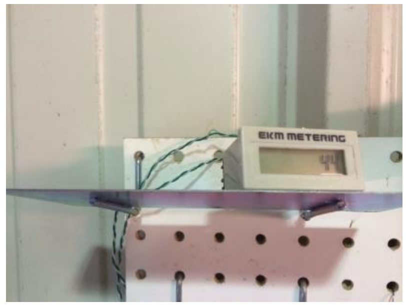

Figure 11. EKM pulse counter installed inside next to still.

The natural gas meter was purchased and installed by Fog's End Distillery. The pulse counter (Figure 11) was also purchased and installed to make the recording of the fuel consumption more convenient.

<u>Temperature Recording Data</u>. An Infrared Temperature gun is used to record the temperatures of various points on the still.

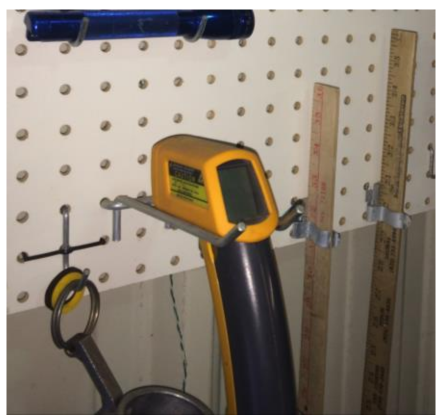

Figure 12. Infrared Temperature Gun used to record temperatures on the still.

<u>Alcohol By Volume (ABV) Data</u>. The ABV of the mash and product are recorded with the use of a hydrometer. Hydrometers are calibrated for specific application. A typical hydrometer for ethanol can be seen in figure 13.

Figure 13. Typical ethanol Hydrometer manufactured by Carlton Glass (Carlton Glass, 2013).

Data Collection Procedure

To begin to analyze the efficiency of the distillation process performed by Fog's End Distillery, data needs to be collected before and during the distillation run. Multiple trials will give a better understanding of the yearly costs associated with fuel usage. Imperative information that will need to be collected: volume of product that is going to be distilled, the percent alcohol of the product, natural gas consumption, what product is collected as an end result with its corresponding percent alcohol, and the time associated with the distillation run. For reasons of consistency and government regulation, much of this data is already recorded during a distillation run. A sample data collection sheet can be seen in appendix B.

Volume of Mash. The volume of the mash is recorded after it is transferred to the still. The height of the mash in the still is recorded with a measuring stick and the diameter of the cylindrical still is known. From this a volume can be calculated.

Volume of Natural Gas. The natural gas is not used at a constant rate. The heat is initially set to high and then lowered after the mash has reached specific points in the distillation process. The heat is later returned to a medium level. The volume of gas passed through the meter is recorded at various points throughout the distillation. For every cubic foot of natural gas that passes through the box one electrical impulse is sent to the counter. A small amount of natural gas is slowly consumed by the pilot light while the stove is not running, so the pulse counter is "zeroed out" before starting.

Percent Alcohol. The alcohol content of the mash is recorded as percent alcohol (alcohol by volume calculated by hydrometer readings) before it is transferred to the still. Percent alcohol of the mash is calculated with the specific gravities of the mash before and after, but only the percent alcohol was recorded. The percent alcohol of the product is recorded at various points throughout the distillation, as well a final average percent alcohol.

Time. The time the still has been running is recorded, although it is not taken into account when determining the energy efficiency.

Temperature. The ambient temperature is recorded with a digital temperature gauge. Ambient temperature is not taken into consideration for calculations but it is used to approximate the temperature of the mash before entering the still.

The initial temperature of the mash is recorded to calculate the energy required for calculations of efficiency. The mash is kept at ~80°F during the fermentation. After the first batch is removed from the fermenter the heat is removed, and the second day batch is started at a lower temperature (assumed to be same as ambient shop temperature).

The temperature of the still and product are recorded at various points throughout the distillation process. Temperature readings on the still are taken at several locations. Temperatures are taken at the side of the pot at 3in, 10in, and 14in (Figure 14). Temperatures are also taken at the head of the still, and both ends of the condenser

(Figure 13). These temperature readings are taken with a digital heat gun (Figure 12). Temperature of the product is collected with a digital thermometer (Figure 15).

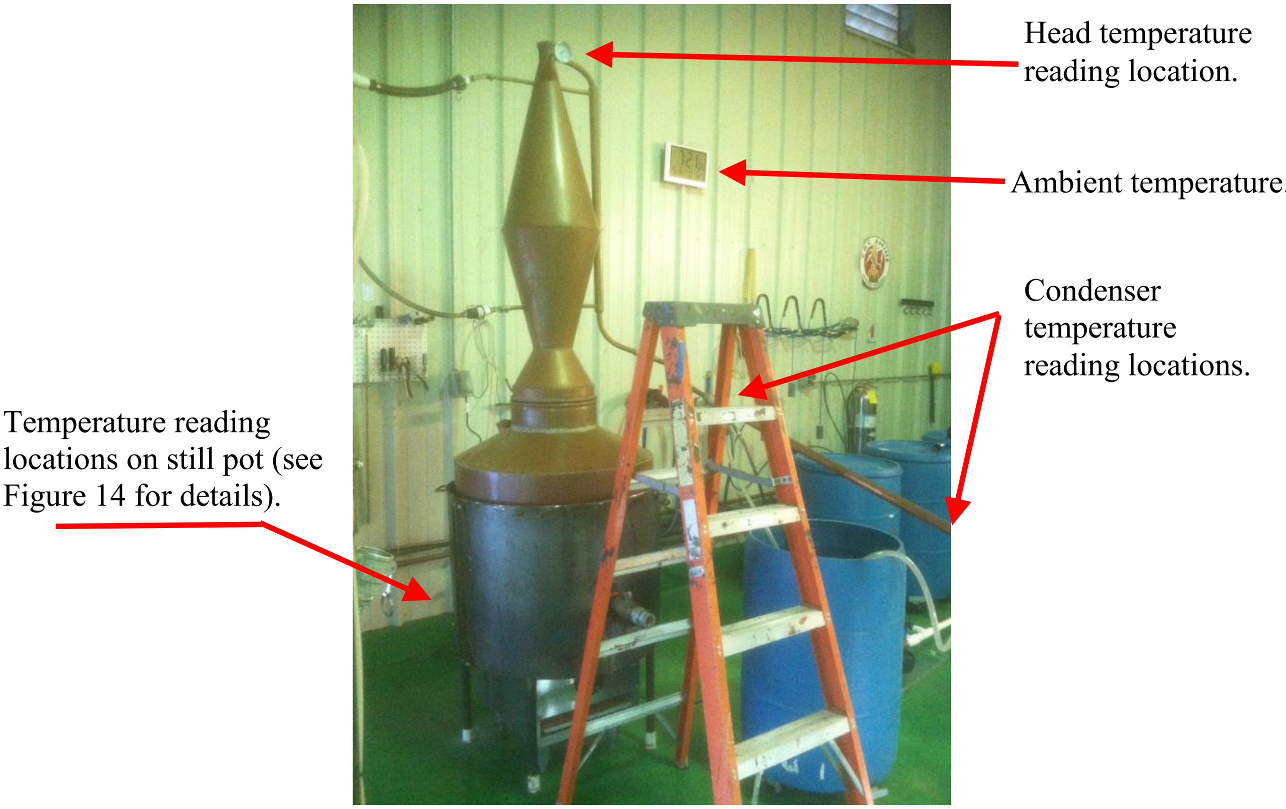

Figure 14. Temperature reading locations for distillation trials.

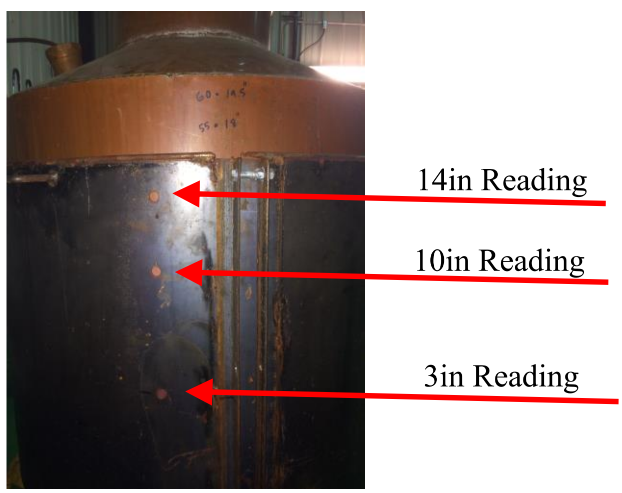

Figure 15. Temperature readings at 3in, 10in, and 14in.

Figure 16. Temperature reading of product outlet.

The Final temperature of the mash remaining in the still is assumed to be 180°F for each run based on estimated values.

Analyzing the Data Procedure

Analyzing the data was made easier with the use of Microsoft Excel.

Initially noted are the volumes of mash to be distilled with the corresponding percent alcohol. The volume of each component (alcohol and water) are calculated based on the percent alcohol of the mash. The corresponding mass of each component is calculated based on the specific weight of each material individually.

Specific heats are known for each material.

The temperatures of starting and final are converted from F to C and K (C for relative understanding) and the final temperature is subtracted from the initial temperature giving the change in temperature (ΔT) with units of K.

The sensible heat is calculated with equation (1) $Q=mc(\Delta T)$. This is the theoretical amount of energy that is required to undergo the heat change from the initial to the final temperature.

The heat of vaporization is calculated with equation (2) $Q=mL_V$. This is the theoretical amount of energy required to vaporize the product that is collected. For this we will use the volume of the collected product at the average percent alcohol to acquire the mass of water and ethanol that was evaporated during the distillation process.

The total theoretical energy required is calculated by summing the energy from the sensible and the latent heat.

It is assumed each cubic foot of natural gas has 1000 BTUs. By multiplying the meter pulses (1Ft^3 = 1 pulse) by 1000 the energy actually used is acquired in BTUs. Converting to kJ is required for comparison.

Acquiring the overall efficiency is calculated by summing the total theoretical amount of energy required for each process and dividing by the amount of fuel used recorded by the gas meter.

RESULTS

Table 1. Summary of Distillation Trials.

Summary of Distillation Trials (See Appendix for data collection sheets)									
Trial	Start Temp (F)	Final Temp (F)	Total Volume (Gal)	% Alcohol	Total FT^3 N.G.	Total P.G. Collected	Average Proof	Overall Efficiency	Price/Bottle
1*	80	180	60	10.80%	405	10.04	111.59	22.76%	$ 0.74
2**	65	180	52.5	10.80%	383	9.43	111.52	23.45%	$ 0.74
3*	80	180	60	8.40%	405	9.97	110.84	22.93%	$ 0.74
4**	63	180	54	8.40%	393	9.48	111.19	23.67%	$ 0.76
5*	80	180	60	7.60%	360	7.62	106.89	23.50%	$ 0.86
6**	67	180	48	7.60%	304	6.42	105.86	24.58%	$ 0.86
7*	80	180	60	7.50%	350	7.51	105.34	24.26%	$ 0.85
8**	65	180	51.8	7.50%	321	6.68	105.48	25.07%	$ 0.88
9*	80	180	60	9.00%	413	10.45	112.97	22.62%	$ 0.72
10**	65	180	50	9.00%	364	9.12	111.35	23.80%	$ 0.73
11*	80	180	60	8.80%	406	10.24	110.72	23.17%	$ 0.72
12**	66	180	53	8.80%	380	9.53	109.35	24.24%	$ 0.73
13*	80	180	60	9.10%	411	10.61	111.59	23.13%	$ 0.71
14**	64	180	50.3	9.10%	366	9.43	111.51	24.20%	$ 0.71
15*	80	180	60	8.70%	404	10.42	109.58	23.68%	$ 0.71
16**	57	180	58	8.70%	402	10.15	109.83	25.72%	$ 0.72
17**	61	180	39.8	8.20%	270	6.13	110.56	24.32%	$ 0.80
Water (Jacket)	65.9	212	20	0	58	0	0.00	42.05%	n/a
Water (No Jacket)	65.5	212	20	0	84	0	0.00	29.11%	n/a
*Temperature on initial batch is based on temperature that heater is at							Average	23.83%	$ 0.76
**Temperature for second batch is assumed to be the same as ambient							STDEV.S	0.83%	$ 0.06

DISCUSSION

General Discussion. The data acquired by Fog's End has consistent results. The average efficiency was 23.8% with a standard deviation of the sample being .8%. This means that nearly four times the amount of energy is being used than the calculated theoretical value. These results are not overwhelmingly shocking. The efficiency of the burner could account for 63% to 85% of the efficiency. The stove appears to be in good working condition and was recently serviced, but a wide variety of variables can change the efficiency of the burner. Even then, the efficiency of the heat transfer could be a large part of the heat loss.

Since the insulation jacket was added the time required for heat up had dropped by 32%. A trial experiment was conducted with and without the insulating jacket. 20 gallons of water was carefully measured and heated at high fire. The initial temperature was recorded and the target temperature was 212 °F. Once steam was evident and temperature readings on the column suggested the water was at 212 °F the heat was removed. With the insulating jacket the time for the trial was 40 minutes and without the jacket 59 minutes. This confirmed the dramatic decrease in time for startup in a typical distillation run. The gas metering pulses for the jacketed run were 58 and 84 pulses without the jacket. This shows that adding the jacket resulted in a 31% drop in energy use, 32% reduction in time, increase of 13% overall efficiency. Without a temperature gauge penetrating the still base it was difficult to pinpoint the exact time the water was at boiling temperature. The efficiency of the water run with the insulation jacket was much higher than the typical distillation run. The water trial without the jacket was still higher than the typical distillation run. The water trial was only accounting for the sensible heat required to bring the mash to temperature. This may be the reason for an increased efficiency. During a typical distillation run the flame is running at medium flame for several hours. During the time when alcohol is evaporating some of the fuel is being used to vaporize alcohol, a small fraction is being used to maintain a constant temperature, and some energy is lost. Although the water trial did not indicate similar efficiencies as a mash, it was useful to see the increased efficiency by adding the jacket. It is unknown if further insulation would help significantly.

Heat transfer through the walls of the still decreases the efficiency. Because the still is large, cylindrical, and tall, there is a large amount of copper sheet metal that is exposed to the ambient air temperature. As the still runs, the conditions inside are constantly changing, and the bottom of the still is much hotter than the top. To calculate the energy lost through the still walls several calculations could be performed that would indicate the energy lost. To be accurate, the calculations would need to be done for many sections at multiple times to accurately acquire the heat transfer. Because these losses are not avoidable in the current still set up they are not taken into consideration for the efficiency.

There are many factors in the heat transfers of a distillation process. Many difficult calculations could be performed at small intervals throughout the distillation process that would result in more accurate data on energy transfers. Many factors such as burner efficiency, heat transfer rates, and radiant heat loss were not taken into account. Overall these inefficiencies added up to be significant. With further testing the least efficient factor could be determined and altered to offer a more efficient distillation run.

Cost Analysis. The average energy cost per bottle for the trails evaluated were $0.76 with a standard deviation of the sample being $0.06. The original estimated cost was $0.23 per bottle. There is a large difference in cost between the estimated and the measured. This will allow Fog's End Distillery to more accurately estimate the assembly cost of each bottle of alcohol, and adjust distribution prices accordingly.

RECOMMENDATIONS

Adding the insulated jacket decreased the time and energy required for heat up. Without the jacket the main focus of improving efficiency would be to add insulation around the still. More surface area of contact between the still and heated air rising will improve the heat transfer and decrease energy lost. With more insulation it is possible that the still could be run at a lower flame during the vaporization of alcohol and produce the same results. Because the jacket was already added it is unknown if further practical improvements to the jacket will make more of a significant impact. If the still pot could be modified several additions could result in better heat transfers. To help make changes to the efficiency of the distillation only practical changes can be implemented. This eliminates many possible solutions to altering equipment and procedure. For example, a protruding electric immersion heating element placed in the mash would result in a higher and more efficient heat transfer. The cost associated with acquiring a new still design is not a solution desired by the owner. Knowing the burner and still set up must be kept the same; the efficiency improvements are limited. If it is assumed the burner is only 75% efficient; the overall efficiency cannot be higher than 75% because each component of efficiency is multiplied together for an overall efficiency. For this reason the maximum efficiency is not likely to significantly improve.

Without the possibility of changing the still it is difficult to speculate if the efficiency can be increased significantly. Energy is lost due to many causes; an inefficient burner, imperfect heat transfers, and little insulation on the still walls. There will always be inefficiencies in distillation because after the mash is heated it is condensed back into liquid. The cooling water takes in a significant amount of energy. Without recycling this energy to heat the next batch or make use of warm water, the possibilities are minimal. With a new still design there are many areas for improvement such as insulation, heat sinks, and more efficient heating methods. Because of the monetary limitations for Fog's End Distillery no significant improvements can be effectively made.

REFERENCES

Berk, Z. 2009. Food Process Engineering and Technology. Academic Press, Inc., New York. Pp. 295 – 315.

Boundy, B., Diegel, S.W., Wright, L., Davis, S.C. 2011. Biomass Energy Data Book. 4th ed. Oak Ridge, Tennessee: U.S. Department of Energy.

Carlton Glass. Hydrometer Information. Scientific Glassblowers. Carlton Glass Company. http://www.carltonglass.com.au/user/image/hydrometer-information.pdf. Dec. 2, 2013.

The Engineering Toolbox (TET). 2013. "Combustion Efficiency and Excess Air". http://www.engineeringtoolbox.com/boiler-combustion-efficiency-d_271.html (June 13, 2013).

Hengstebeck, R. J., 1966. Distillation principles and design procedures. Reinhold publishing corporation, New York.

Kinstlick, M. (2011). "The U.S. Craft Distilling Market: 2011 and Beyond" < http://www.distilling.com/PDF/white_paper.pdf> (June 13, 2012).

Kirschbaum, E., 1948. Distillation and Rectification. Chemical Publishing Co., New York.

Stichlmair, J., Fair, J., 1998. Distillation Principles and Practices. Wiley-VCH, New York. Pp. 363 – 368.

TBB. 2013. Bulk Wines FAQ. U.S. Department of the Treasury. Alcohol and Tobacco Tax and Trade Bureau. <http://ttb.gov/forms_tutorials/f511040/faq_instructions.html>

ThinkQuest, Oracle Foundation. 2013. "Thermodynamics: Temperature, Heat, and Work" <http://library.thinkquest.org/C006669/data/Chem/thermodynamics/tempheat.html> (October 28, 2013).

U.S. Energy Information Administration (EIA – 1). (January 6, 2012). "U.S. refineries and blenders produce record amounts of distillate fuels" < http://www.eia.gov /todayinenergy/detail.cfm?id=4470> (June 13, 2013).

U.S. Energy Information Administration (EIA – 2). (2004). "Petroleum Supply Annual 2004, Volume 1" <U.S. Energy Information Administration (EIA – 1). (January 6, 2012). "U.S. refineries and blenders produce record amounts of distillate fuels" < http://www.eia.gov /todayinenergy/detail.cfm?id=4470> (June 13, 2013).

Young, H., Freedman, R., 2006. University Physics 12e.

APPENDICES

Appendix A:

How Project Meets Requirements for the BRAE Major

HOW PROJECT MEETS REQUIREMENTS FOR THE BRAE MAJOR

Major Design Experience

The BRAE senior project must incorporate a major design experience. Design is the process of devising a system, component, or process to meet specific needs. The design process typically includes the following fundamental elements outlined below. This project addresses these following issues:

Establishment of Objectives and Criteria. Project objectives will investigate energy efficiencies for the production of ethanol on a small batch scale. Data trials will be conducted by Fog's End Distillery in Gonzales, CA. See "Design Parameters and Constraints" section below for specific objectives and criteria for the project.

Synthesis and Analysis. The project will incorporate thermodynamic evaluations, real-world testing to analyze data, and applying the analysis to benefit the client.

Construction, Testing, and Evaluation. The energy use was calculated for multiple distillation trials. Energy usage is compared to theoretical values to determine an efficiency. Energy use was calculated to assembly cost of price of fuel per bottle.

Incorporation of Applicable Engineering Standards. N/A

Capstone Design Experience. The BRAE senior project is an engineering design project based on the knowledge and skills acquired in multiple major and support classes. This project incorporates learning from the following classes: BRAE 129 Lab Skills/Safety, BRAE 133 Engineering Graphics, BRAE 152 SolidWorks, BRAE 240 working in the shop, BRAE 232 Ag systems planning, BRAE 236 principals of irrigation, BRAE 403 ag systems engineering, BRAE 421/422 Equipment Engineering, ME 302 Engineering Thermodynamics, ENGL 149 Technical Writing, CHEM 124 and CHEM 125.

Design Parameters and Constraints

Physical. N/A

Economic. Testing equipment must not exceed $300. Proposed improvements to the distillation equipment or procedure will be individually evaluated.

Environmental. A benefit of the project will be raising awareness to the inefficiencies associated with distillation. Improvements in efficiency will result in less natural gas consumption.

Sustainability. More efficient use of energy will ensure the low cost associated with natural gas for the future, as well as less expensive alcohol.

<u>Manufacturability</u>. N/A
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<u>Health and Safety</u>. N/A

<u>Ethical</u>. N/A

<u>Social</u>. N/A

<u>Political</u>. Less greenhouse gases.

<u>Aesthetic</u>. N/A

<u>Other – Productivity</u>. The data that is recorded must be repeatable for future production in other situations

Appendix B:

Data Collection Tables

DATA COLLECTION TABLES

Table 2. Sample data collection sheet from Fog's End Distillery.

Date	Gallons	Start Time	Grain	Batch Barrel	Run	Ph	Indoor Temp	Notes		CuFt
7/1/13	60.0	2:55am	Rye	1,2,3	2.1	3.97	64ºF	60 gal. @ 10.8% alc. Yields 12.96 pg 1135ml heads cut 400+350+350=1,100ml Primary condensers: Start 72ºF; 68ºF		0
Time	Temp. Pot @ 3"	Temp. Pot @ 10"	Temp. Pot @ 14"	Temp. Head	Temp. Parrot	Proof	Corrected Proof		Exit Temp. at #1 condenser	CuFt
3:21	224	164	139	130				Start Both Condensers	90	44
4:01	239	182	158	135				Stove set to low		100
4:26	187	150	135	140						113
4:39	173	136	123	150						125
4:52	175	141	127	160						135
4:59	175	139	123	163	65.9	150	147.9	**2 hr. 4 mins.** Start parrot collecting	71°F	139
5:19	174	138	121	182	62.8	151	150	**400ml- 20 mins.**		153
5:25	175	138	124	186	64.1	145	143.6	**350ml- 6 mins.**		157
5:29	175	139	121	187	67.9	143	140.1	**350ml - 4 mins.**	91°F	160
7:15	183	143	125	194	82.4	131	122.6	**3 gals. - 35 mins**	91°F	235
7:50	185	145	131	196	83.3	125	116.1	**4 gals. - 35 mins.**	87°F	261
8:27	186	149	130	197	83.7	120	110.5	**5 gals. - 37 mins.**	89°F	289
9:03	187	149	136	198	82.3	114	105.2	**6 gals. - 36 mins.**	102°F	316
9:41	191	153	142	200	80.5	106	97.4	**7 gal. - 38 mins.**	102°F	345
10:20	188	154	141	201	79	96	87.9	**8 gals. - 39 mins.**	106°F	374
10:48	188	153	142	202	77.6	90	82.2	**33L - 28 mins.**	99	396
10:59	188	154	145	203	77.6	86	78.1	**9 gals. - 39 mins.**	96	405
Stop							111.59	**10.04 pg produced**		
								8hrs. 4 mins. Run time		
								1 pulse = 1 CuFt		
								86ºF; 56ºF		

Table 3. Calculations performed on data from Fog's End Distillery.

Energy Use Calculations			Product Collected		
Starting temp	80.0	F	total proof gallons	10.04	proof gallons
	26.7	C			
	299.7	K	average proof	111.59	proof
Final temp	180.0	F	Total Volume of Product	34.05844	L
	82.2	C			
	355.2	K	% Alcohol product	56%	
total volume	60.0	gal	Volume of Alcohol (100%)	19.00291	L
	227.1	L			
	227.1247	kg	Mass of Alcohol (100%)	14.9933	Kg
% alcohol	10.8%		Volume of Water	15.05554	L
Heat for Bringing up to temperature			Mass of Water	15.05554	Kg
Q = mcdT					
Mass water	202.60	Kg water	Heat for vaporization		
c	4.187	kJ/Kg K	Q = mLv		
dT	55.56	K			
			Lv Water	2256	kJ/Kg
Q for water	47126	kJ	Q for Water	33965	kJ
Mass ethanol	24.53	kg ethanol			
C	2.46	kJ/kg K			
dT	55.56	K			
			Lv Ethanol	854	kJ/Kg
Q for ethanol	3352.36	kJ	Q for Ethanol	12804	kJ
Total kJ sensib	50478	kJ	total kJ for latent	46770	kJ
total actual:	405	ft^3 N.G.	total energy use:	97248	kJ
	427275	kJ	overall efficiency:	22.76%	
Energy Cost	$ 0.09	$/Ft^3	Bottling Proof	100	proof
Total Energy cost	$ 37.34	USD	Total # Liters (at bottle proof)	38.01	liters
			Total # 750ml bottles	50.67	bottles
Energy Cost/Bottle	$ 0.74	Dollars/Bottle			

Table 4. Formulas from calculations performed on data from Fog's End Distillery.

Energy Use Cal				Product Collected		
Starting temp	80	F		total proof gallons	10.04	proof g
	=(B5-32)*(5/9)	C				
	=B6+273	K		average proof	111.59	proof
Final temp	180	F		Total Volume of Produ	=(F5*(100/F7)*(3.78544))	L
	=(B9-32)*(5/9)	C				
	=B10+273	K		% Alcohol product	=F7/200	
total volume	60	gal		Volume of Alcohol (10	=F11*F9	L
	=B13*3.7854118	L				
	=B14	kg		Mass of Alcohol (100%	=F13*0.789	Kg
% alcohol	0.108			Volume of Water	=F9-F13	L
Heat for Bringing up to temperature				Mass of Water	=F17	Kg
Q = mcdT						
Mass water	=(B15-(B17*B15))	Kg water		Heat for vaporization		
c	4.187	kJ/Kg K		Q = mLv		
dT	=B11-B7	K				
				Lv Water	2256	kJ/Kg
Q for water	=B21*B22*B23	kJ		Q for Water	=F24*F19	kJ
Mass ethanol	=B17*B15	kg ethanol				
C	2.46	kJ/kg K				
dT	=B11-B7	K				
				Lv Ethanol	854	kJ/Kg
Q for ethanol	=B27*B28*B29	kJ		Q for Ethanol	=F30*F15	kJ
Total kJ sensibl	=B31+B25	kJ		total kJ for latent	=SUM(F31,F25)	kJ
total actual:	405	ft^3 N.G.		total energy use:	=B34+F34	kJ
	=B36*1055	kJ		overall efficiency:	=(F36/B37)	
Energy Cost	0.0922	$/Ft^3		Bottling Proof	100	proof
Total Energy cost	=B36*B40	USD		Total # Liters (at bottle	=Sheet2!F5*(100/F40)*3.78544	liters
				Total # 750ml bottles	=F41/0.75	bottles
Energy Cost/Bottle	=B41/F42	Dollars/Bottle				