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Distillery

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CAPSTONE PROJECTS FINAL REPORT

SENIOR DESIGN

MECE 471

HONORS PROJECT

MECE 497

By

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Abstract

The purpose of the senior design project for this group is to create a cost-effective distillation column (still) that produces a quality liquor. Traditionally, a copper still is used in the whiskey-making industry. Copper reacts with volatile sulfur compounds to prevent them from being in the final product. The downside of using copper as the material of construction for the distillation column is that copper is very expensive. An economical alternative would be to use a stainless steel still. This project tests the effectiveness of the steel still with copper mesh packing in reducing the concentration of sulfur volatile compounds in the final product.

This project demonstrates that there is not much difference between a copper still and a steel still with copper packing regarding sulfur volatiles and ABV of the distillate. Because of that, it is much more economical to use a steel still when distilling ethanol. This can significantly save costs for distilleries that are looking to buy new distillation columns since the price to build a steel still is a small fraction of the cost of an equally sized copper still.

If one were to continue off this project, and had enough money to spare, it would be beneficial to make a like-geometry copper still to compare with. Additionally, if future researchers have access to a higher quality testing method, there may an improvement in the accuracy of the results.

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1. Outline of Subject Matter

1.1 Introduction

The purpose of the senior design project for this group is to create a cost-effective distillation column (still) that produces a quality liquor. To make whiskey, a mixture of grain and water is heated to make "wort", then fermented to produce ethanol. To boost the alcohol concentration, or alcohol by volume (ABV), this fermented wort is distilled in a still. Traditionally, a copper still is used in the whiskey-making industry for two main reasons: 1. Copper is highly thermally conductive to promote effective heat transfer and 2. Copper reacts with volatile sulfur compounds to prevent them from being in the final product, thus making it taste better. The downside of using copper as the material of construction for the distillation column is that copper is very expensive. An economical alternative would be to use a stainless steel still that has copper mesh packing in the column. This project tests the effectiveness of the steel still with copper mesh packing in reducing the concentration of sulfur volatile compounds in the final product.

A number of liquor stills already exist in the market today, giving a benchmark of how much stills cost. The end goal will be to make modifications to the stainless steel still giving it copper components so that the sulfur compounds can still be removed. The cost of the final still will be compared to the copper still to show that cost of the modified on will be less expensive to manufacture. Additionally, the group will be comparing the sulfur compound concentrations of the modified still to the steel and copper still giving an upper and lower bound of the target we are trying to hit.

In order to create a product that is accepted by the customer and by society, the group had to keep in mind societal considerations and professional responsibilities. When creating this project idea, the interest of the customer was what was kept in the forefront of our minds. Multiple things were considered in the importance of this project. This product acknowledges the attitudes towards product quality for the people buying the product coming from the stills as well the buying habits of those needing to buy the still to create thus product. This still is being aimed at those who want to start learning and investing in their own liquor company, while also being able to save some money on this product so that they can invest it elsewhere in the company. The hope of this is to be able aid, even if it is just slightly, in the creation of new small business owners, like the people doing this project. In helping the potential new business owners, it will therefore help the economy of state and country.

When creating this still, public health and safety are kept in high regard in the decisions being made. As this is a device making a consumable product, we are taking precautions to use materials that are safe for the people. Follwing FDA Code 4-202.11, the still is smooth, free of imperfections, free of sharp internal angles, corners, and crevices, and finished to have smooth welds and joints [1]. Multiple cleaning agents are used constantly on the equipment being used for brewing and distillation. This is to ensure the following of FDA Code 4-602.11 [1]. This is also in accordance to Code 4-701.10 "equipment food-contact surfaces and utensils shall be sanitized" and Code 4-701.11 "UTENSILS and FOOD-CONTACT SURFACES of EQUIPMENT shall be SANITIZED before use after cleaning" [1]. In the creation of the still, it is also noted that it is structurally sound and heat safe as the still will be heated when in use.

1.2 Design

1.2.1 Design procedure

At the beginning of the design process, we started with the designing of the steel still. We knew that we wanted to keep the size on the smaller end, so we chose to make a 10 liter still. This measurement is in reference to the side of the pot at the bottom. The length of the column was chosen to be 2 feet and the diameter 2 inches. These measurements came from research. According to [2], columns are generally 2 inch or 3 inch in diameter. This particular site would do 2 inches for 30 liters, meaning 2 is plenty for 10. The length of the column is 24 inches plus an approximate 5 inches for the 90-degree bend. The optimal height ratio is 15:1 on the low end. At 14.5:1 for ours, this fits [3]. Other components used are two thermocouples for temperature monitoring. One is on the pot while the other is at the top of the column. A copper pipe was used in this steel still in the condenser part. This was decided because the product would be in a liquid state by that point, no longer having a reaction of the vapor with the copper. This was coiled into a circle inside of an 8-liter pot with room to put ice in.

Taking from what was taught in Concepts of Design, we started with an initial function diagram, figure 1, to get our thoughts down. After this, a basic preliminary design, figure 2, was drawn

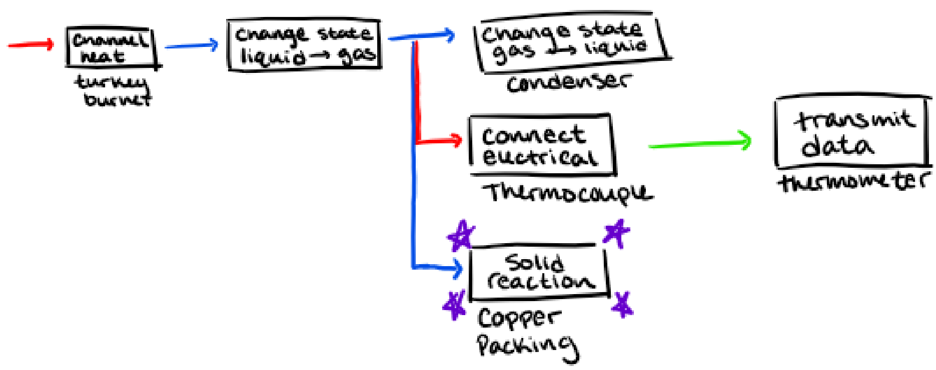

Figure 1: Initial Function Diagram

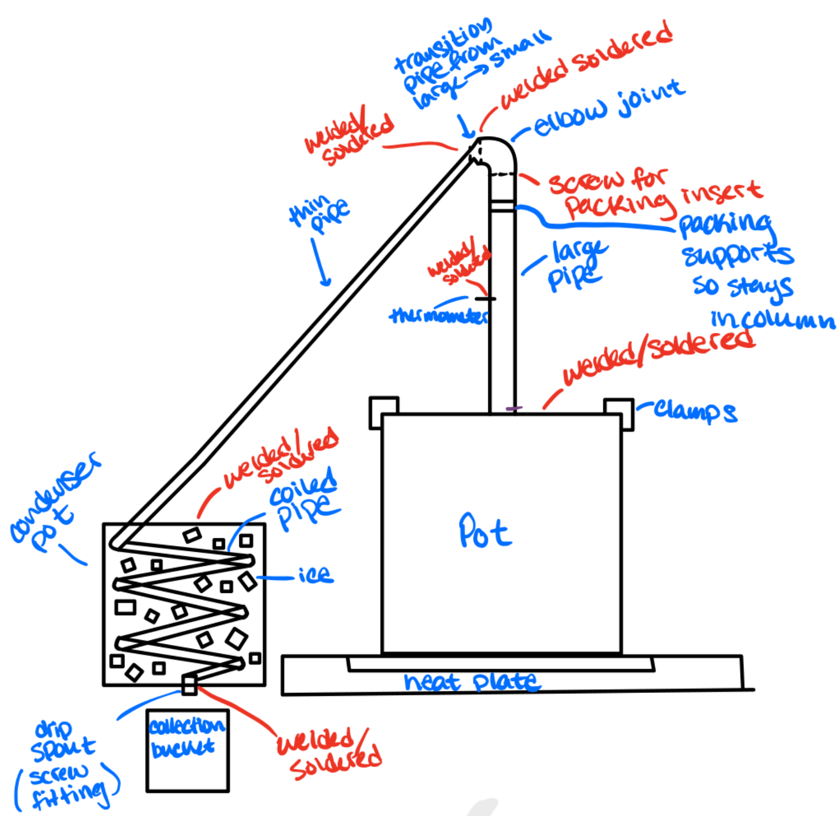

Figure 2: Preliminary Design

The next part of the design process was determining how to incorporate copper into the column. We knew that it was going to be some sort of component inside of the column itself as that is where the vapor must pass through. To help gather our thoughts we made an objective tree, figure 3, and weighted decision matrix, figure 4.

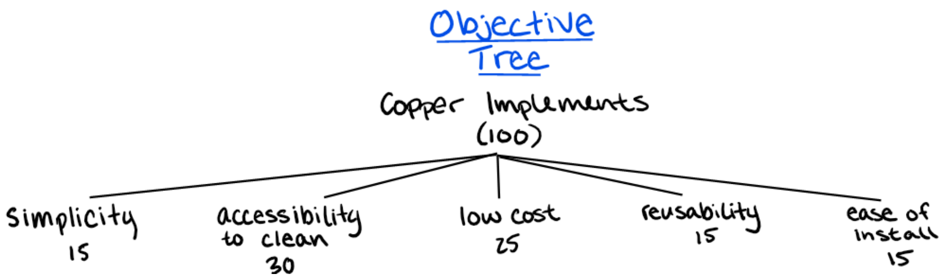

Figure 3: Objective Tree With Weighting Factors

	Evaluation Criterea	Weighting Factor, W	FINS Concept A		CHIPS Concept B		MESH Concept C	
1.	Simplicity	15	1	15	4	60	4	60
2.	Accessibility to clean	30	1	30	3	90	3	90
3.	Low Cost	25	4	100	4	100	4	100
4.	Reusability	15	5	75	2	30	2	30
5.	Ease of Install	15	1	15	3	45	5	75
			=	235	=	325	=	355

Figure 4: Weighted Decision Matrix

From this information, it was decided to not go with a permanent fixture inside of the column such as copper fins. After each time copper is used in a distilling process, it needs to be thoroughly cleaned. This was a big reason in not choosing fins as it would be very hard to clean them inside the column. Plus, if the fins were too big, it may inhibit the vapor moving up the column. This left using copper chips or a thin wire mesh. In the weighted decision matrix, the two came very close, but we ended up choosing the copper wire mesh.

1.2.2 Design details

Present the detailed design, with diagrams and component values. Show how the design equations were applied. Give equations and diagrams with specific design values and data. Place large data tables in an appendix. Circuit diagrams that are too large to be readable on a single page should be broken into pieces for presentation. The full diagram may be included in an appendix. Use photographs only as necessary and treat them, along with all other graphics except tables, as *figures*.

The first step after we had decided on the design of the still was making a basic model in SolidWorks to get all of our thoughts down. This is shown in figure 5.

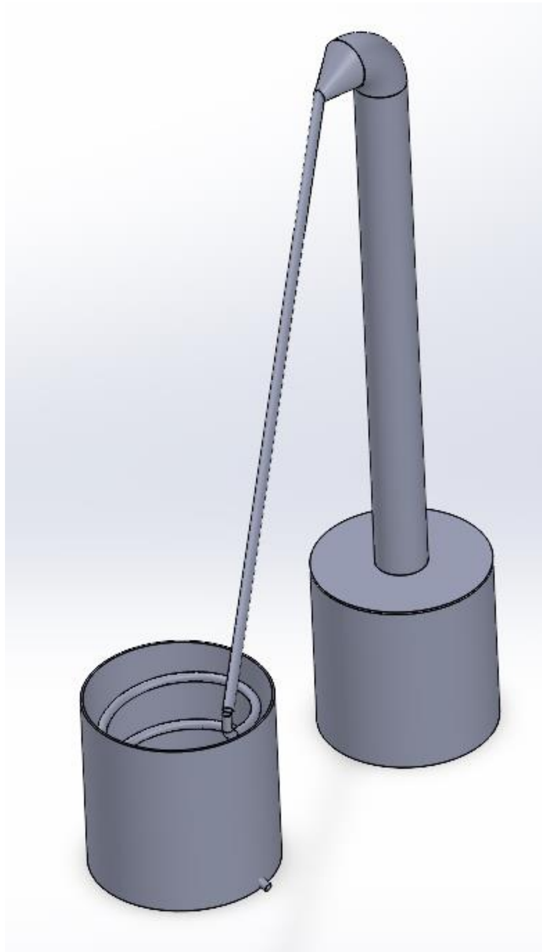

Figure 5: SolidWorks Model

In order to connect the pieces together, some of which being different materials that could not be welded together, we decided to use clamps and gaskets. Some soldering was also used. With all these materials a simple Bill of Materials was formed, figure 6.

PARTNO	DESCRIPTION	QTY
1	10L STEEL POT	1
2	10L STEEL POT LID	1
3	MALE COMPRESSION CONNECTOR	4
4	2IN TRICLAMP COMPRESSION FITTINGS	1
5	THERMOMENTER	1
6	THERMOCOUPLE	2
7	THREADED BRASS COUPLING	2
8	90DEG 2INOD STEEL TUBE ELBOW	1
9	2IN TRICLAMP	5
10	2IN GUSSETS	5
11	2IN-1IN PIPE	1
12	1.5IN COPPER PIPE TRI CLAMP COMPATABLE	1
13	2IN-0.5IN STEEL REDUCER COUPLING	1
14	0.5IN COPPER PIPE	1
15	0.5IN-0.375IN COPPER REDUCER COUPLING	1
16	0.375INID 0.5INOD COPPER TYPE L COIL	1
17	8QT STEEL POT	1
18	0.5INX0.25IN COMPRESSION STOP VALVE	1
19	0.375IN 45DEG COPPER ELBOW FITTING	1

Figure 6: Bill of Materials

We then took this Bill of Materials and searched for existing parts from local hardware stores. To keep track of all the parts needed and what were sourced, a detailed drawing was made, figure 7.

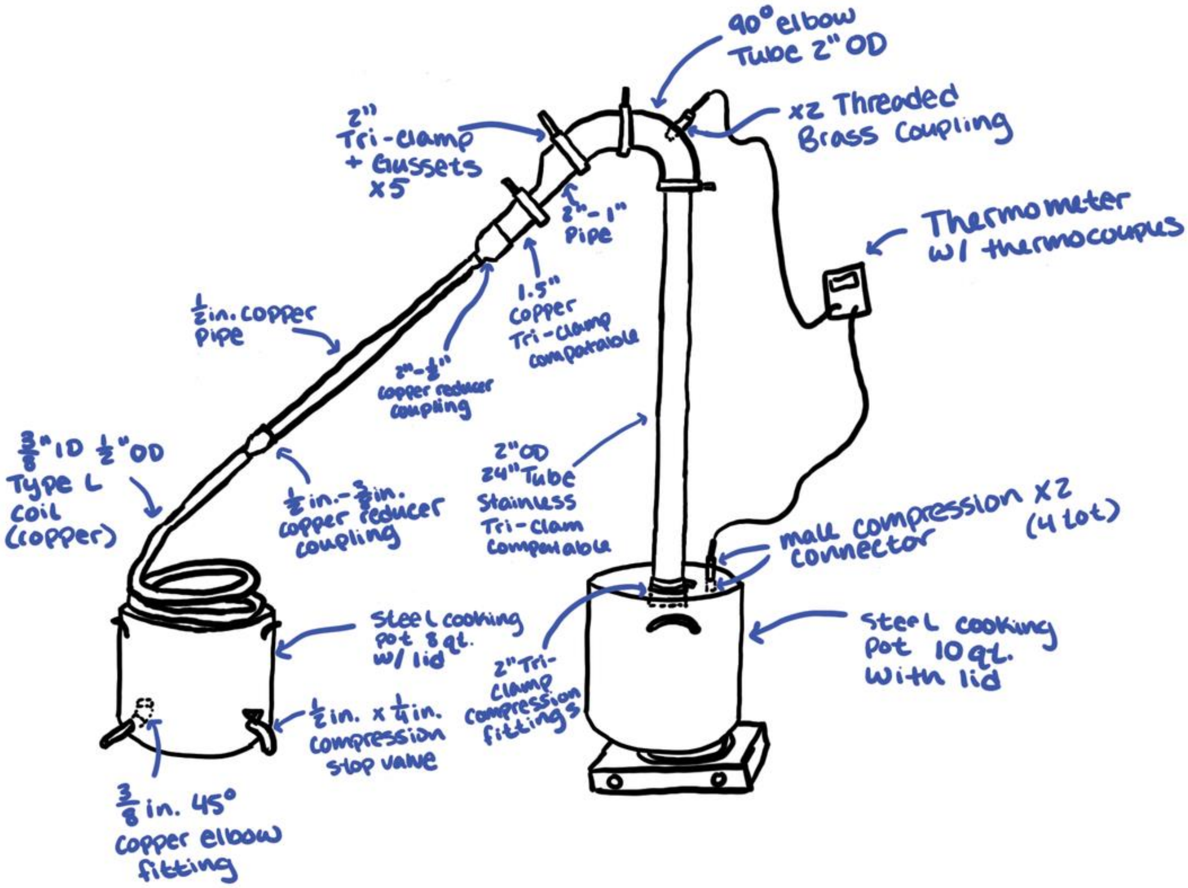

Figure 7: Detailed Sketch with Parts

From this point all that was needed was to assemble the still. This was done with the help of a friend of ours. A secondary 10-liter copper still was purchased online. Early on in the design process we were planning on making both the copper and the steel still so as to ensure the size and shape was the same for it to be a control. Unfortunately, the cost to buy the parts ourselves was extremely high compared to buying a prebuilt one online. It would have cost us the same amount to buy a singular 10-liter copper cooking pot as it was the buy a completed still online. We acknowledge the difference in shape and column length, but this was beyond our control. The completed steel still is shown in figure 8, and the copper still is in figure 9.

Figure 8: Completed Steel Still

Figure 9: Purchase Copper Still

The last part that needed to be dealt with was the copper mesh insert. All this required was purchasing copper wire from a store and wrapping it upon itself in the shape of the column. We ensured that the diameter of the mesh column was approximately half an inch wider than the diameter of the column. This was so that when inserted into the column it would stay snug and not fall out.

1.3 Verification

The verification of the design includes two main parameters for the finished product: 1. The distillate is a high-proof alcohol that is at least 40% ABV and 2. The distillate has a low concentration of volatile sulfur compounds. Combined, these two parameters ensure that the still design creates a quality product.

For all distillation testing throughout the project, the same procedure was followed for creating every batch of fermented wort. The procedure is as follows:

1. Obtain 8.5# of dehydrated rye, 6# of dehydrated corn, and 2# of dehydrated 6-row barley.
2. Put the grain into a closed 5-gallon bucket and shake the bucket vigorously to evenly mix the grain.
3. Heat 3 gallons of water in a large pot to 160 degrees Fahrenheit and turn off the heat source.
4. Immediately transfer the grain from the bucket to a brew bag and place in the heated water.
5. Using a spoon, mix up the grain to get rid of any dry clumps of grain (dough balls) to ensure even extraction.
6. Stir the mixture every 10 minutes and continuously monitor the temperature to maintain 155 degrees Fahrenheit, turning the heat source on and off as necessary to maintain the set temperature.
7. After 45 minutes of brewing, turn off the heat source and remove the brew bag from the wort. Holding the brew bag above the pot, let the bag drain for 3 minutes.
8. Transfer the hot wort from the pot to a sanitized fermentation bucket and let cool to 90 degrees Fahrenheit.

9. Using a sanitized cup, scoop out approximately 2 cups of wort and pour into a sanitized hydrometer. Use the hydrometer to measure the starting gravity (S.G.) of the wort.
10. Add one packet of SafAle BE-256 yeast to the bucket and shake the closed bucket for 1 minute to disperse the yeast and incorporate oxygen into the wort.
11. Place the airlock in the hole on the top of the fermentation bucket and let the wort ferment for 1 week.
12. After 1 week of fermentation, measure the final gravity (F.G.) of the wort using the same method as in step 9. If the F.G. is not 1.000, let the fermentation continue for another 4 days to allow further fermentation.

Using the method outlined above, we were able to consistently achieve a fermented wort that has a starting ABV of 4.5%.

The first stage of testing for the project was to see if we could achieve the 40% ABV target for the finished product. This testing was done on a benchtop laboratory setup as seen in figure 10.

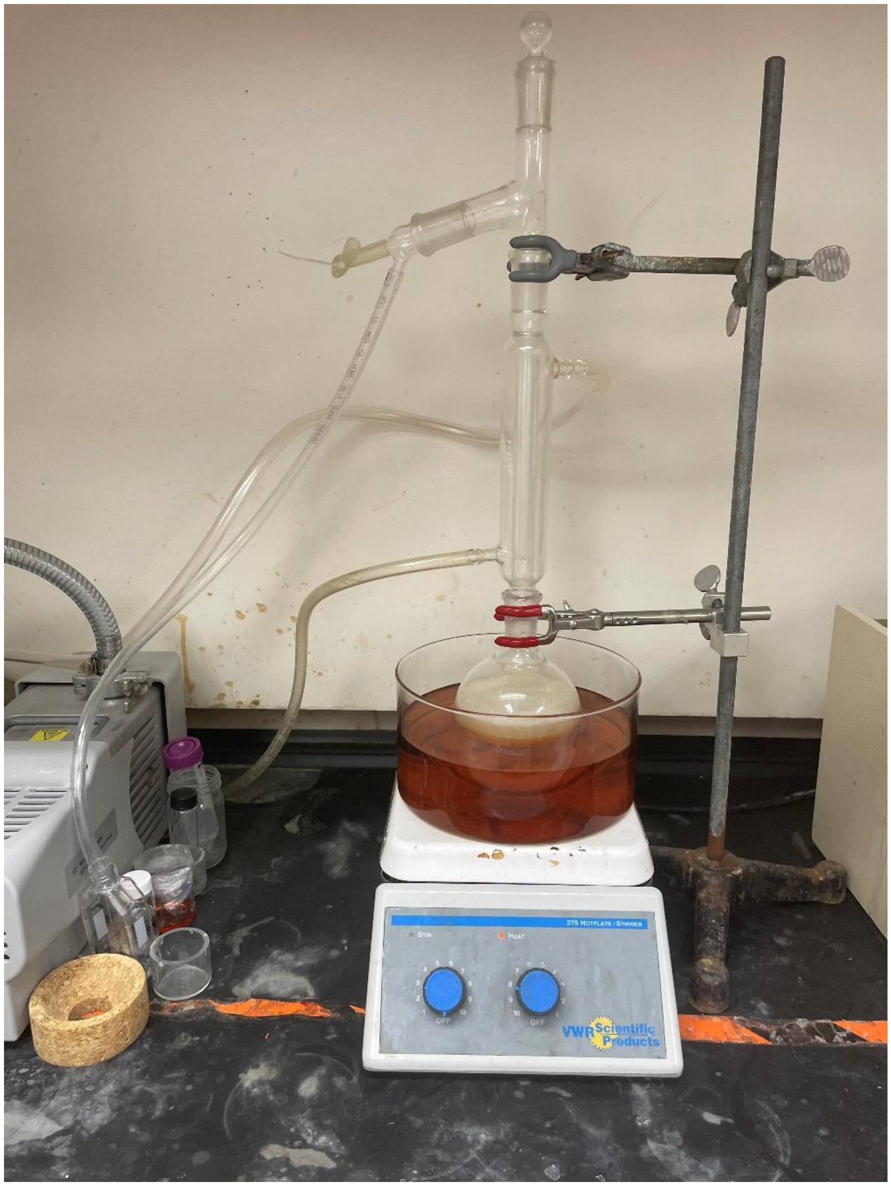

Figure 10: Setup for Benchtop Distillation in the Lab

To do this, the fermented wart was placed in a round-bottom flask that was submerged in an oil bath on a hot plate, a simple distillation was carried out. During the distillation, the temperature of the round-bottom flask was monitored, and the distillation ended when the temperature reached 99 degrees Fahrenheit. At this point, the amount of ethanol in the distillate is considerably lower than at the start. The distillate was collected into four different "cuts", with the first cut being the first 10% of the overall mixture, and the remaining four cuts being 22.5% of the mixture each. The first cut was discarded because it contains a higher concentration of methanol (up to 10% of the first cut is methanol) which is toxic.

After the cuts were cooled down to room temperature, the density of each of the cuts was measured using a pycnometer. The measurements were plotted against the calibration curve to calculate the ABV of the solution.

Several methods can be used to test the ABV of a solution, including pycnometer density measurements, surface tension testing, viscosity, etc. For this project, we used pycnometer density measurements because the equipment was accessible, and the procedure was already known by our team. Since the density of an ethanol + water solution changes based on the concentration of ethanol, if the density of the sample of an unknown ABV is plotted against a calibration curve, the ABV can be easily determined. To create the calibration curve, the densities samples of known concentrations of ethanol were measured using a pycnometer and plotted on a curve to create a calibration curve. The calibration curve can be seen below in figure 11.

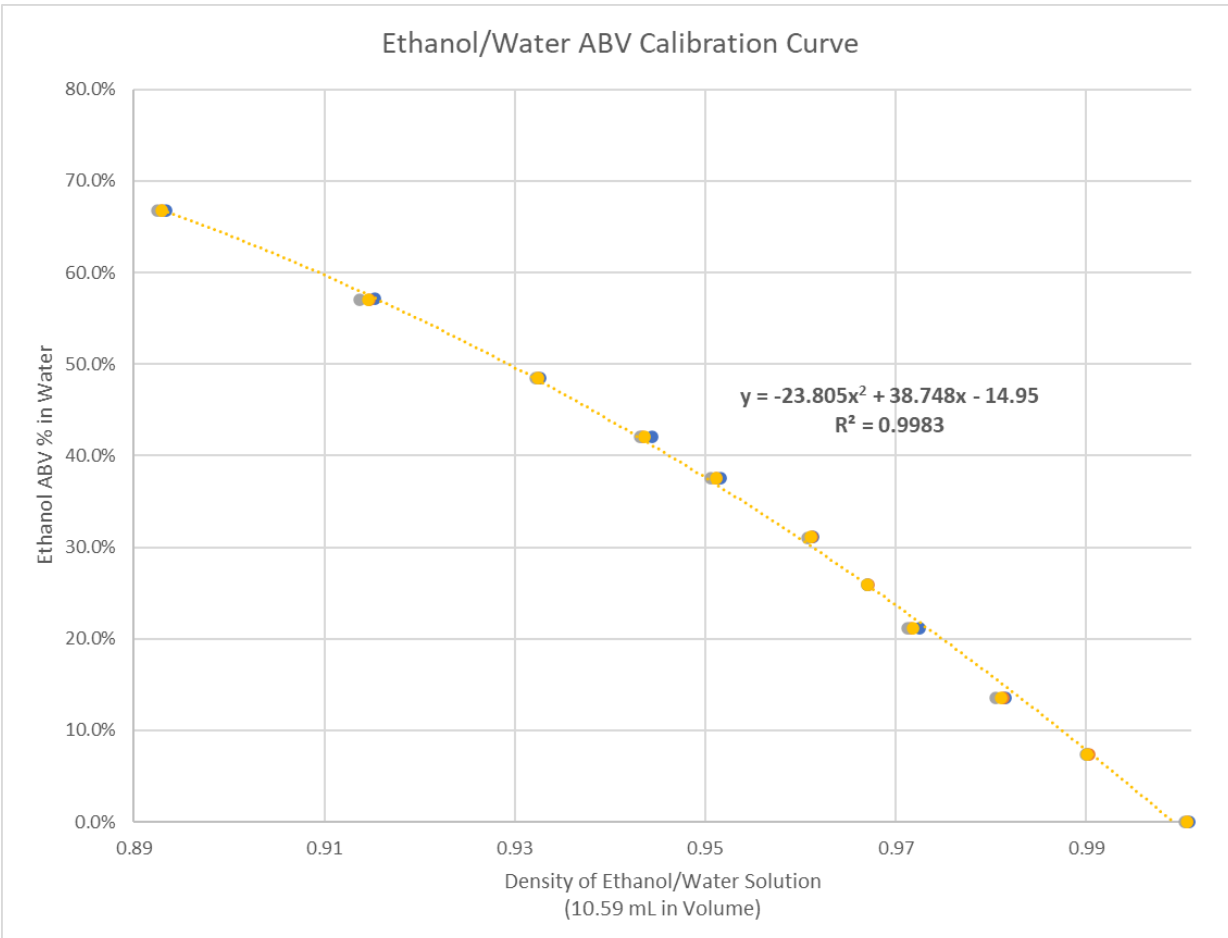

Figure 11: Calibration Curve for Determining Ethanol Concentration

As seen in figure 11, as the concentration of ethanol in solution increases, the density decreases. This is due to the density of ethanol being lower than water. To test the ABV of our unknown samples, we first determined the mass of solution within a pycnometer of constant volume and then plotted it on the calibration curve. The results from that testing can be seen below in table 12.

	Pycnometer Mass 1 (g)	Pycnometer ABV 1	Pycnometer Mass 2 (g)	Pycnometer ABV 2
Copper Cut 2	9.9372	44.50%	9.9254	45.16%
Copper Cut 3	10.0663	36.91%	10.057	37.48%
Copper Cut 4	10.2346	25.96%	10.2286	26.37%
Copper Cut 5	10.3651	16.64%	10.3615	16.90%
Steel Cut 2	9.8895	47.13%	9.8844	47.40%
Steel Cut 3	10.1856	29.27%	10.1751	29.97%
Steel Cut 4	10.2985	21.48%	10.2916	21.97%
Steel Cut 5	10.4005	13.98%	10.3973	14.22%
Steel w/ Copper Packing Cut 2	9.9948	41.20%	9.9867	41.68%
Steel w/ Copper Packing Cut 3	10.1437	32.02%	10.137	32.46%
Steel w/ Copper Packing Cut 4	10.308	20.80%	10.3016	21.26%
Steel w/ Copper Packing Cut 5	10.4131	13.02%	10.4108	13.20%

Table 12: Ethanol Concentration Results of Unknown Samples from the Copper Still, Steel Still, and Steel Still with Copper Packing.

The distillation performed is a simple batch distillation, which is where the vapors are taken directly from the still to the condenser in a batch process. Our batch process is a batch rectifier, which consists of a reboiler, column, and condenser. The reboiler is filled with the wort and heated to boiling temperature to vaporize it. We chose a simple batch process for our distillation because the column has a basic design (which cuts down on manufacturing costs), and ethanol and water have a wide enough gap in boiling points to allow easy separation for our 40% ABV target.

For all three still setups (copper, steel, and steel with copper packing), the first cut was discarded because it contains a relatively high concentration of methanol compared to the rest of the cuts. Methanol comprises approximately 1% of the total distillate and is almost entirely removed in the first cut. The boiling points of methanol, ethanol, and water are 64.7 Celsius, 78 Celsius, and 100 Celsius respectively. The vapor pressure of methanol, ethanol, and water at STP are 13.02 kPa, 5.95 kPa, and 3.17 kPa, so the relative volatility of methanol/ethanol is 2.19, and ethanol/water is 1.87. Since the relative volatility of methanol is so high and the boiling point so low, this supports that it will be removed first during distillation.

For all the still setups, the second cut was above the threshold of 40% ABV, which is a success regarding the target alcohol concentration. It should be noted that after the second cut the ethanol concentration drops, so the remaining cuts will have to go through a repeat distillation in order to achieve the 40% ABV mark.

To test for the sulfur content of the distilled samples, a group of 7 people were given the samples to smell for sulfur odors in a blind smell test. The scale that was given to them is in figure 13, as well as the results from the smell test.

Scale				
1	2	3	4	5
Very Sulfury, eggy, garlic smell	Prominent sulfur odor that can be easily detected	Moderate sulfur smell, detectable garlic/eggy odor	Barely detectable sulfur odor with mainly corn and ethanol smell	No sulfur odor detected, only corn and ethanol sweet smell

Participant Responses			
Participant	Copper Still	Steel	Steel w/ Copper Packing
1	4	4	4
2	4	4	5
3	5	4	3
4	5	4	5
5	5	3	4
6	5	4	5
7	4	5	4
Average	4.57	4.00	4.29

Figure 13: Scale and Results from Sulfur Testing

The results from the smell test show that the copper still had the least amount of sulfur odors, while the steel still had the most. The results from the testing also show that there isn't much difference between each of the stills; the range of the averages of all the stills is only 0.57. Repeat testing is recommended because we were limited in how many people we could get to participate in the smell test, and they were not trained beforehand

1.4 Costs

Steel Still Costs					Copper Still Costs			
Item	Amount	Cost/Item	Total Item Cost		Item	Amount	Cost/Item	Total Item Cost
3/8" ID Type L Coil	1	21.8	21.8		3/8" ID Type L Coil	1	21.8	21.8
1/2" Copper Pipe	1	11.74	11.74		1/2" Copper Pipe	1	11.74	11.74
2" Tri-Clamp and Gaskets	1	27.99	27.99		2" Tri-Clamp and Gaskets	1	27.99	27.99
40 degree elbow	1	13.59	13.59		40 degree elbow	1	13.59	13.59
Threaded Brass Coupling	2	4.98	9.96		Threaded Brass Coupling	2	4.98	9.96
Thermocouples	1	39.38	39.38		Thermocouples	1	39.38	39.38
Male compression connector	2	2.68	5.36		Male compression connector	2	2.68	5.36
Steel cooking pot 10 qt w/ lid	1	12.74	12.74		Steel cooking pot 10 qt w/ lid	1	591	591
3/8" 45 degree copper elbow fitting	1	4.95	4.95		3/8" 45 degree copper elbow fitting	1	4.95	4.95
1/2" x 1/4" compression stop valve	1	7.76	7.76		1/2" x 1/4" compression stop valve	1	7.76	7.76
Steel cooking pot 8qt w/ lid	1	8.94	8.94		Steel cooking pot 8qt w/ lid	1	8.94	8.94
1/2" copper reducer coupling	1	2.34	2.34		1/2" copper reducer coupling	1	2.34	2.34
2" copper reducer coupling	1	8.44	8.44		2" copper reducer coupling	1	8.44	8.44
1.5" copper tri-clamp compatable	1	27	27		1.5" copper tri-clamp compatable	1	27	27
2" pipe	1	47.58	47.58		2" pipe	1	43	43
2" od 24" tube stainless	1	36.99	36.99		2" od 24" tube stainless	1	36.99	36.99
2" tri-clamp compression fittings	1	23.99	23.99		2" tri-clamp compression fittings	1	23.99	23.99
Copper Packing	1	19.95	19.95		Copper Packing	1	19.95	19.95
Welder Labor	1	200	200		Welder Labor	1	200	200
Total Cost			**530.5**		**Total Cost**			**1104.18**

Figure 14: Costs to Build the Steel Still and a Copper Equivalent Still

Figure 14 is a complete list of all the required materials and labor that were used to build both the copper and steel stills. Looking at the total cost for the stills, the copper still costs approximately twice as much as the steel still. Most of the cost is in the materials that are used for the reboiler (cooking pot) section of the still. If the stills were going to be scaled up to a larger size, the difference in total cost between steel and copper would likely increase due to the large difference in cost between steel and copper.

1.5 Conclusions

Overall, it was determined that there is no significant difference between a steel still, steel still with copper packing, or a copper still regarding the sulfur content of the distillate. In our testing and surveying, the ABV of the distillate was very similar between all of the stills in addition to the sulfur content.

The design of the steel still was a success. The results from our testing of the ABV and sulfur content were aligned with the testing we did on the copper still and the benchtop lab testing. All three of the stills were able to achieve over a 40% ABV solution on the second cut. Additionally, there was not a significant difference of sulfur content detected by the people who were surveyed. While we are very confident in the results from the ABV testing due to low error and low deviation in repeated tests, there still lies some uncertainty in the results from our sulfur detection testing. Originally, we were going to use gas chromatography (GC) to test for the sulfur content of our solutions. This method of testing was not feasible for two main reasons: 1. The GC machine was not properly set-up like we had planned in earlier months and would have taken too long to prepare for testing, and 2. The concentration of sulfur volatiles was in the parts-per-billion (PPB) range, which is too small for a GC machine to detect. Because we couldn't use GC, we had looked into using a sulfur detector such as potassium permanganate, but this also wasn't feasible because it wouldn't be able to detect sulfur in the PPB range. This led us to using people as our detectors because the human nose is surprisingly capable of detecting the odors from hydrogen sulfide and other volatile sulfur compounds in the PPB range. However, the subjects that were used for this testing method were not trained on sulfur detection and we had a limited number of subjects (7). If repeat testing is going to be done in the future, we would advise using trained cuppers (taste testers) and have more of them.

This project demonstrates that there is not much difference between a copper still and a steel still regarding sulfur volatiles or ABV of the distillate. Because of that, it is much more economical to use a steel still when distilling ethanol. This can significantly save costs for distilleries that are looking to buy new distillation columns since the price to build a steel still is a small fraction of the cost of an equally sized copper still.

References

[1] FDA 2022 Food Code, web page. Available at: https://www.fda.gov/media/164194/download. Accessed October 2022.

[2] North Stills: Reflux Stills, web page. Available at: https://www.northstills.com/reflux-still/. Accessed October 2022.

[3] Essential Distilling: Still Columns, web page. Available at: https://www.essentialdistilling.com/still-columns. Accessed October 2022.

Appendix A Possible Abbreviations

Unit or Term	Symbol or Abbreviation
alternating current	ac
American wire gauge	AWG
ampere	A
ampere-hour	Ah
amplitude modulation	AM
angstrom	Å
antilogarithm	antilog
atomic mass unit (unified)	u
audio frequency	AF
automatic frequency control	AFC
automatic gain control	AGC
automatic volume control	AVC
average	avg
backward-wave oscillator	BWO
bar	bar
barn	b
beat-frequency oscillator	BFO
bel	B
billion electronvolts*	BeV
binary coded decimal	BCD
bit	b
British thermal unit	Btu
byte	B
calorie	cal
candela	cd
candela per square foot	cd/ft^2
candela per square meter	cd/m^2
cathode-ray oscilloscope	CRO
cathode-ray tube	CRT
centimeter	cm
centimeter-gram-second	CGS
circular mil	cmil
continuous wave	CW
coulomb	C
cubic centimeter	cm^3
cubic foot per minute	ft^3/min
cubic meter	m^3
cubic meter per second	m^3/s
curie	Ci
cycle per second	Hz
decibel	dB
decibel referred to one milliwatt	dBm
degree Celsius	°C
degree Fahrenheit	°F
degree Kelvin**	K
degree (plane angle)	...°
degree Rankine	°R
degree (temperature interval or difference)	deg
diameter	diam
direct current	dc
double sideband	DSB
dyne	dyn
electrocardiograph	EKG
electroencephalograph	EEG
electromagnetic compatibility	EMC
electromagnetic unit	EMU

*Deprecated: use gigaelectronvolt (GeV).
**Preferably called simply *kelvin.*

Unit or Term	Symbol or Abbreviation
electromotive force	EMF
electronvolt	eV
electrostatic unit	ESU
erg	erg
extra-high voltage	EHV
extremely high frequency	EHF
extremely low frequency	ELF
farad	F
field-effect transistor	FET
foot	ft
footlambert	FL
foot per minute	ft/min
foot per second	ft/s
foot-poundal	ft-pdl
foot pound-force	ft•lbf
frequency modulation	FM
frequency-shift keying	FSK
gallon	gal
gallon per minute	gal/min
gauss	G
gigacycle per second	Gc/s
gigaelectronvolt	GeV
gigahertz	GHz
gilbert	Gb
gram	g
henry	H
hertz	Hz
high frequency	HF
high voltage	HV
horsepower	hp
hour	h
inch	in
inch per second	in/s
inductance-capacitance	LC
infrared	IR
inside diameter	ID
intermediate frequency	IF
joule	J
joule per degree	J/deg
joule per kelvin	J/K
kilobit per second	kb/s
kilobyte	kB
kilocycle per second	kHz/s
kiloelectronvolt	keV
kilogauss	kG
kilogram	kg
kilogram-force	kgf
kilohertz	kHz
kilohm	kΩ
kilojoule	kJ
kilometer	km
kilometer per hour	km/h
kilovar	kvar
kilovolt	kV
kilovoltampere	kVA
kilowatt	kW

Unit or Term	Symbol or Abbreviation
kilowatthour	kWh
lambert	L
liter	l
liter per second	l/s
logarithm	log
logarithm, natural	ln
low frequency	LF
lumen	lm
lumen per square foot	lm/ft^2
lumen per square meter	lm/m^2
lumen per watt	lm/W
lumen-second	lm•s
lux	lx
magnetohydrodynamics	MHD
magnetomotive force	MMF
maxwell	Mx
medium frequency	MF
megacycle per second	MHz/s
megaelectronvolt	MeV
megahertz	MHz
megavolt	MV
megohm	MΩ
metal-oxide semiconductor	MOS
meter	m
microampere	μA
microfarad	μF
microgram	μg
microhenry	μH
micrometer	μm
micron†	μ
microsecond	μs
microsiemens	μS
microwatt	μW
mil	mil
mile per hour	mi/h
mile (statute)	mi
milliampere	mA
milligram	mg
millihenry	mH
milliliter	ml
millimeter	mm
millimeter of mercury, conventional	mmHg
millimicron‡	nm
millisecond	ms
millisiemens	mS
millivolt	mV
milliwatt	mW
minute (plane angle)	...'
minute (time)	min
nanoampere	nA
nanofarad	nF
nanometer	nm
nanosecond	ns
nanowatt	nW
nautical mile	nmi

†The name *micrometer* (μm) is preferred.
‡The name *nanometer* is preferred.

Unit or Term	Symbol or Abbreviation
neper	Np
newton	N
newton meter	N•m
newton per square meter	N/m^2
oersted	Oe
ohm	Ω
ounce (avoirdupois)	oz
outside diameter	OD
phase modulation	PM
picoampere	pA
picofarad	pF
picosecond	ps
picowatt	pW
pound	lb
poundal	pdl
pound-force	lbf
pound-force foot	lbf-ft
pound-force per square inch	lbf/in^2
pound per square inch§	psi
power factor	PF
private branch exchange	PBX
pulse-amplitude modulation	PAM
pulse code modulation	PCM
pulse count modulation	PCM
pulse duration modulation	PDM
pulse position modulation	PPM
pulse repetition frequency	PRF
pulse-repetition rate	PRR
pulse-time modulation	PTM
pulse-width modulation	PWM
radian	rad
radio frequency	RF
radio-frequency interference	RFI
resistance-capacitance	RC
resistance-inductance-capacitance	RLC
revolution per minute	r/min
revolution per second	r/s
roentgen	R
root-mean-square	rms
second (plane angle)	..."
second (time)	s
short wave	SW
siemens	S
signal-to-noise ratio	SNR
silicon controlled rectifier	SCR
single sideband	SSB
square foot	ft^2
square inch	in^2
square meter	m^2
square yard	yd^2
standing-wave ratio	SWR
steradian	sr
superhigh frequency	SHF
television	TV
television interference	TVI

§Although the use of the abbreviation psi is common, it is not recommended. See pound-force per square inch.

Unit or Term	Symbol or Abbreviation
tesla	T
thin-film transistor	TFT
transverse electric	TE
transverse electromagnetic	TEM
transverse magnetic	TM
traveling-wave tube	TWT
ultrahigh frequency	UHF
ultraviolet	UV
vacuum-tube voltmeter	VTVM
var	var
variable-frequency oscillator	VFO
very-high frequency	VHF
very-low frequency	VLF
vestigial sideband	VSB
volt	V
voltage controlled oscillator	VCO
voltage standing-wave ratio	VSWR
voltampere	VA
volume unit	vu
watt	W
watthour	Wh
watt per steradian	W/sr
watt per steradian square meter	$W/(sr \bullet m^2)$
weber	Wb
yard	yd