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Designing a distillation process for a local brewery

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Designing a Continuous Distillation Process for a Local Brewery

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By

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Chemical, Biomolecular and Corrosion Engineering

Honors Research Project

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Executive Summary

Background

The owner of a local brewery[1] is evaluating a business expansion into distilling spirits. Since the owner did not have a background in distillation, he requested information on a continuous distillation column. He had previously received information regarding a batch still, and wanted data on a continuous column for comparison.

The distillation products for distilled spirits are split into three categories: the heads, heart, and tails. The heads and tails are biproducts and are generally not consumed. The heart is the middle product that is desired for consumption. The heads are the most volatile and will be distilled off first in a batch, or at the top of a continuous column. The heart is distilled next, or slightly lower on a continuous column. The tails are distilled last or at the bottom and usually contain mostly water.

Many different distillers have their own unique opinions on which style is better, and that is mainly rooted in which spirits they wish to distill. Continuous columns typically can reach higher alcohol concentrations than batch stills and require less labor-intensive supervision once installed. Large columns can have automated controls that generally require the least amount of operator labor. Batch columns work well on lower equipment budgets, but are more labor intensive as every action must be performed by the operator. The batch still usually produces around 40% ethanol by volume (v/v%), and preserves more flavors from the fermented mash. This paper will focus on the calculations and operations of a continuous column to assist the owner in making an informed business decision.

[1] The names of the owner and the brewery are omitted to maintain the confidentiality of the business' plans.

Results

The column designed in this paper contains eight stages. The column has a height of four feet with a six-inch diameter. The flooding of the column ranges from 20 to 55%, which is acceptable for distilling. The project's scale is 42.5 gallons per hour, which would allow the brewery to convert a 15-beer barrel (465 gallon) fermented brew tank to spirits in 11 hours. Each pilot system brew tank would create, 65 gallons of 39.8 v/v%, 81 gallons of 45 v/v%, or 87 gallons 55 v/v% for feed concentration 7.5 v/v%, 10 v/v%, and 12 v/v% ethanol feed.

This project used heat integration in the heart condensation process. In heat integration, the energy of one stream is transferred to the other in lieu of using a utility such as cooling water. The heat integration method eliminated the need for cooling water to condense the product (heart) by using the cold feed stream (entering at 60°F). The energy from condensing the product heated the feed stream resulting in a 170-180°F feed. Normally, preheated feeds are not beneficial to distillation because they decrease the quality of the feed and increase the condenser duty. In this case, preheated stream was acceptable because the column's condenser duty was very low due to the additional side stream for the heart.

The current design requires 3 heat exchangers: a product condenser/feed preheater (HE1), a heads condenser (T1 Condenser), and a column reboiler (T1 Reboiler). The heat exchangers' area requirements are 19.43 ft^2, 5.93 ft^2, 12.98 ft^2 for HE1, T1 Condenser, and T1 Reboiler, respectively.

Three different feeds of alcohol concentration (7.5 v/v%, 10 v/v%, and 12 v/v%) were evaluated. The feeds and impurities are based on a whiskey from Valderrama; the feed contained: 92.472 v/v%, 7.500 v/v%, 0.001 v/v%, 0.005 v/v%, 0.0083 v/v%, and 0.0142 v/v% for water, ethanol, acetaldehyde, n-propanol, iso-butanol, and isoamyl alcohol, respectively. The

12 v/v% would likely be diluted as the impurities of Isoamyl Alcohol (0.11 v/v%) exceed Food Chemicals Codex (FCC) limit of 1000μL/L for any single impurity [1].

Conclusions

Due to potentially shorter run times for distillation per volume, the continuous column could be used to produce a larger volume of ethanol if desired. The continuous column has the ability to produce higher alcohol concentrations if the brewery owner desires high proof spirits. The brewery should be cautious with using higher ethanol feeds, as they may need diluted to follow FCC rulings. The brewery owner will have to select the market for his product and choose how he elects to allocate resources.

Broader Implications

This project has enhanced my knowledge and proficiency regarding process design. I have learned to efficiently use CHEMCAD's programming, as well as understand heuristics of project design to create feasible designs. Regarding the more technical implications, this project presents background information on continuous columns. This paper gives information for a potential small continuous column without building and testing a physical model.

Recommendations for Future Research

This work could be continued by using CHEMCAD to compare and verify a specific operation from a real distillation column. The CHEMCAD model could be utilized for a scaled-up process with doubling or perhaps tripling the volumetric flow. Additional feed compositions could be tested to see their effects on the column's performance.

Introduction

Project Justification

A local brewery is planning to begin production of spirits. The owner requested information comparing a continuous distillation column to a batch still. Since he had previously acquired information regarding a batch still, this report focuses on the continuous column and its performance.

Background

The distillation process plays a vital role in converting fermented grains or fruits into high quality spirits. Arguments for either batch or continuous (column) distillation vary depending on which spirits are being produced. Batch distillation usually preserves more of the off flavors treasured in the whiskeys, rums, and other darker spirits. Batch stills are often used because they can achieve approximately 40% alcohol in a single pass [2], which is a typical alcohol concentration for most spirits. A spirit's proof is twice the alcohol volume percent. While batch stills are typically less expensive to purchase than continuous columns, they are more labor intensive to operate. Distillation columns, such as packed or tray, can create a cleaner tasting spirit and produce 10-20 v/v% higher alcohol per distillation run.

During distillation, the ethanol feed is distilled into three parts: the head, heart, and tail. The head of the spirits "also known as congeners, are organic species from chemical families including acetals, [other] alcohols, carbonyl compounds, carboxylic acids, esters, furans, norisoprenoids, sulphur compounds and terpenes" [3]. The components in the heads create many off flavors and can be hazardous if consumed. The heart is the main ethanol portion that is slightly heavier than the head, but lighter than the tails. The heart is the consumable product from alcohol spirits. The heavier component, the tails, (sometimes referred to the bottoms on a column) contain mostly water [4]. The tails are not consumed as they usually only contain a few volume percent alcohol [2]. The heads and the tails contain most of the feed components that result in off flavors and unpleasant tastes [2].

The separation of the three parts is different for the two distillation processes under consideration. For instance, in batch distillation, “it is possible to establish the correct time at which undesirable congeners are produced in higher concentrations so such cuts can be disposed and not mixed with the rest of the product. In the case of continuous distillation simulation packages can be tuned so certain requirements of the final product can be achieved” [4]. The column distillation requires close attention to flow rates, temperatures, and pressure within the column to ensure that the head, heart and tail are flowing into their appropriate outlet streams. Turton [7] is frequently referenced for column heuristics.

Experimental Methods

This project's simulation was developed using CHEMCAD (V. 7.1.8.13642, Chemstations™, Houston, TX) with the design constraints based on expected needs of the brewery. The preliminary design was derived from textbooks such as *Unit Operations of Chemical Engineering* [5] and *Distillation Operation* [6]. McCabe, et al. [5] offered extensive detail on distillation theory and calculations, including but not limited to heat transfer, packing material, column heights, number of stages and efficiency. Kister, et al. [6] provided details on troubleshooting and determining efficiency relationships based on actual column performance.

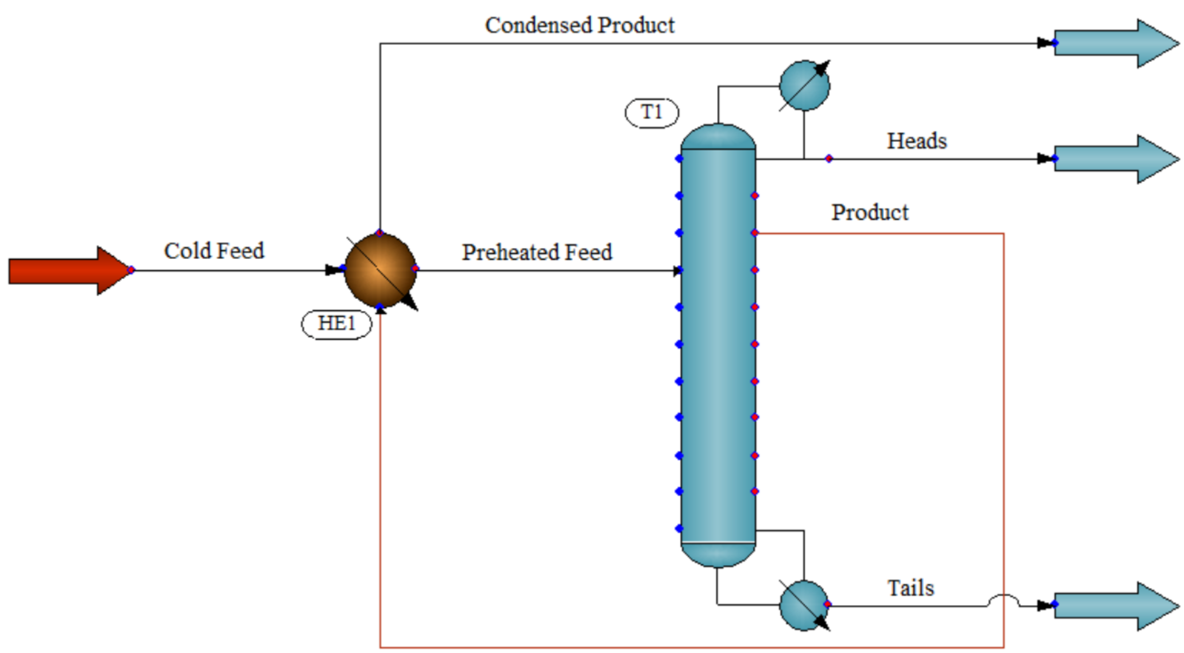

Figure 1. CHEMCAD distillation column schematic for project design. It includes stream names, and equipment. The distillation column is numbered T1. Three heat exchangers are shown: the reflux condenser (T1 Condenser), the column reboiler (T1 Reboiler) the feed preheater/product condenser (HE1).

In alignment with previous research from Valderrama, et al. [4], the thermodynamic model was set to Non-Random Two-Liquid (NRTL). The Simultaneous Correction Distillation

System (SCDS) distillation column with a reboiler and condenser was used for the simulations. Since ethanol and water have an azeotropic behavior, the CHEMCAD Shortcut Column was not used for the determination of initial operational parameters and hardware requirements, such as number of trays.

Instead, trial-and-error methodology was utilized to identify working physical and operational parameters for the column (e.g., number of stages and fractional recoveries of the parts). Originally, a five stage column was designed, but its temperature profile was highly irregular with poor distillation results. The stages were increased until a working column was created. The heart exited on stage three to reach adequate separation of volitiles. The column had to be fed at a lower stage than product extraction stage; thus, stage four was chosen for feed. Once a working column was created, sensitivity studies were performed to optimize the number of stages. Sensitivity studies vary one parameter to see the effect on another parameter. For instance, the feed temperature could be varied to determine its effect on the reflux ratio or duties of the condenser or reboiler. The sensitivity studies can be found in Appendix F. The optimum number of stages was seven for the 7.5 v/v% ethanol feed, and eight for the 10 v/v% and 12 v/v% ethanol feeds. Since the differences between stages seven and eight were minimal for the 7.5 v/v% column, an eight stage design was chosen.

The final column model (T1 in *Figure 1*) had eight stages (seven sieve trays, a reboiler, and a total condenser). A sieve-type tray was selected based on its versatility noted by McCabe, et al. [5]. The simulated column had six-inch diameter trays, and a height of four feet. These sizes were based on CHEMCAD's suggestions for column flooding and heuristics of using a height to diameter ratio of less than 20:1 [5]. The column had three output streams as shown in *Figure 1*. Under specifications, the product stream exited on stage three. To achieve convergence, the Vapor Mass/Feed Mass setting was varied to 0.13 for the ethanol feed of 7.5 v/v% and 0.16 for the ethanol feeds of 10 v/v% and 12 v/v%. The condenser mode was set to "distillate total fractional recovery" of 0.015 and the reboiler was set to "bottom component mole fraction" (water) of 0.999. This set of parameters resulted in roughly 1% of the total feed exiting via the heads, a water purity of 99.9% exiting the bottom, and a yield of 13-16% of the total feed as product.

The feed stage was set at stage four; this was determined by viewing the column's temperature profile (Appendix *Figures B1-B3*) and determining which stage would result in the least disruption to the temperature profile. Using the heuristics outlined in Turton, et al. (Chapter 11, Table 11.14) tray efficiency ranged from 60%-90%. The CHEMCAD model was scaled to a 70% tray efficiency for every tray. Heat integration was used to eliminate the need of cooling water to condense the heart. The feed preheater/product condenser heat exchanger (HE1 in *Figure 1*) was used to preheat the cold feed prior to entering the column while condensing and cooling the product stream.

Sizing of the column and heat exchangers was performed using the CHEMCAD's "Shell & Tube" model. Condenser and kettle reboiler was used for the column's condenser and kettle reboiler, respectively. The utility specifications based on the brewery's current resources. The brewery has a saturated steam system (vapor fraction of 1) available at 15 psig. The steam is returned as a saturated liquid at 15 psig. Cooling water is available at 70°F, and is returned at 90°F. The recycled cooling water and 99.9% pure water from the bottoms could be collected and used elsewhere.

The owner of the brewery stated that the feed into the column would likely have 10 v/v% ethanol, but the brewery may use higher or lower depending on the strain of yeast used;

therefore, a few trials were performed at 7.5 v/v%, 10 v/v%, and 12 v/v% ethanol to gather information on the column's performance given a few different feed concentrations. The concentrations and estimated impurities of the feed were based on the study of Valderrama, et al. [4] and a scaling factor. For the 10% and 12% feed concentration, the ethanol and impurities were multiplied by 1.33 and 1.6, respectively. The remaining fraction for water was determined by the following equation:

$$water\% = 100\% - ethanol\% - impurities\%$$

Results

The results are summarized in this section, including the flow results at their respective feed concentrations, the equipment summary for a 10 v/v% ethanol feed, and the pipe sizing.

Product Results

The simulation was performed for each of the ethanol feeds of 7.5 v/v%, 10 v/v%, and 12 v/v%. Table 1 focuses on the stream information resulting from those simulations.

Table 1: Summary of the compositions of the feed stream and resulting exiting streams from the three scenarios. The 7.5 v/v%, 10 v/v%, and 12 v/v% ethanol feeds are listed in orange, blue, and green, respectively. The product is the heart; the heads and tails are byproducts. The complete stream tables with their temperatures and energies can be found in the appendices.

	7.5 v/v% Ethanol Feed				10 v/v% Ethanol Feed				12 v/v% Ethanol Feed			
Stream Name	Feed	Head	Tails	Heart	Feed	Head	Tails	Heart	Feed	Head	Tails	Heart
Total Flow (gph liquid)	42.592	1.061	35.596	5.935	42.592	1.151	34.264	7.399	42.592	1.200	33.903	7.488
Ethanol (liq v/v%)	7.499	67.560	0.320	39.820	10.000	69.567	0.320	45.553	12.000	74.113	0.320	54.923
Water (liq v/v%)	92.472	32.212	99.680	60.017	89.962	30.210	99.680	54.262	87.954	25.689	99.680	44.850
N-Propanol (liq v/v%)	0.005	0.048	0.000	0.027	0.007	0.048	0.000	0.031	0.008	0.045	0.000	0.038
IsoButanol (liq v/v%)	0.008	0.064	0.000	0.047	0.011	0.065	0.000	0.053	0.013	0.059	0.000	0.066
Isoamyl Alcohol (liq v/v%)	0.014	0.099	0.000	0.084	0.019	0.096	0.000	0.095	0.023	0.075	0.000	0.117
Acetaldehyde (liq v/v%)	0.001	0.016	0.000	0.004	0.001	0.016	0.000	0.005	0.002	0.020	0.000	0.006

Equipment Results

The following equipment results are for the four heat exchangers and distillation column at a 10 v/v% ethanol feed. The sizing for heat exchangers at the other concentration can be found in the appendices. Piping information is consistent for the different feed concentrations and is listed below.

Heat Exchangers

The feed preheater/product condenser is HE1. The product cooler is HE2. The column's condenser and reboiler are T1 Condenser and T1 Reboiler, respectively. Table 2 provides information regarding heat exchanger equipment.

Table 2: The heat transfer area, the actual physically required area, and the heat duty of the heat exchanger for a 10% ethanol feed. Additional heat exchanger specifications for the 10% ethanol feed can be found in the Appendix C. Heat duty is in Mega (one million) British Thermal Units (MMBTU). The equipment information regarding the other feed concentration can be found in Appendices D and E.

Equipment	feed preheater/product condenser (HE 1)	Column Condenser (T1 Condenser)	Column Reboiler (T1 Reboiler)
Effective Transfer Area (ft^2)	19.43	5.93	12.98
Required Area (ft^2)	15.45	3.75	8.07
Heat Duty (MMBTU/hr)	0.00385	0.0266	0.0759

Piping and Flow Results

The pipe sizing did not vary for the different feed concentrations. Schedule 40S piping with appropriate sizing for single phases was used. Table 3 contains information with pipe sizing, as well as the fluid flow and dynamics in the pipes.

Table 3: The specifications for the piping as determined using CHEMCAD. The liquid only analyses for the pipes are highlighted in blue; the vapor only stream is highlighted in yellow. The calculated piping size, as well as the information on the next larger sizing is indicated. The pipe outer diameters are in National Pipe Size (NPS) threads.

Stream Name		Flow Regime	Pipe ID (in)	Nominal Dia (in)	Pressure Drop (psi/100ft)	Velocity (ft/sec)	Reynolds Number	Friction Factor	Pressure Drop (psi/100ft)
Cold Feed	Calculated Size	Single Phase	0.364	0.250	4.498	2.192	5242	0.043	4.498
	Next Larger Size	Single Phase	0.493	0.375	1.028	1.195	3870	0.045	1.028
Preheated Feed	Calculated Size	Single Phase	0.364	0.250	3.816	2.279	18561	0.035	3.816
	Next Larger Size	Single Phase	0.493	0.375	0.826	1.242	13704	0.035	0.826
Heads	Calculated Size	Single Phase	0.269	0.125	0.018	0.054	264	0.242	0.018
	Next Larger Size	Single Phase	0.364	0.250	0.005	0.030	195	0.328	0.005
Tails	Calculated Size	Single Phase	0.269	0.125	11.903	3.356	23760	0.037	11.903
	Next Larger Size	Single Phase	0.364	0.250	2.527	1.833	17559	0.035	2.527
Product	Calculated Size	Wave	1.049	1.000	0.285	51.435	29696	0.028	0.472
	Next Larger Size	Stratified	1.380	1.250	0.024	29.720	22573	0.028	0.121
Condensed Product	Calculated Size	Single Phase	0.269	0.125	0.778	0.777	3219	0.050	0.778
	Next Larger Size	Single Phase	0.364	0.250	0.148	0.424	2379	0.043	0.148

Column Operating Parameters

The reflux ratio is the ratio of the condensed head vapor returned to the column to that removed as the heads. The reflux ratio governs the flow rate of distillate collected and the purity of the product. An infinite reflux ratio means that all of the distillate is returned to the column (no flow) and would yield the highest product purity. To increase the amount of distillate collected, the reflux ratio should be decreased. Thus, the choice of the reflux ratio is a balance between product flow rate and product purity. The columns reflux ratios were varied for each model: for 7.5 v/v% 10 v/v%, and 12 v/v%, the reflux ratios were 7.5, 8.7, and 7.2, respectively.

Discussion/Analysis

Product Discussion

In reference to Table 1, the 12% ethanol feed yields the most product and the highest exiting concentration. This is logical as the highest volume of ethanol is entering the column. Increasing the alcohol feed concentration is not the only way to create a higher proof product; the brewery owner could reduce the fraction taken off in the heart to increase the alcohol content of the heart (the 7.5 v/v% had the lowest head fraction cut to create a higher concentrated spirit). If the brewery would like to create a higher proof, they can increase the feed's alcohol volume concentration by three to five percent or lower the column's heart cut. Note that according to the FCC, the total allowable impurities for any distilled alcoholic beverage is 1000μL/L for a single impurity, and 5000μL/L for total impurities [1]. The 12% ethanol feed's product would have to be diluted to reduce the isoamyl content.

The distillation results differed from original expectations based on boiling points (Table G1, Appendix G). Since isobutanol and isoamyl alcohol have higher boiling points than water, the general assumption is that those compounds would exit with the tails. The results showed otherwise; this is likely due to their low solubility in water or hydrogen bonding interactions. Unfortunately, those alcohols can cause health concerns if consumed in larger quantities. Isoamyl alcohol is also a fusel alcohol and can yield some unwanted harsh flavors. Importantly, the acetaldehyde followed expectations based on boiling point. Due to it low boiling point, it is mostly contained in the head, which is crucial because acetaldehyde can be a significant health hazard.

The brewery's pilot system operates on an 11-beer barrel (465 gallon) batch system; the distillation of one pilot system brew tank will take approximately 11 hours at the current flow rate. Noting the flooding percent of the column in the appendices *Figures C1, D1,* and *E1*, the column could be operated at a higher flow rate with larger heat exchangers if the brewery wished to do so. Since flow rate is highly important to the column performance, flow sensors and controls should be installed to monitor and correct the column's throughput. These sensors should be installed in the input flow stream, as well as the three exit streams.

Equipment Discussion

Heat Exchangers Discussion

The process design requires three heat exchangers. The design would require three heat exchangers regardless of heat integration because the product needs to be condensed before storage. Using heat integration in HE1 (*Figure 1*) eliminated utility costs by reducing the amount of cooling water for the product stream without sacrificing column performance. Unlike other distillation systems, the preheated feed reduced the reboiler's requirement. The condenser's utility requirement increased slightly with the heated feed, but it was not significant to warrant a design change. Heat integration is usually beneficial in the operational long run because of the operational utility cost reduction. Although the heat integration worked well for this design, one should be cautious that the preheated feed temperature does not exceed the boiling point of the mixture (around 190F); this would result in a vapor feed and poor distillation performance.

Piping and Flow Discussion

The CHEMCAD simulation results (shown in Table 3) show that the majority of the pipes are similar in size ranging from ¼ inch to ½ inch NPS. The only pipe that is not within the ¼ to ½ range is the one with product exiting the column; it is larger because it is in vapor phase and has a pipe diameter over 1-inch NPS. With the exception of the head and condensed product, the fluid flow is in the turbulent range (Reynolds number greater than 3500).

Conclusions

This CHEMCAD simulation yields initial design and operational information for the brewery owner to assist in choosing between batch or continuous column spirit distillation.

Broader Implications of project

This project has enhanced my knowledge and proficiency regarding process design. The research project process taught me how to apply software to solve real world problems. I have learned how to efficiently use CHEMCAD's programming to build and size columns, heat exchangers, and piping. The project cemented the heuristics portion of project design and my ability to look at a design and determine if it will be heuristically feasible.

Regarding the more technical implications, this project presents background information on continuous columns which will hopefully entice people to study distillation and the parameters that can be changed in CHEMCAD to produce realistic models. This paper presents information for a potential small continuous column without building and testing a physical model.

Recommendations for Future Research

This work could be continued by calibrating a CHEMCAD model to compare and verify the feed concentration data from a real distillation column. The CHEMCAD model could be utilized for a scaled-up process with doubling or perhaps tripling the volumetric flow. Additional feed compositions could be tested to see their effects on the column's performance.

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Appendices

Appendix A: Stream Information for General Operation

For the following tables, the *Cold Feed* is the feed from the fermentation tank. The *Preheated Feed* is the feed stream exiting HE 1. The *Head* is the distillate exiting the top of the column. The *Tails* are the bottoms exiting the bottom of the column. The *Tails* will be transferred into the hot water tank for later use. The *Product* is the uncondensed product exiting the column's stage two. The *Condensed Product* is the product exiting HE1. The pressure is in pounds per square inch atmospheric (PISA); the enthalpy is in Mega British Thermal Units per hour (MBTU/hr); total flow rate is in liquid gallons per hour (gph liquid).

Table A1. The complete stream information for the 7.5% ethanol feed simulation.

	7.5% ethanol					
Stream Name	Cold Feed	Preheated Feed	Head	Tails	Product	Condensed Product
Temp (F)	60	155.011	177.251	211.447	202.291	140
Pressure PSIA	14.7	14.7	14.7	14.7	14.7	14.7
Vapor Fraction	0	0	0	0	0.8648376	0
Enthalpy (MBTU/hr)	-2.3019	-2.2695	-0.0312	-1.9810	-0.2085	-0.2410
Total Flow (gph liquid)	42.5922	42.5922	1.0608	35.5961	5.9353	5.9353
Ethanol (v/v%)	7.4994	7.4994	67.5601	0.3203	39.8199	39.8199
Water (v/v%)	92.4722	92.4722	32.2118	99.6795	60.0172	60.0172
N-Propanol (v/v%)	0.0050	0.0050	0.0481	0.0000	0.0272	0.0272
IsoButanol (v/v%)	0.0083	0.0083	0.0643	0.0001	0.0473	0.0473
Isoamyl Alcohol (v/v%)	0.0142	0.0142	0.0993	0.0000	0.0841	0.0841
Acetaldehyde (v/v%)	0.0010	0.0010	0.0164	0.0000	0.0042	0.0042

Table A2. The complete stream information for the 10% ethanol trial

	10% ethanol					
Stream Name	Cold Feed	Preheated Feed	Head	Tails	Product	Condensed Product
Temp (F)	60	184.459	176.917	211.447	200.612	170
Pressure PSIA	14.7	14.7	14.7	14.7	14.7	14.7
Vapor Fraction	0	0	0	0	0.9086224	0
Enthalpy (MBTU/hr)	-2.2712	-2.2289	-0.0330	-1.9068	-0.2437	-0.2822
Total Flow (gph liquid)	42.5922	42.5922	1.1514	34.2636	7.3994	55.9997
Ethanol (v/v%)	10.0000	10.0000	69.5665	0.3204	45.5533	45.5533
Water (v/v%)	89.9620	89.9620	30.2096	99.6795	54.2622	54.2622
N-Propanol (v/v%)	0.0067	0.0067	0.0476	0.0000	0.0311	0.0311
IsoButanol (v/v%)	0.0111	0.0111	0.0646	0.0001	0.0535	0.0535
Isoamyl Alcohol (v/v%)	0.0189	0.0189	0.0959	0.0000	0.0946	0.0946
Acetaldehyde (v/v%)	0.0013	0.0013	0.0157	0.0000	0.0053	0.0053

Table A3. The complete stream information for the 12% ethanol simulation.

Table A3	12% Ethanol					
Stream Name	Cold Feed	Preheated Feed	Head	Tails	Product	Condensed Product
Temp (F)	60	176.539	176.132	211.447	195.653	160
Pressure PSIA	14.7	14.7	14.7	14.7	14.7	14.7
Vapor Fraction	0	0	0	0	0.8647502	0
Enthalpy (MBTU/hr)	-2.2254	-2.1864	-0.0322	-1.8868	-0.2245	-0.2583
Total Flow (gph liquid)	42.5922	42.5922	1.2003	33.9034	7.4885	7.4885
Ethanol (v/v%)	12.0000	12.0000	74.1128	0.3204	54.9227	54.9227
Water (v/v%)	87.9544	87.9544	25.6887	99.6795	44.8503	44.8503
N-Propanol (v/v%)	0.0080	0.0080	0.0448	0.0000	0.0383	0.0383
IsoButanol (v/v%)	0.0133	0.0133	0.0588	0.0001	0.0656	0.0656
Isoamyl Alcohol (v/v%)	0.0227	0.0227	0.0752	0.0000	0.1172	0.1172
Acetaldehyde (v/v%)	0.0016	0.0016	0.0197	0.0000	0.0059	0.0059

Appendix B: Column Operation

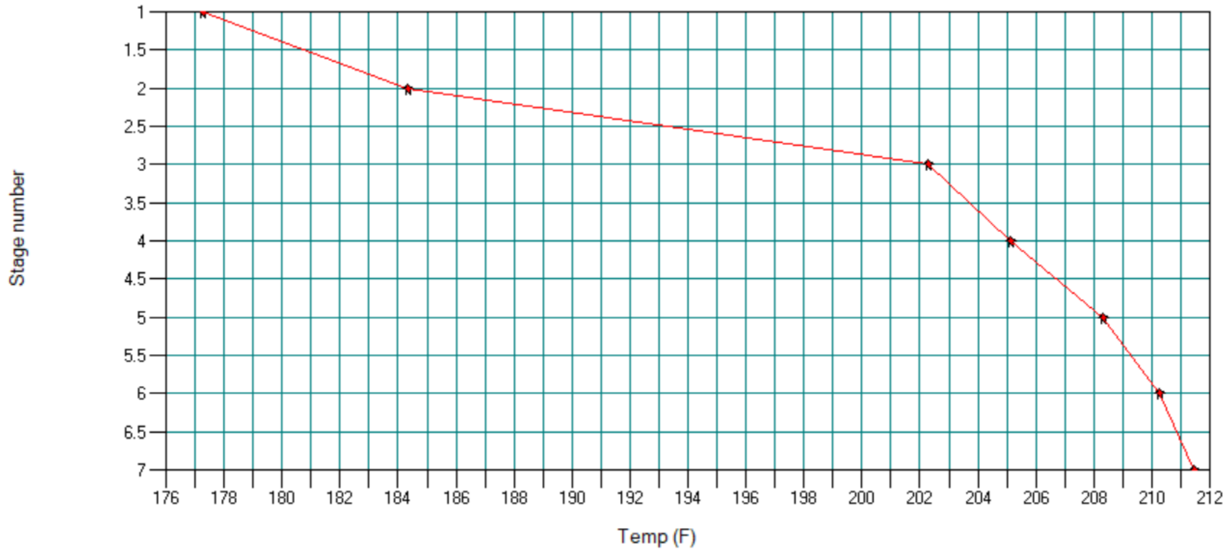

Figure B1: The column temperature profile for the 7.5% ethanol simulation. The curve is overall smooth. Stage 1 to Stage 3 have a larger temperature differential, but this may be due to the take off of the product (heart) on Stage 3, and the remaining head is volatile with a lower boiling point.

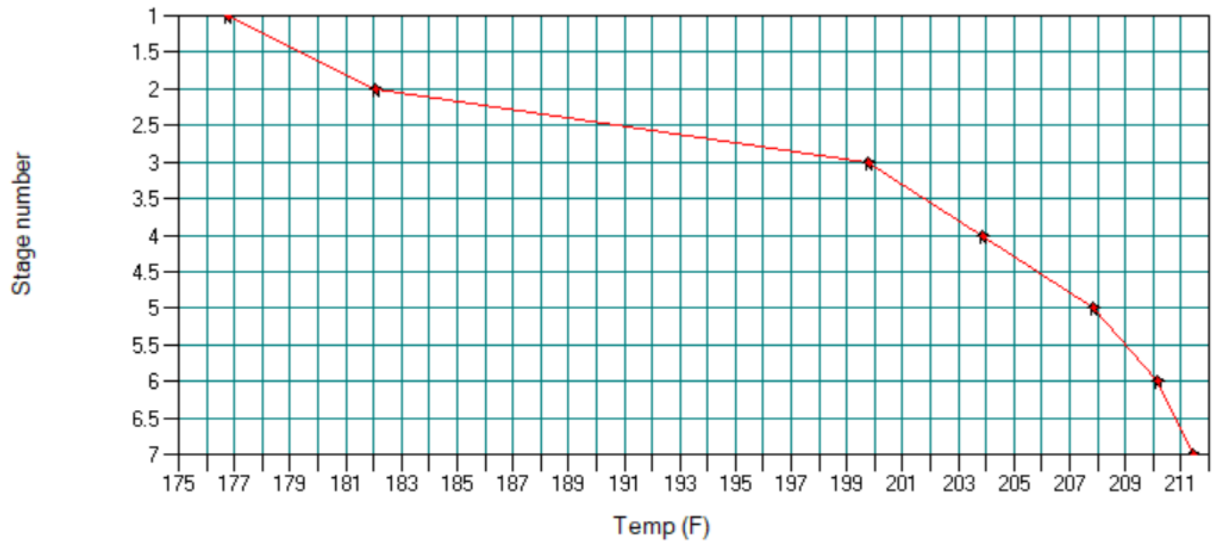

Figure B2: The column temperature profile for a 10 v/v% ethanol feed. Note that temperature curve still has a large range in temperature from Stage 1 to Stage 3 similar to *Figure B1*. The feed stage, Stage 4, has no disruption, thus it is the optimal feed stage.

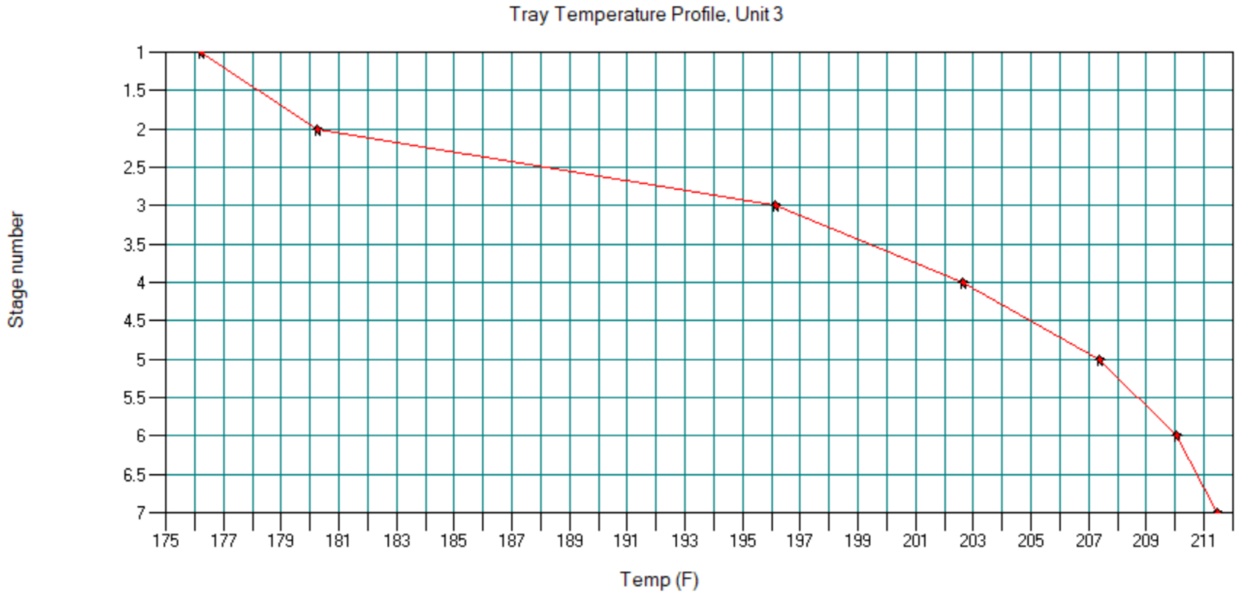

Figure B3: The column thermal profile for 12 v/v% ethanol feed. This column profile is the smoothest of the three feed concentration simulations. No disturbance occurs at the feed stage, indicating the feed stage is located for optimal operation.

Appendix C: Heat Exchanger and Column Information for 10 v/v% Ethanol Feed

NOTE: The heat exchangers (HE1, Column Reboiler, and Column Condenser) follow same naming and location as discussed earlier in the paper (Experimental Methods, Results, and Appendix A).

Table C1: The column specifications on mass flow through the column, as well as column dimensions. The tray spacing is approximately six inches, which means the overall column would be four foot tall. The diameter is six inches, which means the height to diameter ratio would be 10:1, which is well within Heuristics outlines in Turton [7]. The overall Pressure drop is 0.428 psi.

Tray	Vapor (lb/h)	Liquid (lb/h)	Space (in)	Number of Passes	Diameter (ft)	% flood	PresDrop (psi)
2	35.73	27.49	6	1	0.5	18.26	0.0584
3	87.34	23.1	6	1	0.5	40.37	0.0584
4	87.5	373.26	6	1	0.5	49.2	0.0619
5	83.08	368.84	6	1	0.5	47.94	0.0622
6	80.37	366.13	6	1	0.5	47.19	0.0625
7	78.87	364.63	6	1	0.5	46.78	0.0626
8	78.87	285.76	6	1	0.5	45.3	0.0621

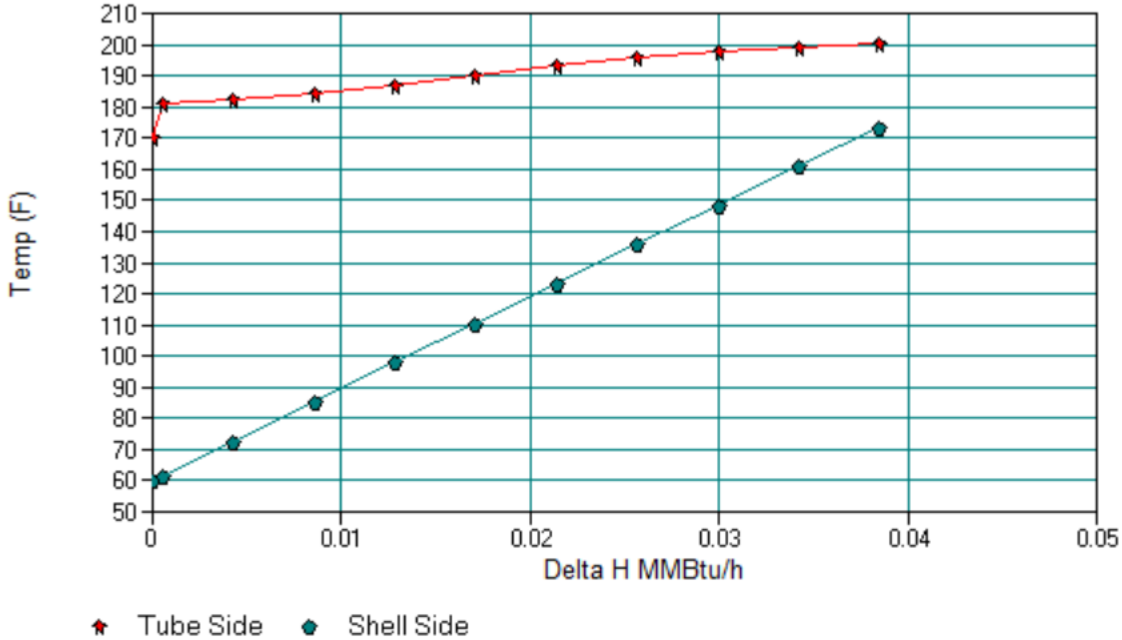

Figure C1: Shows the HE1's heat curve. This heat exchanger uses the product exiting the column to preheat the feed stream. The heat curve follows the general heuristics outlined in Turton [7].

Table C2: Outline of the stream temperatures, compositions, flow rates, and energies flowing through HE1. The preheated feed's exit temperature was set to 190°F, which aligns with heat exchanger heuristics in Turton [7] that suggest a minimum of 10°F temperature differential. The cold feed is on the shell of the heat exchanger.

Stream Name	Cold Feed	Preheated Feed	Product	Condensed Product
Temperature F	60	173.446	200.612	170
Pressure psia	14.7	14.7	14.7	14.7
Enthalpy MMBtu/h	-2.2712	-2.2327	-0.24368	-0.28217
Vapor mole frac.	0	0	0.90862	0
Total lbmol/h	18.4618	18.4618	2.3474	2.3474
Total lb/h	350	350	55.9998	55.9998
Total std L ft3/hr	5.7235	5.7235	0.9892	0.9892
Total std V scfh	7005.87	7005.87	890.79	890.79
Flow rates in lbmol/h				
Ethanol	0.6176	0.6176	0.4862	0.4862
Water	17.8428	17.8428	1.86	1.86
N-Propanol	0.0003	0.0003	0.0003	0.0003
Isobutanol	0.0004	0.0004	0.0004	0.0004
Isoamyl Alcohol	0.0006	0.0006	0.0005	0.0005
Acetaldehyde	0.0001	0.0001	0.0001	0.0001

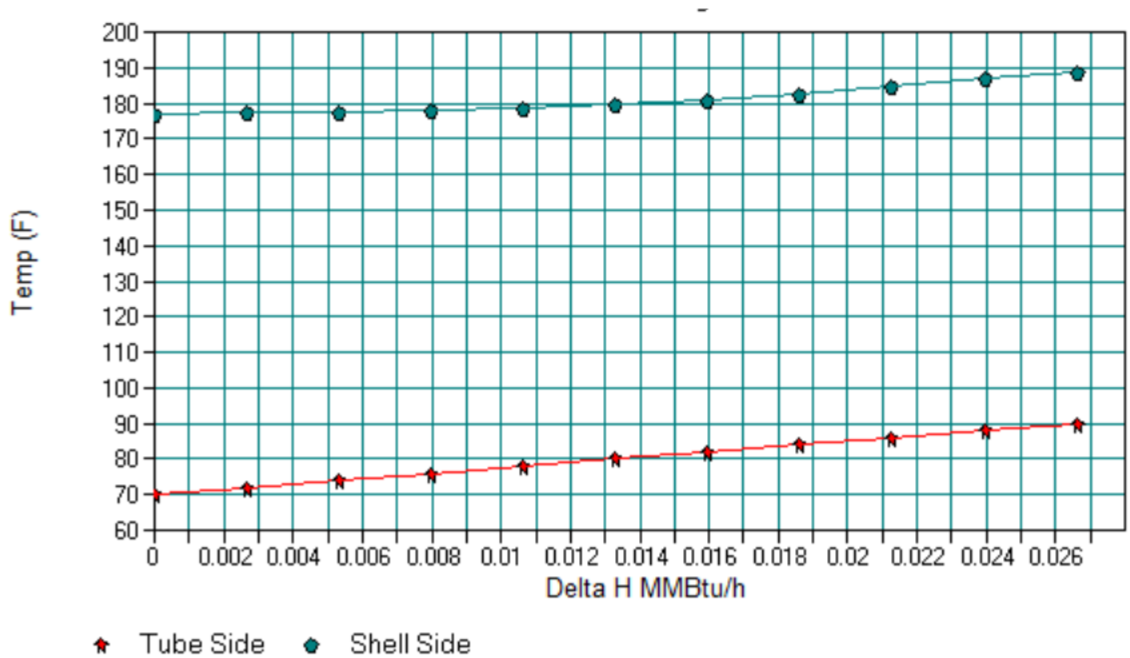

Figure C2 is the heat curve for the distillation column's condenser. The cooling water is in the tube and the head's vapor is in the shell. Similar to the other heat exchangers, it follows Turton's heuristics.

Table C3: Outlines the stream flows and compositions for the column's condenser. The utility is the brewery's cooling water. The process is the head flow through the condenser.

Stream Name	Utility IN	Utility OUT	Process in	Process out
Temperature F	70	90	183.2342	176.9169
Pressure psia	14.7	11.7	14.7	14.7
Enthalpy MMBtu/h	-9.0802	-9.0536	-0.15522	-0.18181
Vapor mole frac.	0	0	1	0
Total lbmol/h	73.851	73.851	1.5269	1.5269
Total lb/h	1330.4258	1330.4258	45.4531	45.4531
Total std L ft3/hr	21.3114	21.3114	0.8487	0.8487
Total std V scfh	28024.88	28024.88	579.43	579.43
Flow rates in lbmol/h				
Ethanol	0	0	0.6371	0.6371
Water	73.851	73.851	0.8885	0.8885
N-Propanol	0	0	0.0003	0.0003
Isobutanol	0	0	0.0004	0.0004
Isoamyl Alcohol	0	0	0.0005	0.0005
Acetaldehyde	0	0	0.0001	0.0001

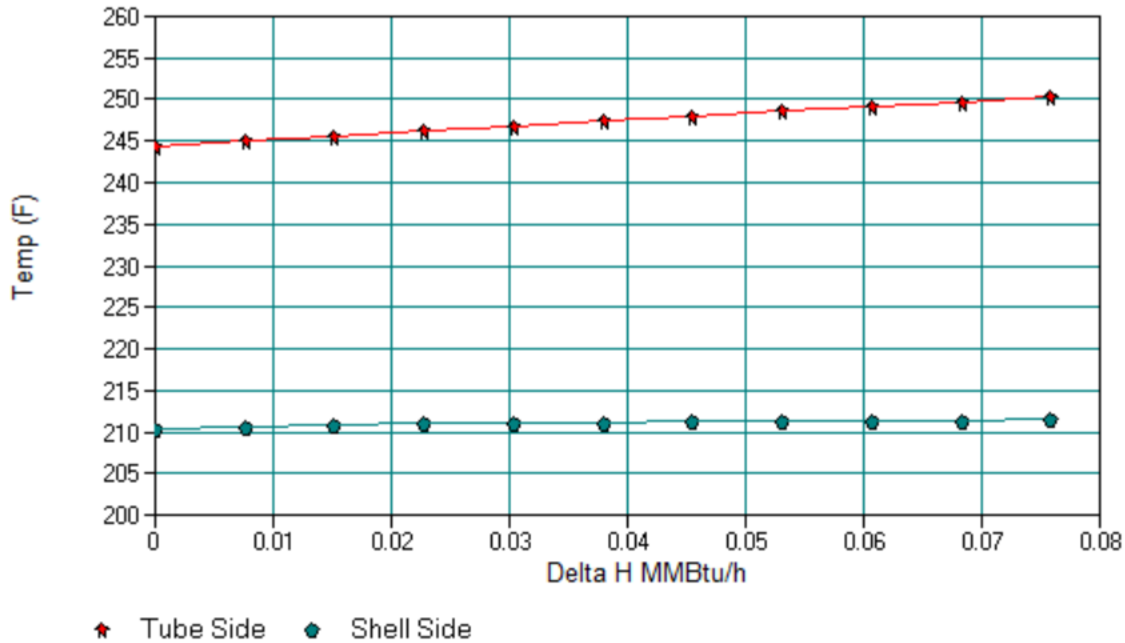

Figure C3: The column reboiler's heat curve from the distillation column. The tails are in the shell side and the steam utility is in the tube side. The curve follows general heuristics of Turton [7].

Table C4: The column reboiler's stream information. The process in/process out are the tails at the bottom of the column. The Utility is the brewery's saturated steam at 15psig.

Stream Name	Process in	Process out	Utility in	Utility out
Temperature F	210.3403	211.4467	250.3032	244.3261
Pressure psia	14.7	14.7	30	27
Enthalpy MMBtu/h	-2.425	-2.3491	-0.4522	-0.52804
Vapor mole frac.	0	0.21363	1	1.00E-05
Total lbmol/h	20.14	20.14	4.4075	4.4075
Total lb/h	364.6271	364.6271	79.4011	79.4011
Total std L ft3/hr	5.8529	5.8529	1.2719	1.2719
Total std V scfh	7642.69	7642.69	1672.55	1672.55
Flow rates in lbmol/h				
Ethanol	0.0643	0.0643	0	0
Water	20.0756	20.0756	4.4075	4.4075
N-Propanol	0	0	0	0
Isobutanol	0	0	0	0
Isoamyl Alcohol	0	0	0	0
Acetaldehyde	0	0	0	0

Table C6: Shows the detailed CHEMCAD design information regarding sizing of all the shell and tube heat exchanger used for the process in Figure 1. The units for the modeling are as follows: Temperature is in °F, Flow/Hour is in (lb/h)/h, Pressure is in psia, Enthalpy is in MMBtu, Diameter is in inches, Area is in ft^2, respectively, Length is in feet, Velocity is in ft/second, Film is in Btu/hr-ft^2-°F, Fouling is in hr-ft^2-°F/Btu.

	HE 1	T1 Condenser	T1 Reboiler
Exchanger Class/Type	R/AEL	R/AEL	R/AKL
Shell I.D.	6	6	10
Shell in Series/Parallel	1/1	1/1	1/1
Number of Tubes	23	23	23
Tube Length	6	3	3
Tube O.D./I. D	0.75/0.62	0.75/0.62	0.75/0.62
Tube Pattern	TRI 60	TRI 60	TRI 60
Tube Pitch	0.94	0.94	0.94
Number of Tube Passes	1	1	2
Number of Baffles	151	150	6
Baffle Spacing	0.1	0.1	4.5
Baffle Cut, Diameter	15	15	35
Baffle Type	SSEG	SSEG	SSEG
Baffle Space Def.	Edge-Edge	Edge-Edge	Edge-Edge
Effective Transfer Area	19.43	5.93	12.98
Area Required	15.45	3.75	8.07
Cor LMTD	63.68	100.86	35.83
U (Calc/Service)	39.11/31.11	70.25/44.48	262.22/163.03
SS Film Coeff	61.28	291.02	932.4
TW Resist	0.000203	0.000201	0.000206
TS Film Coeff	176.92	144.21	3712.4
TS Vel	0.07	0.12	0.22

Appendix D: Heat Exchanger and Column Information for 7.5 v/v% Ethanol Feed

This section follows section C in terminology and order. The data is now adapted for the 7.5 v/v% ethanol feed.

Table D1: The column specifications on mass flow through the column, as well as column dimensions. The tray spacing is approximately six inches, which means the overall column would be approximately four foot tall. The diameter is six inches, which means the height to diameter ratio would be 8:1, which is well within Heuristics outlines in Turton [7]. The overall Pressure drop is 0.352 psi.

Tray	Vapor (lb/h)	Liquid (lb/h)	Space (in)	Number of Passes	Diameter (ft)	% flood	PresDrop (psi)
1	64.17	56.54	6	1	0.5	33.04	0.0493
2	49.36	41.73	6	1	0.5	25.52	0.0559
3	88.83	35.7	6	1	0.5	42.61	0.059
4	96.15	393.02	6	1	0.5	54.88	0.0632
5	92.56	389.43	6	1	0.5	53.85	0.0634
6	90.69	387.56	6	1	0.5	53.33	0.0635

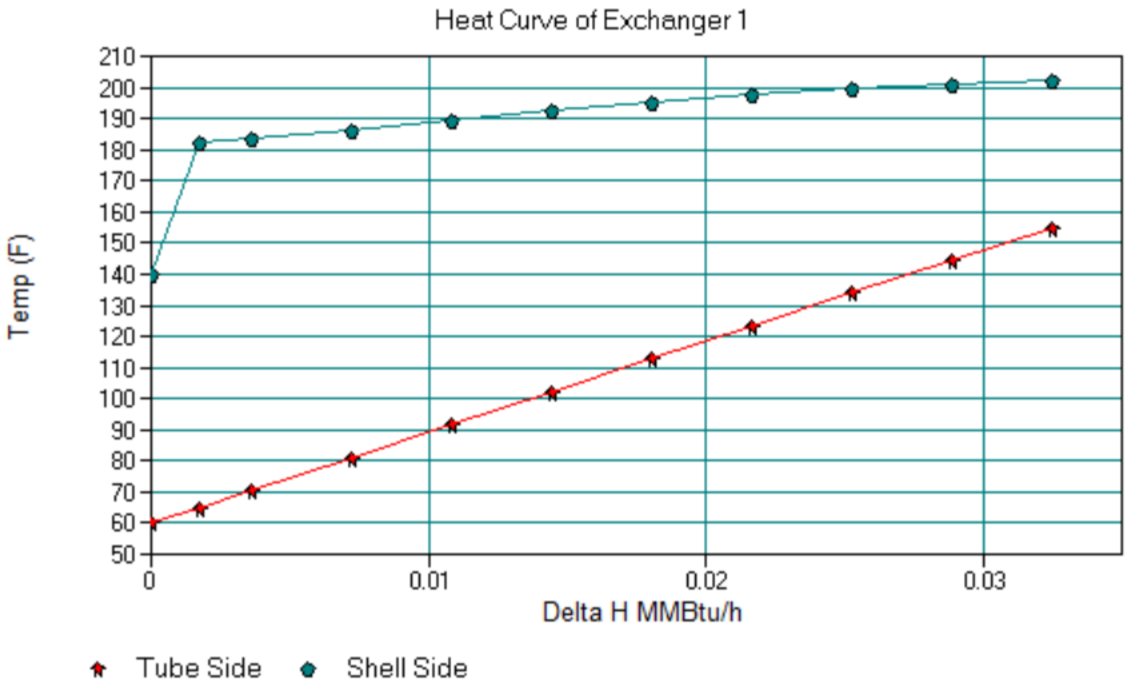

Figure D1: The heat Curve for HE 1.

Table D2: Outline of the stream temperatures, compositions, flow rates, and energies flowing through HE1. Streams titles are the same as C2.

Stream Name	Cold Feed	Product	Preheated Feed	Condensed Product
Temperature F	60	202.291	155.011	140
Pressure psia	14.7	14.7	14.7	14.7
Enthalpy MMBtu/h	-2.3019	-0.20854	-2.2695	-0.24099
Vapor mole frac.	0	0.86484	0	0
Total lbmol/h	18.7073	1.992	18.7073	1.992
Total lb/h	350	45.4999	350	45.4999
Total std L ft3/hr	5.6937	0.7934	5.6937	0.7934
Total std V scfh	7099	755.91	7099	755.91
Flow rates in lbmol/h				
Ethanol	0.4608	0.3409	0.4608	0.3409
Water	18.2454	1.6502	18.2454	1.6502
N-Propanol	0.0002	0.0002	0.0002	0.0002
Isobutanol	0.0003	0.0003	0.0003	0.0003
Isoamyl Alcohol	0.0005	0.0004	0.0005	0.0004
Acetaldehyde	0.0001	0	0.0001	0

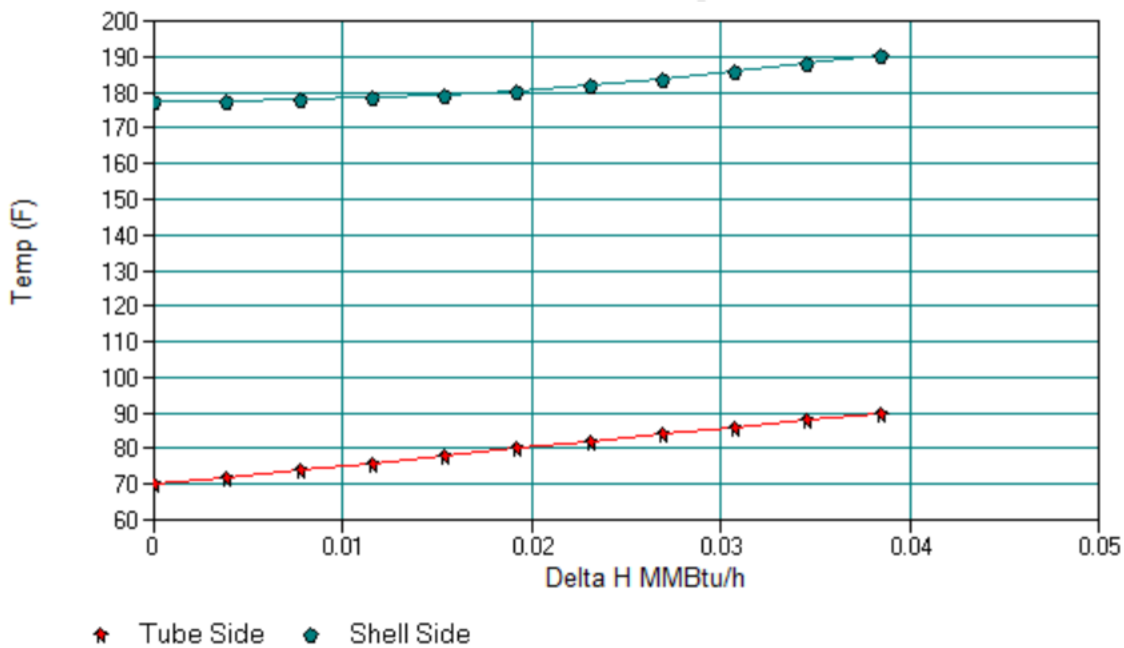

Figure D2: The column condenser's heat curve.

Table D3: The column condenser's stream information. It is the same as described in Table C3.

Stream Name	Process in	Utility in	Process out	Utility out
Temperature F	184.3233	70	177.2508	90
Pressure psia	14.7	14.7	14.7	11.7
Enthalpy MMBtu/h	-0.22402	-13.122	-0.26245	-13.084
Vapor mole frac.	1	0	0	0
Total lbmol/h	2.2024	106.7264	2.2024	106.7264
Total lb/h	64.1681	1922.6758	64.1681	1922.6758
Total std L ft3/hr	1.1925	30.7984	1.1925	30.7984
Total std V scfh	835.75	40500.38	835.75	40500.38
Flow rates in lbmol/h				
Ethanol	0.8694	0	0.8694	0
Water	1.3311	106.7264	1.3311	106.7264
N-Propanol	0.0005	0	0.0005	0
Isobutanol	0.0005	0	0.0005	0
Isoamyl Alcohol	0.0007	0	0.0007	0
Acetaldehyde	0.0002	0	0.0002	0

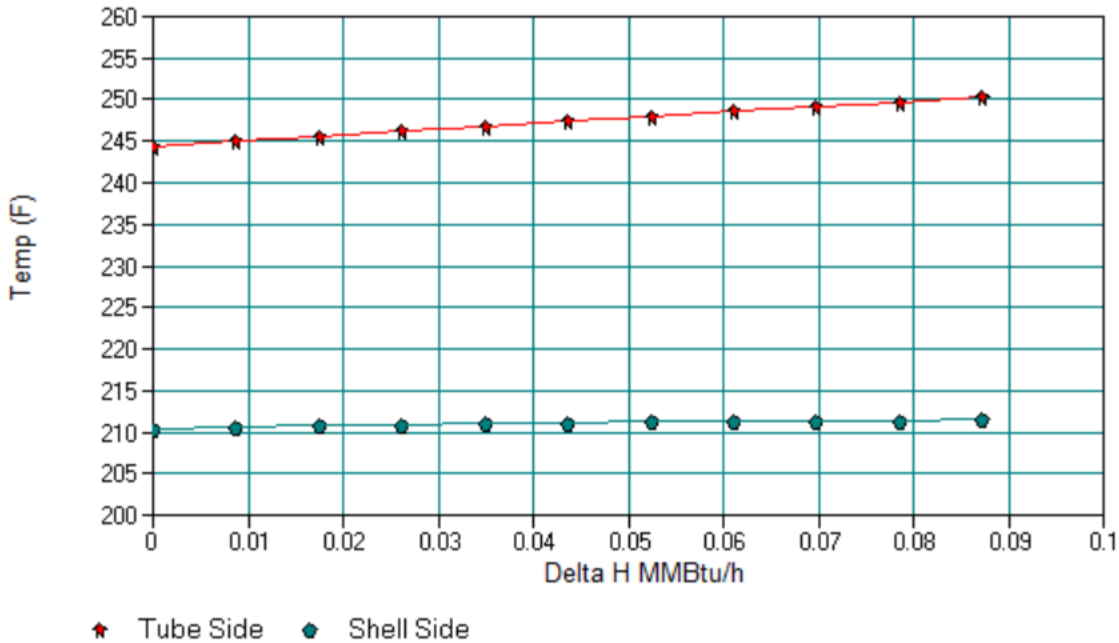

Figure D3: Column Reboiler's heat curves. The steam is on the tube side, and the tails are on the shell side.

Table D4: Column Reboiler's stream information. The information labels are the same as the ones described in Table C4.

Stream Name	Process in	Utility in	Process out	Utility out
Temperature F	210.2513	250.3032	211.4466	244.3261
Pressure psia	14.7	30	14.7	27
Enthalpy MMBtu/h	-2.5768	-0.52	-2.4896	-0.6072
Vapor mole frac.	0	1	0.23118	1.00E-05
Total lbmol/h	21.4009	5.0683	21.4009	5.0683
Total lb/h	387.5642	91.3047	387.5642	91.3047
Total std L ft3/hr	6.2218	1.4626	6.2218	1.4626
Total std V scfh	8121.18	1923.3	8121.18	1923.3
Flow rates in lbmol/h				
Ethanol	0.0722	0	0.0722	0
Water	21.3287	5.0683	21.3287	5.0683
N-Propanol	0	0	0	0
Isobutanol	0	0	0	0
Isoamyl Alcohol	0	0	0	0
Acetaldehyde	0	0	0	0

Table D5: Shows the detailed CHEMCAD design information regarding sizing of all the shell and tube heat exchanger used for the process in Figure 1. The units for the modeling are as follows: Temperature is in °F, Flow/Hour is in (lb/h)/h, Pressure is in psia, Enthalpy is in MMBtu, Diameter is in inches, Area is in ft^2, respectively, Length is in feet, Velocity is in ft/second, Film is in Btu/hr-ft^2-°F, Fouling is in hr-ft^2-°F/Btu.

	HE 1	T1 Condenser	T1 Reboiler
General Heat Exchanger Data			
Exchanger Class/Type	R/AEL	R/AEL	R/AKL
Shell I.D.	6	6	10
Shell in Series/Parallel	1/1	1/1	1/1
Number of Tubes	10	23	23
Tube Length	8	3	3
Tube O.D./I.D	0.75/0.62	0.75/0.62	0.75/0.62
Tube Pattern	TRI 60	TRI 60	TRI 60
Tube Pitch	0.94	0.94	0.94
Number of Tube Passes	4	1	2
Number of Baffles	150	124	6
Baffle Spacing	0.5	0.15	4.5
Baffle Cut, Diameter	15	15	35
Baffle Type	SSEG	SSEG	SSEG
Baffle Space Def.	Edge-Edge	Edge-Edge	Edge-Edge
Heat Transfer Data			
Effective Transfer Area	12.39	7.15	12.98
Area Required	8.84	5.35	9.27
Cor LMTD	50.49	101.78	35.83
U (Calc/Service)	72.70/51.85	70.54/52.80	262.61/187.47
SS Film Coeff	440.97	286.35	936.92
TW Resist	0.000203	0.000201	0.000206
TS Film Coeff	133.31	146.23	3719.18
TS Vel	0.31	0.18	0.26

Appendix E: Heat Exchanger and Column Information for 12 v/v% Ethanol Feed

This section follows section C in terminology and order. The data is now adapted for the 12 v/v% ethanol feed.

Table E1: The column specifications on mass flow through the column, as well as column dimensions. The tray spacing is approximately six inches, which means the overall column would be approximately four foot tall. The diameter is six inches, which means the height to diameter ratio would be 8:1, which is well within Heuristics outlines in Turton [7]. The overall Pressure drop is 0.411 psi.

Tray	Vapor (lb/h)	Liquid (lb/h)	Space (in)	Number of Passes	Diameter (ft)	% flood	PresDrop (psi)
2	65.06	56.56	6	1	0.5	33.06	0.0486
3	52.52	44.02	6	1	0.5	27.11	0.0531
4	97.98	34	6	1	0.5	45.53	0.0582
5	98.71	381.46	6	1	0.5	54.64	0.0624
6	92.73	375.48	6	1	0.5	52.87	0.0628
7	89.22	371.97	6	1	0.5	51.86	0.063
8	87.4	370.15	6	1	0.5	51.35	0.0632

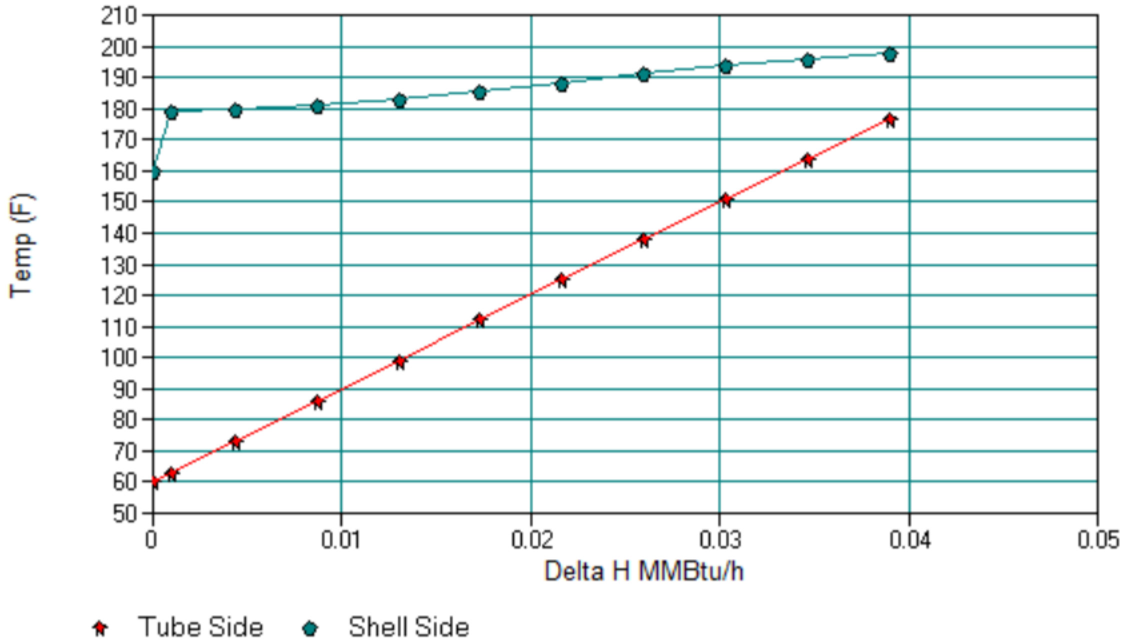

Figure E1: The heat Curve for HE 1.

Table E2: Outline of the stream temperatures, compositions, flow rates, and energies flowing through HE1. Streams titles are the same as Table C2.

Stream Name	Cold Feed	Product	Preheated Feed	Condensed Product
Temperature F	60	195.6528	176.538	160
Pressure psia	14.7	14.7	14.7	14.7
Enthalpy MMBtu/h	-2.2254	-0.21939	-2.1864	-0.25832
Vapor mole frac.	0	1	0	0
Total lbmol/h	18.093	2.1507	18.093	2.1507
Total lb/h	346.73	55.4763	346.73	55.4763
Total std L ft3/hr	5.6937	1.0011	5.6937	1.0011
Total std V scfh	6865.92	816.13	6865.92	816.13
Flow rates in lbmol/h				
Ethanol	0.7373	0.5933	0.7373	0.5933
Water	17.354	1.5559	17.354	1.5559
N-Propanol	0.0004	0.0003	0.0004	0.0003
Isobutanol	0.0005	0.0004	0.0005	0.0004
Isoamyl Alcohol	0.0008	0.0007	0.0008	0.0007
Acetaldehyde	0.0001	0.0001	0.0001	0.0001

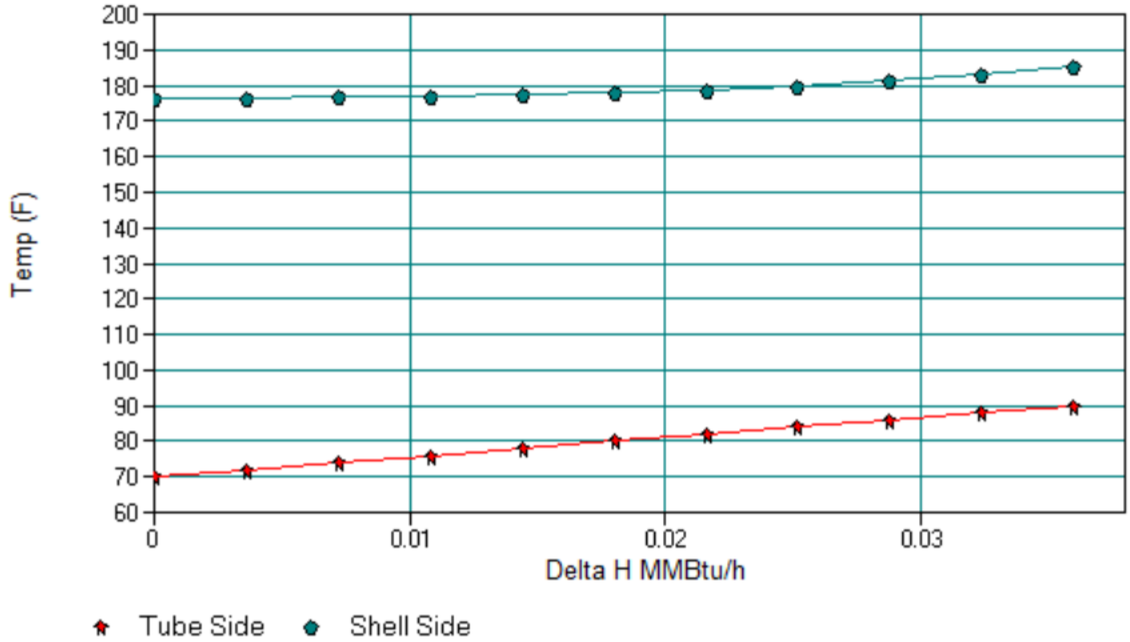

Figure E2: The column condenser's heat curve

Table E3: The column condenser's stream information. The table's is the same notation as described in Table C3.

Stream Name	Process in	Utility in	Process out	Utility out
Temperature F	180.1242	70	176.1316	90
Pressure psia	14.7	14.7	14.7	11.7
Enthalpy MMBtu/h	-0.21082	-12.287	-0.2468	-12.251
Vapor mole frac.	1	0	0	0
Total lbmol/h	2.0771	99.9339	2.0771	99.9339
Total lb/h	65.062	1800.3085	65.062	1800.3085
Total std L ft3/hr	1.228	28.8382	1.228	28.8382
Total std V scfh	788.2	37922.77	788.2	37922.77
Flow rates in lbmol/h				
Ethanol	0.9821	0	0.9821	0
Water	1.0932	99.9339	1.0932	99.9339
N-Propanol	0.0005	0	0.0005	0
Isobutanol	0.0005	0	0.0005	0
Isoamyl Alcohol	0.0005	0	0.0005	0
Acetaldehyde	0.0003	0	0.0003	0

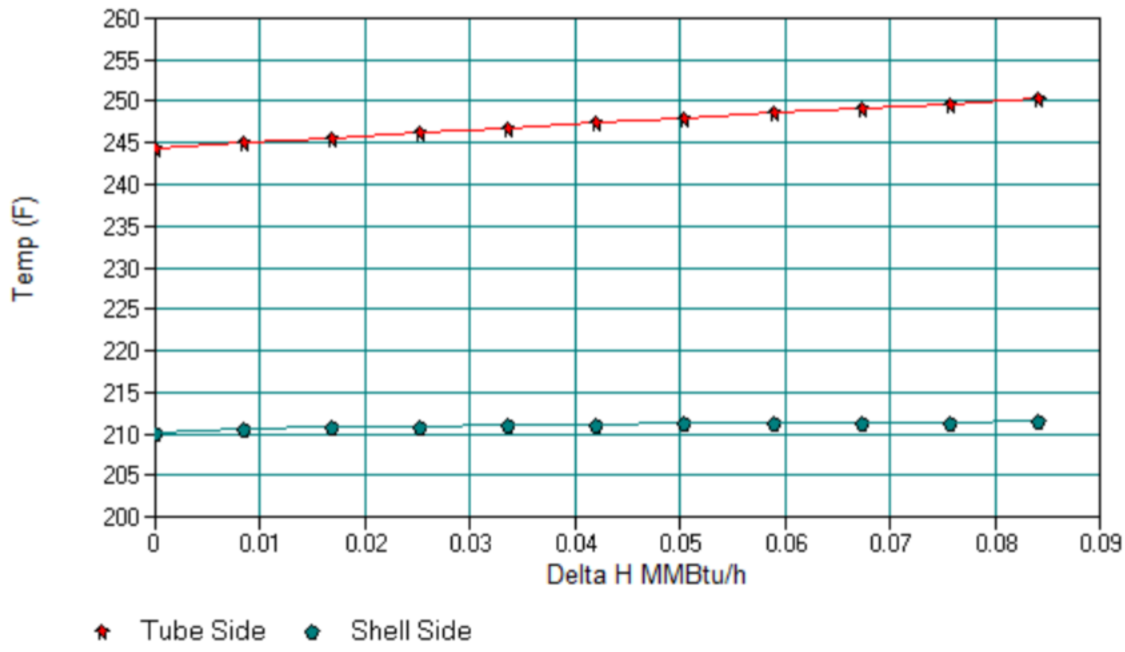

Figure E3: Column Reboiler's heat curves. The steam is on the tube side, and the tails are on the shell side.

Table E4: Column Reboiler's stream information. The information labels are the same as the ones described in Table C4.

Stream Name	Process in	Utility in	Process out	Utility out
Temperature F	210.241	250.3032	211.4467	244.3261
Pressure psia	14.7	30	14.7	27
Enthalpy MMBtu/h	-2.461	-0.50111	-2.3769	-0.58514
Vapor mole frac.	0	1	0.23327	1.00E-05
Total lbmol/h	20.4388	4.8842	20.4388	4.8842
Total lb/h	370.1534	87.988	370.1534	87.988
Total std L ft3/hr	5.9424	1.4094	5.9424	1.4094
Total std V scfh	7756.1	1853.43	7756.1	1853.43
Flow rates in lbmol/h				
Ethanol	0.0694	0	0.0694	0
Water	20.3694	4.8842	20.3694	4.8842
N-Propanol	0	0	0	0
Isobutanol	0	0	0	0
Isoamyl Alcohol	0	0	0	0
Acetaldehyde	0	0	0	0

Table E5: Shows the detailed CHEMCAD design information regarding sizing of all the shell and tube heat exchanger used for the process in Figure 1. The units for the modeling are as follows: Temperature is in °F, Flow/Hour is in (lb/h)/h, Pressure is in psia, Enthalpy is in MMBtu, Diameter is in inches, Area is in ft^2, respectively, Length is in feet, Velocity is in ft/second, Film is in Btu/hr-ft^2-°F, Fouling is in hr-ft^2-°F/Btu.

	HE 1	T1 Condenser	T1 Reboiler
General Heat Exchanger Data			
Exchanger Class/Type	R/AEL	R/AEL	R/AKL
Shell I.D.	6	6	10
Shell in Series/Parallel	1/1	1/1	1/1
Number of Tubes	23	23	23
Tube Length	8	3	3
Tube O.D./I.D	0.75/0.62	0.75/0.62	0.75/0.62
Tube Pattern	TRI 60	TRI 60	TRI 60
Tube Pitch	0.94	0.94	0.94
Number of Tube Passes	1	1	2
Number of Baffles	150	129	6
Baffle Spacing	0.18	0.14	4.5
Baffle Cut, Diameter	15	15	35
Baffle Type	SSEG	SSEG	SSEG
Baffle Space Def.	Edge-Edge	Edge-Edge	Edge-Edge
Heat Transfer Data			
Effective Transfer Area	14.96	6.92	12.98
Area Required	10.84	5.08	8.93
Cor LMTD	56.23	98.83	35.83
U (Calc/Service)	63.87/46.29	71.62/52.65	262.61/180.66
SS Film Coeff	246.47	304.06	936.98
TW Resist	0.000203	0.000201	0.000206
TS Film Coeff	131.68	146.38	3719.94
TS Vel	0.03	0.17	0.25

Appendix F: Sensitivity and Other Analysis

Appendix F includes information from the CHEMCAD sensitivity studies. Sensitivity studies vary one parameter to see the effect it has on another parameter.

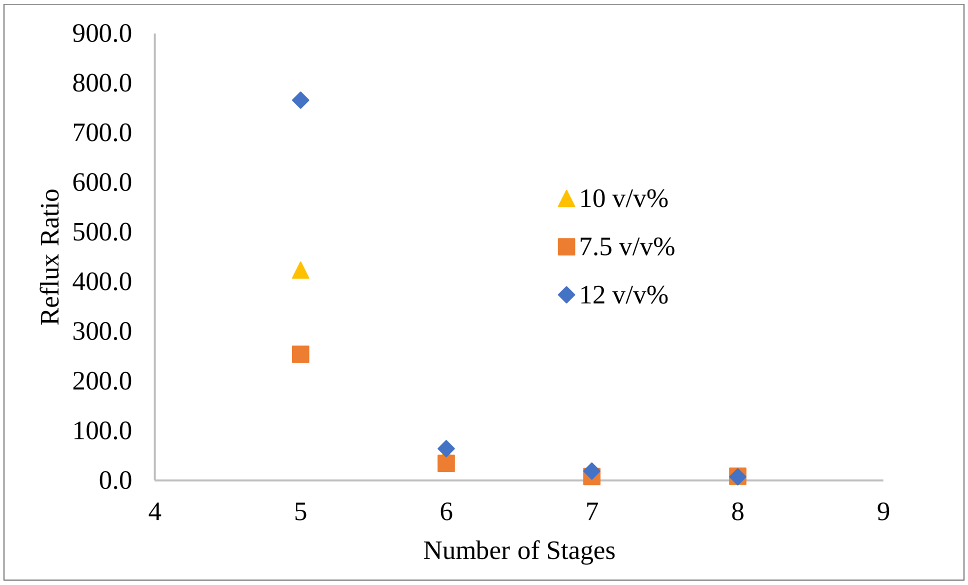

Figure F1: The plot of the CHEMCAD Sensitivity Study to determine the optimal number of stages based on the reflux ratio. Usually smaller reflux ratios are optimal, thus the 8 stages was generally best for the group.

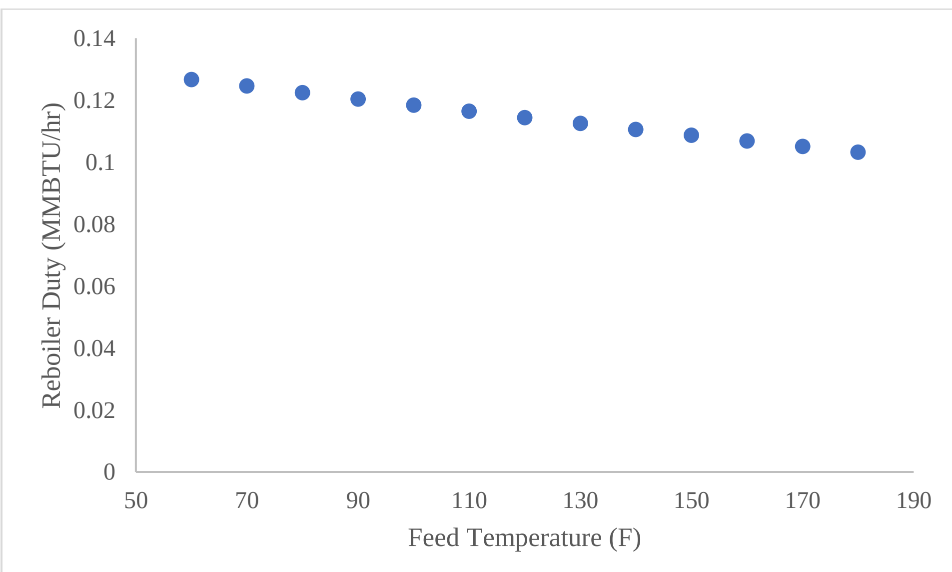

Figure F2: The plot of the sensitivity study relating the feed temperature to the reboiler duty. The increased temperature resulted in a lower reboiler duty. This is contrary to most distillation processes, where the increased feed temperature often results in a higher reboiler duty.

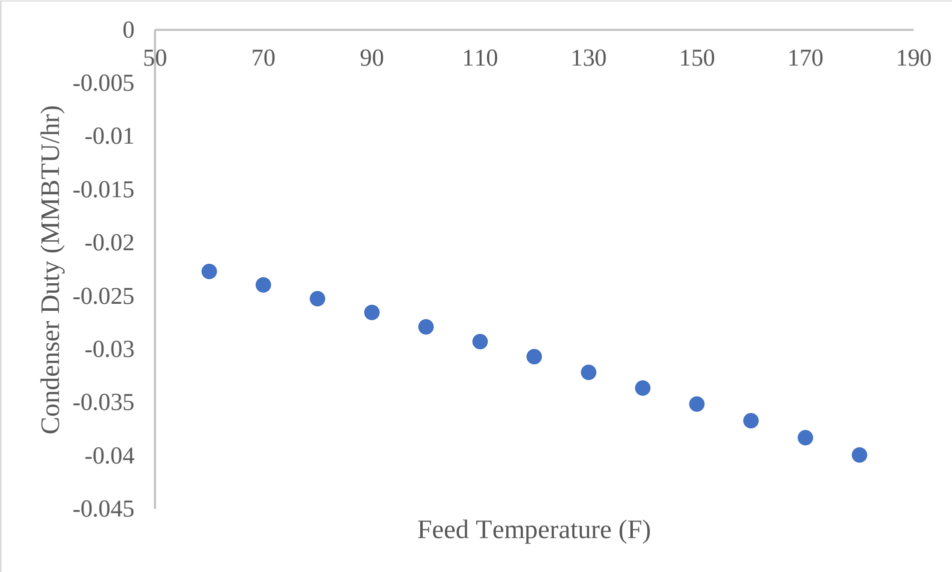

Figure F3: The plot of the sensitivity study relating the feed temperature to the condenser duty. The increased temperature did not have a significant impact on the condenser duty; the duty was overall very low; thus, the heat integration could be justified.

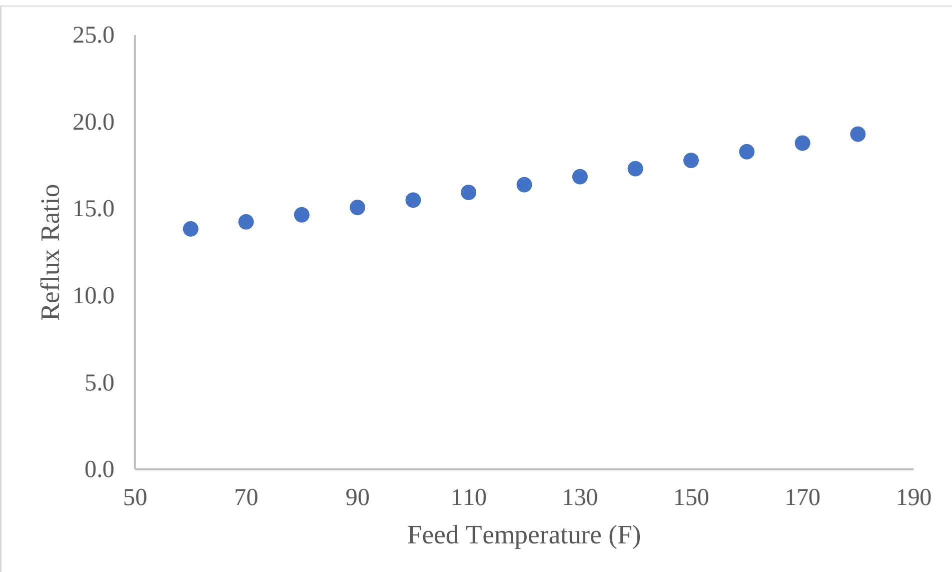

Figure F4: The CHEMCAD sensitivity study regarding feed temperature and reflux ratio. The heating of the feed resulted in a slight increase of the reflux ratio.

Appendix G: Additional Chemical Info

Table G1: The general information regarding the chemicals found in the distillation. Note that the Isobutanol, Isoamyl alcohol, and n-propanol had boiling points close to or above water. However, due to their lack of solubility in water, many of these were found in the heads or heart of the products.

	Boiling Point (F)	Toxicity	Solubilty in Water
Water	212	N/A	N/A
Ethanol	172	Mild	High
acetaldehyde	68	High	High
n-propanol	208	Mild/Medium	Low
isobutanol	226	Mild	Very Low
isoamyl alcohol	268	Mild/Medium	Very Low