BOURBON PRODUCTION ENGINEERING: TEACHING CHEMICAL ENGINEERING CONCEPTS THROUGH A COURSE ON AMERICA'S NATIVE SPIRIT

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INTRODUCTION

Bourbon is a distilled spirit produced from a grain recipe with at least 51% corn and aged in a new, charred oak barrel.[1] In Kentucky, bourbon is a key driver for the state's economy, where the industry contributes to over nine billion US dollars annually and over 20,000 jobs.[2,3] Recent higher demands for bourbon [3] and other distilled spirits have resulted in increased production scales for many distilleries,[5-9] with production levels increasing from 456,000 barrels in 1999 to current levels of 2.7 million barrels per year.[2] This scale-up has necessitated hiring across all areas, with significant opportunities for engineers to aid in process optimization and design of new production facilities. Additionally, all employees are being challenged to think about increasing product output while reducing production costs. To accommodate this need, the University of Kentucky established the James B. Beam Institute for Kentucky Spirits, a multidisciplinary research institute dedicated to exceptional teaching, research, and outreach related to bourbon and other distilled spirits.[10] Importantly, efforts across the Beam Institute have aimed to aid in workforce development, with a specific focus on increasing the diversity of workers in the bourbon production industry through training, internships, and scholarship opportunities, as well a workforce apprenticeship program for existing distillery operators. To enhance undergraduate education, a certificate in Distilled Spirits, Wine and Brewing Studies has been developed to allow students across a wide range of majors to gain expertise in a variety of topics related to the beverage alcohol industry.[11] Courses have been developed by faculty from a wide range of programs including plant and soil sciences, food sciences, hotel management and tourism, history, biosystems and agricultural engineering, chemical engineering, and writing, rhetoric and digital studies.

In chemical engineering, a course in bourbon production engineering has been developed to introduce students outside of chemical engineering to the science and engineering aspects that control the production of bourbon in a distillery setting. Similar to the course "The Design of Coffee" at UC Davis, this course aims to introduce students with no expected background in engineering to core concepts related to chemical engineering.[12] Through this paper we aim to highlight how a course on bourbon production has been used to introduce core chemical engineering concepts to a wide variety of learners from diverse disciplines (business to pharmacy) and career stages (college students to retirees).

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COURSE DETAILS

Through this course, students receive an in-depth description of the bourbon production process, with an emphasis on the connection between core chemical engineering concepts and the bourbon industry (Table 1). For instance, in learning about the bottling process, students are taught introductory concepts related to unit conversions (converting between volume percent, mole percent, and mass percent), with an emphasis on the challenges introduced to these calculations due to non-ideal mixtures.[13] Throughout this overview there is a focus on the economics of bourbon production, with students learning to estimate capital and operating costs associated with each stage of the production process. Over the second half of the course, students learn basic chemical engineering concepts (material and energy balances, thermodynamics) and their application to batch and continuous distillation processes. By the end of the course, students can apply their knowledge of equilibrium processes to understand the key decisions driving design of both continuous and batch distillation processes.

During Summer 2020, this course was developed as a fully online, six-week course offering and has been offered each of the following summers to students across the nation. The course requires prerequisites including a standard first-semester general chemistry course and an algebra course. The course does not involve any consumption or marketing of alcoholic beverages and is offered to students of all ages. To accommodate student schedules, all lecture content was offered asynchronously. Modules were released to students weekly, with concept quizzes on the lecture content due by the end of each week. In addition to asynchronous content, class discussions were held twice weekly through Zoom®. For these sessions 8-10 industry experts were invited over the length of the course to discuss different aspects of the bourbon production process. These guest speakers spanned a wide variety of distilleries and production scales, allowing students to learn about key aspects of bourbon production from experts in the field. Speakers have covered topics including distillery design and start-up, flavor chemistry, sustainability, and aging. Over the length of the course, student learning gains were assessed through two open note mid-semester exams and a cumulative final exam.

While all aspects of the bourbon production process can be linked to core chemical engineering concepts (Table 1), we will highlight two areas through this paper: mashing and continuous distillation. The following sections will focus on core concepts introduced during lectures on these aspects of bourbon production, with example problems that students were asked to solve during a mid-semester or final examination. While we will briefly overview some aspects of the bourbon production process through these representative examples, the six-week course takes a much deeper dive into the key features and complexities of America's native spirit.

MASHING

To start the bourbon production process, grains (typically corn, rye and malted barley) are ground to reduce particle size, and starches are extracted into water through a process called mashing.[14] During mashing, grains are added to the mash cooker sequentially to allow the extraction of starches from each grain at an ideal temperature.[15] The different properties of each grain require the sequential addition of grains at decreasing temperatures. Corn, which is most difficult to extract, is added first with water at temperatures exceeding 195 °F to gelatinize starches.[16] Small amounts of

TABLE 1
Overlap of Key Steps in the Bourbon Production Process With Core Concepts in Chemical Engineering — Grey Boxes Represent Concepts That Are Represented Within That Part of the Bourbon Production Process

	Grains	Mashing[1]	Fermentation	Distillation	Aging	Bottling	Stillage[2]
MEB		■	■	■	■	■	■
Heat/Mass		■	■	■			■
Reactions		■	■				
Separations				■			■
Safety	■	■		■	■		
Economics	■	■		■	■	■	■

*MEB: Material and Energy Balances; Heat/Mass: Heat and Mass Transfer.

1. Mashing is the process of cooking the grains to extract the starches into water and convert them to simple sugars through the addition of malted barley or exogenous enzymes.

2. Stillage is the non-volatile waste product consisting of spent grains and water that is removed during the distillation process.

malted barley or amylase enzymes are added to break down the starches to simple sugars and decrease the viscosity of the cook, preventing burning within the cooker due to high viscosity and poor mixing.[15] Prior to the addition of wheat and/or rye, the temperature of the cook is decreased with cooling water.[14] The temperature is further decreased as the rye and/or wheat are added to the mash cooker. It is then held at this temperature for extraction. Finally, the cook is cooled to 165 °F with cooling water, and malted barley is added and held for enzymatic conversion of the starches to simple sugars.[17] To increase extraction efficiencies from corn and wheat/rye, higher temperatures and pressures can be used, but temperatures must be decreased prior to the addition of malted barley to prevent damage to enzymes present in the grain. During the last step of mashing, extracted starches are converted to simple sugars (primarily glucose and maltose) by amylase enzymes in malted barley.[14] Further, exogenous enzymes can be added to increase conversion of starches during this process After cooking, the mash is cooled down to approximately 70 °F and added to the fermentation vessel.[18]

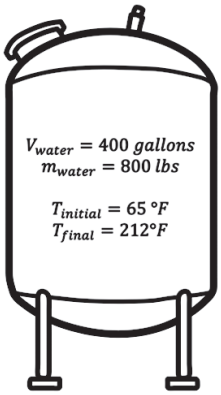
Students learn how to calculate energy associated with heat transfer by modeling the mashing process. Consequently, the students understand the operating costs associated with the mashing process through calculation of the heat required for heating the mash (Figure 1). To solve this problem, students must not only understand how to apply heat transfer equations but must also convert from gallons to pounds of water to ensure proper conversion of units. Assuming that the heat required to increase the temperature of each individual component is equal to the heat required to increase the temperature of the mixture, they can then determine the cost associated with the heating of the mash cooker.

CONTINUOUS DISTILLATION

One of the most crucial stages of bourbon production is distillation, where flavor molecules and ethanol are concentrated prior to entering the barrel. This distillation process allows students to learn about the complexities of multi-component distillation through both batch and continuous processes. While ethanol and water are the major compounds considered within these distillations, students learn about the complex mixture of trace compounds that can result in both favorable flavor profiles within the bottle (e.g., ethyl hexanoate, ethyl octanoate), as well as unfavorable flavors and mouthfeel (e.g., acetaldehyde, diacetyl (2,3-butanedione), ethyl decanoate, phenylethyl ethanol).[19] While the pot still process is traditional to bourbon production, most modern distilleries have transitioned towards continuous distillation column operation [20] to increase production capacity and decrease operating costs (Figure 2).[21]

In a continuous process, beer from the fermentation tank is sent to the beer column, which is a large distillation column that allows for separation of the ethanol and flavor compounds from the residual water and grains.[14] Steam is fed to the base of the beer column to provide energy for the separation. At the feed stage, ethanol is evaporated and travels up the column while the grains and water flow down the column. Water and grains exit the column as stillage and move downstream for further processing or removal.[22] A condenser at the top of the column, called a beer heater, is used to pre-heat the beer feed while supplying reflux back to the column.[23] A total condenser is then used to condense the vapor phase producing the low wines product.[14]

Estimate how much energy (in BTU) it takes to heat 400 gallons of water with 800 lb of corn from 65 °F to 212 °F? If needed, the heat capacity of water is 1 BTU/lb/°F, the heat capacity of all grains are 0.5 BTU/lb/°F, the latent heat of vaporization of water is 970 BTU/lb, and the density of water is 8.34 lb/gallon. If energy costs are $2.50 per million BTU, how much would it cost to run this process?



$$Q_{water} = m_{water} C_{p,water} \Delta T$$

$$Q_{water} = 400\ gal \times 8.34 \frac{lb}{gal} \times 1 \frac{BTU}{lb\ °F} \times (212\ °F - 65\ °F)$$

$$\boldsymbol{Q_{water} = 490,400\ BTU}$$

$$Q_{corn} = m_{corn} C_{p,corn} \Delta T$$

$$Q_{corn} = 800\ lb \times 0.5 \frac{BTU}{lb\ °F} \times (212\ °F - 65\ °F)$$

$$\boldsymbol{Q_{water} = 58,800\ BTU}$$

$$Q_{total} = Q_{water} + Q_{corn}$$

$$Q_{total} = 490{,}400\ BTU + 58{,}800\ BTU$$

$$\boldsymbol{Q_{total} = 549,200\ BTU}$$

$$Cost = 549{,}200\ BTU \times \frac{\$2.50}{1{,}000{,}000\ BTU}$$

$$\boldsymbol{Cost = \$1.37}$$

Figure 1*. Example heat transfer problem and solution for non-engineering students based on the bourbon mashing process.*

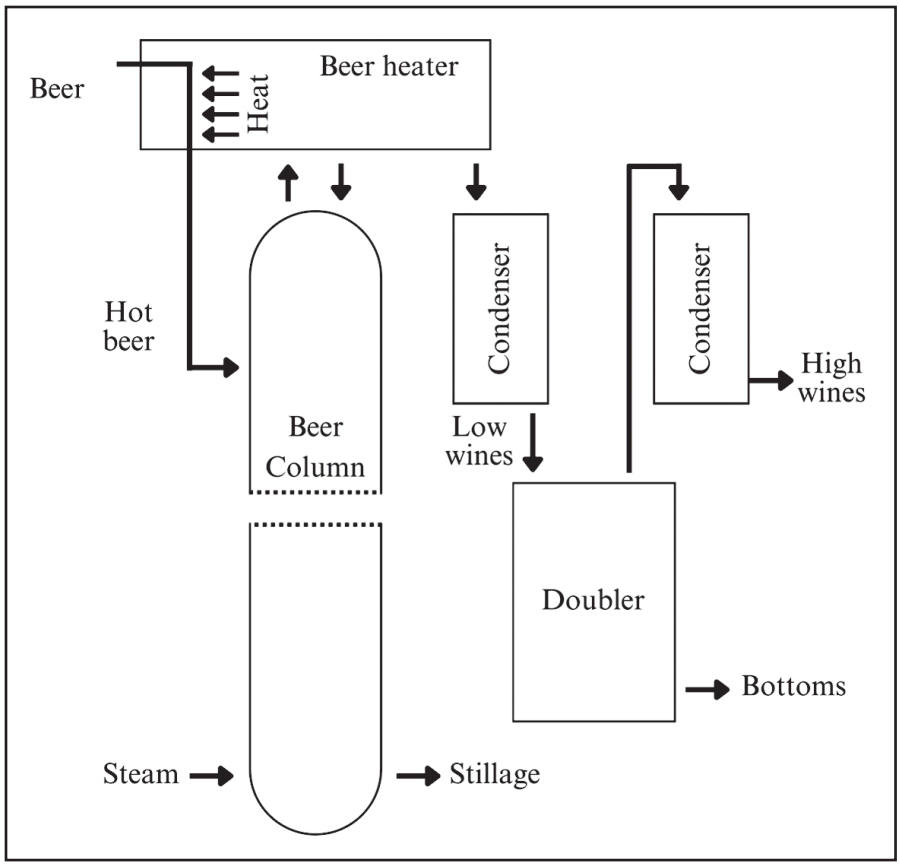


***Figure 2**. Process flow diagram for the continuous distillation of ethanol.*

This is then further distilled in the doubler, which is a single stage, semi-batch pot still.[14] The distillate leaving the doubler, the high wines, cannot exceed 160 proof for bourbon or 80% alcohol by volume (ABV) [24] and is typically closer to 135 proof (67.5 ABV). The high wines are then condensed, and the final proof is adjusted to less than 125 proof prior to barreling.[24]

Through learning about continuous distillation processes, students are introduced to the concept of separation through vapor-liquid equilibrium. They learn how to read XY, Txy, and Pxy diagrams to understand the composition of the liquid and vapor feed given a known system temperature. They complete complex material balances on multicomponent, multi-phase systems. An example of a complex material balance problem can be seen in Figure 3.

To solve this problem, students must establish a material balance around the system, as well as utilize vapor-liquid equilibrium data. A material balance on the column allows students to solve for the unknown vapor composition coming off the top of the column. To do a balance on the beer heater, students need to first determine the composition of vapor in equilibrium with the liquid leaving the beer heater at 7.1 mol% using an XY diagram. With this information, they can then use a material balance around the beer heater to determine the vapor flowrate. Finally, students are asked to determine the reflux ratio for the column using the liquid and vapor flowrate from the beer heater.

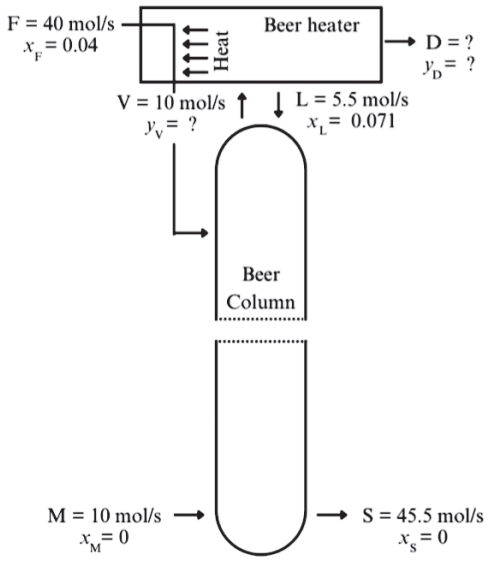
Further, they are taught how to determine stage compositions and characterize an ethanol-water distillation column through McCabe-Thiele analysis (Figure 4). At the start of the course, students are taught how to convert between proof, ABV, and mole and mass percents. Because alcohol is a non-ideal mixture, these calculations are not straightforward. As a result, students are provided with a table that allows them to easily convert between different concentration units. This allows students to identify their key concentrations for the McCabe-Thiele diagram and calculate the slope of their top operating line. They can then step off trays and apply efficiencies to determine the number of stages above the feed (accounting for the beer heater as an equilibrium stage), as well as the feed stage.

ASSESSMENT OF KNOWLEDGE IN CORE CONCEPT AREAS

After approval from the Institutional Review Board, student knowledge of core chemical engineering concepts areas was assessed through the aggregation of their scores across two semester exams and a final. Exams included multiple choice, fill-in-the-blank, essay, and calculation-based questions. For each exam, approximately 50% of the grade was related to calculation-based questions (such as those shown through the examples above). Exam questions were grouped by concept area, and scores were aggregated across 32 non-chemical engineering students who completed the course in 2020 and 2021. Students enrolled in the course included current undergraduate students enrolled in majors such as business and pharmacy. Additionally, several students enrolled in the course as continuing education with careers in fields such as medicine and electrical engineering, and as Donovan Scholars, who received tuition support for adults 65 and older. Student scores in these concept areas can be seen in Figure 5. Overall, students demonstrated high levels of content knowledge across all topic areas in chemical engineering with average scores of 80% or above for each of the key concept areas.

In a standard beer column, beer enters at 40 mol/s and 4.0 mol% ethanol. Steam enters the column at 10 mol/s and stillage exits at 45.5 mol/s and 0 mol% ethanol. The liquid reflux enters the tops of the column at 5.5 mol/s at 7.1 mol% and vapor exits the top of the column 10 mol/s.

a) Draw the column and label all the streams. Determine the mol% ethanol in the vapor exiting the top of the column.
b) Draw your beer heater and label your streams. What is the composition (mol% ethanol) of the vapor leaving the beer heater?
c) What is the flow rate (mol/s) of the vapor leaving the beer heater?
d) What is the reflux ratio associated with this process?



a. Ethanol balance on the column to calculate mol% ethanol in the vapor:

$$x_F F + x_M M + x_L L = y_V V + x_S S$$

No ethanol in the steam or stillage:

$$x_F F + x_L L = y_V V$$

$$(0.04)\left(40\frac{mol}{s}\right) + (0.071)\left(5.5\frac{mol}{s}\right) = y_V\left(10\frac{mol}{s}\right)$$

$$y_V = 0.20 = 20\ mol\%$$

b. Using an XY diagram, determine the composition of the vapor in equilibrium with the liquid leaving the beer heater:

$$y_D = 0.39$$

c. Overall material balance on the beer heater:

$$V = L + D$$

$$10\frac{mol}{s} = 5.5\frac{mol}{s} + D$$

$$D = 4.5\frac{mol}{s}$$

d. Reflux Ratio:

$$R = L/D$$

$$R = \frac{5.5\ \frac{mol}{s}}{4.5\ \frac{mol}{s}}$$

$$R = 1.22$$

Figure 3*. Example distillation problem where students must solve a complex, multi-phase material balance problem.*

IMPORTANT DECISIONS IN DEVELOPING A COURSE FOR NON-ENGINEERS

The development of a course on bourbon production presented a unique opportunity to teach chemical engineering concepts to students without a background in engineering. The subject matter of bourbon results in high interest from learners of all ages, allowing for high levels of engagement of students from not only the University of Kentucky but also outside institutions and industries. Importantly, significant care was taken to ensure that course concepts were adequately explained to students from a wide variety of backgrounds. This included the use of analogies and relevant examples that might connect to other aspects of their lives or their prior learning experiences. For instance, when discussing extraction of starches from the grains during mashing, diffusion from the grains was related to coffee brewing, where particle size and the temperature of the water both impact the rate of extraction from the ground coffee. Similarly, the impact of starch extraction on the viscosity of the liquid during mashing was related to the cooking of oatmeal. Together, these examples help to illustrate the importance of processing parameters during the mashing process.

To help with student learning, we provided significant opportunities for students to practice core concepts in a supported environment, especially for material balance and distillation concepts. Because the class was asynchronous, recorded example problems helped to guide students through the key aspects of each calculation. Notes with gaps were provided to students, and students were asked to pause the video to complete calculations. This allowed them to work through the problems with guided notes and then watch through the worked solutions in a recorded video. The multidisciplinary topic of bourbon production, which includes

A column still produces a 150 proof low wines product with a reflux ratio of 2, a 15% ABV beer and a 2% ABV stillage. Assume that the beer heater at the top is a partial condenser, and the trays are 50% efficient.
a) How many trays above the feed are required for this column?
b) At what tray should the feed be added to the column?

150 proof low wines = 46.8 mol% EtOH

Reflux Ratio, R = 2

Slope of Top Operating line: $\frac{R}{(R+1)} = \frac{2}{(2+1)} = \frac{2}{3}$

15% ABV Beer (Feed) = 5.1 mol% EtOH

Trays are 50% efficient → 4 equilibrium stages above the feed
- 3 trays and the beer heater (partial condenser)

Feed should be added on tray 4.

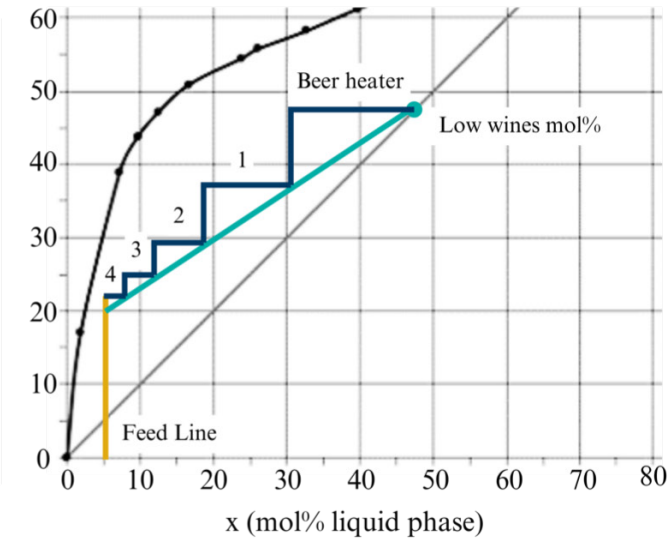


Figure 4. *Analysis of a distillation column through McCabe-Thiele analysis*.

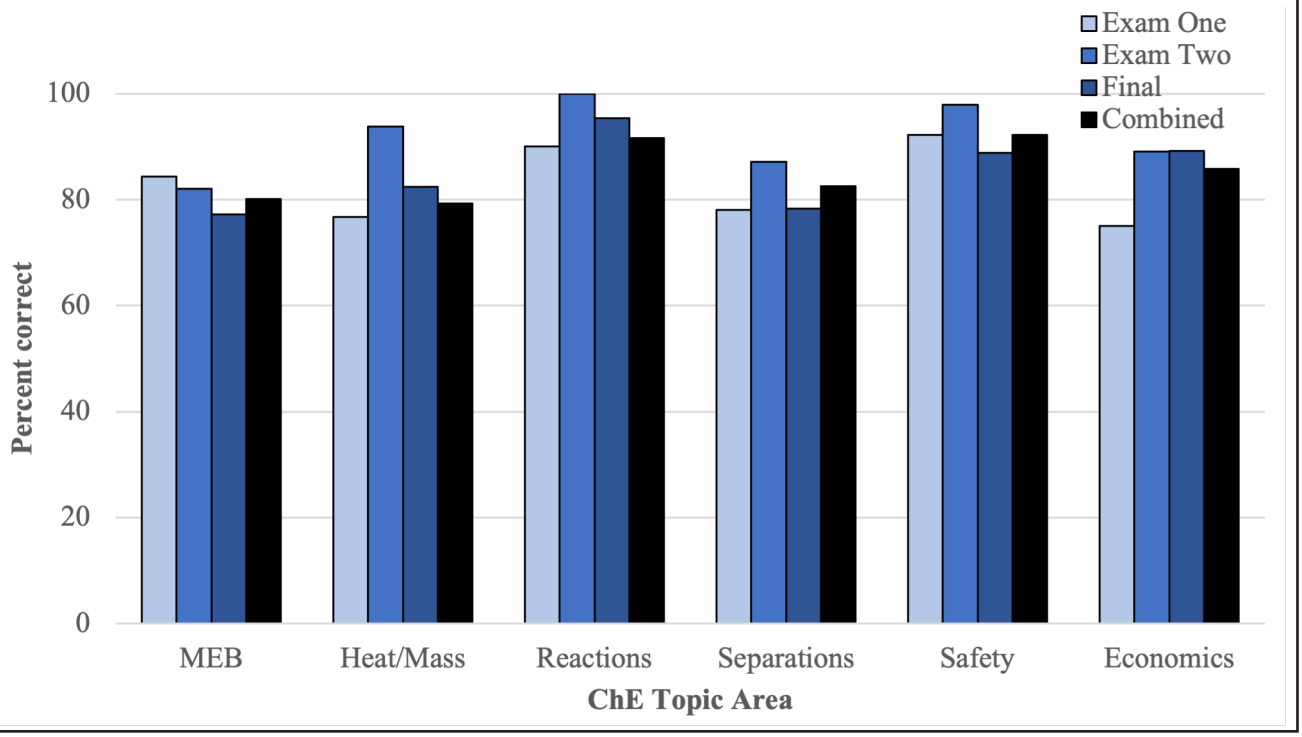


Figure 5. *Assessment of student knowledge (n = 32) in key content areas across two semester exams and a final exam*.

fields like chemistry, biology and economics, also provided many students with opportunities to apply their prior knowledge to what they were learning in the classroom. Overall, the course required significant upfront faculty effort, as well as reflection through each continued offering, to ensure that topics were being clearly communicated and resulted in high knowledge gains for the diverse learners in the classroom.

ELEVATING THE COURSE FOR CHEMICAL ENGINEERING STUDENTS

The course is also offered to junior and senior chemical engineering students by integrating aspects of engineering design to build upon the core chemical engineering content presented in the course. Chemical engineering students complete a base-case design of a distillery inclusive of mashing, fermentation, distillation, and stillage treatment. Students are required to consider raw materials, utilities, scheduling, aging, and State and Federal taxes when calculating production costs and sales revenue.

The design project is broken into three parts:

1. Design of a traditional stillage treatment facility with a research component on alternative methods of stillage treatment
2. Design of the distillation process given a specific production rate and beer composition. This portion includes the evaluation of ethyl carbamate and how the compound can be prevented in the final product
3. Schedule and design of the complete production process along with an estimated economic analysis of the process

The project sections are executed sequentially throughout the semester. Chemical engineering students do not require extensive lectures on the basics of material and energy balances, so these sections of the course are abbreviated to only discuss the application of these balances to these unit operations. The stillage treatment section is placed first because it only requires a preliminary lecture on the design of industrial drying systems. The other projects are tackled after the lectures describe the complete fundamentals of distillery design. In summary, these projects reinforce the connection between the design fundamentals of each part of the distillery and the tangible outcomes of production rate and process economics. Further, they emphasize the challenges associated with multi-component systems that contribute to complex reaction pathways during fermentation, separation and aging that ultimately must work together to create a product that is not only safe for consumers but also meet the flavor preferences of diverse consumers.

SUMMARY

The bourbon production process is an engaging platform that has facilitated the delivery of a broad spectrum of chemical engineering fundamentals to over 100 students from a diversity of backgrounds and stages of life. While courses have been developed on beer brewing [24] and culinary science [25] for engineering students, few courses have focused on using these popular topics (e.g., bourbon, coffee) to introduce chemical engineering to those outside of the field. We encourage faculty to consider how they can use these popular topics as an outreach opportunity to introduce chemical engineering concepts to students from a wider variety of educational backgrounds. These courses provide an opportunity to not only expand the knowledge of students on topics of interest, but also facilitate the spread of chemical engineering concepts beyond the chemical engineering classroom. With the UC Davis course on coffee production, which is offered to first-year students, this has been shown to impact students' decisions to enroll in STEM majors.[12] While the bourbon production course is typically taken by students in their junior or senior year (or beyond college), it can help to expand the public knowledge of the field of chemical engineering and how chemical engineers contribute to the production of not only high value but also highly popular commercial products. Further, concepts from this course have been integrated into a distillery operator training program, allowing employees with significant knowledge of the operations of distillery equipment to learn about some of the fundamentals that drive distillery performance. Together, these courses have the potential to impact distillery operations and efficiency. Further, they contribute to the public perception of how chemical engineers contribute to society beyond the traditional fields of oil, gas, and high value chemical commodities.

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