Unifying Multiple Concepts with a Single Semester-Long Project: A Brewery Design Project for Heat Transfer Courses

Jacob J. Elmer and Noelle Comolli
Villanova University, 217 White Hall, 800 East Lancaster Avenue, Villanova, PA 19085

Abstract

Student learning and retention of material can be significantly enhanced by assigning group projects that challenge students to apply concepts covered in class. However, a key challenge in many engineering courses is developing projects that effectively relate the multitude of distinctly different concepts taught throughout the semester. For example, most heat transfer courses cover several different modes of heat transfer, including conduction, radiation, and multiple types of convection (e.g. natural, forced, boiling, condensation, etc.). Many excellent assignments have been developed to address these concepts individually or in small groups (e.g. combined effects of convection and radiation in an oven), but it is relatively difficult to find or formulate an assignment that challenges students to apply all of these different concepts. In this paper, we describe a novel design project for heat transfer courses that requires students to use many different heat transfer concepts (e.g. conduction, insulation, forced and natural convection, boiling, condensation, heat exchanger design, process safety, and radiation) to design several different pieces of equipment in a fermentation process for a new brewery. In each step of the process, students are required to optimize their designs with Mathcad sheets that help them to see the influence of each variable in an equation. Several of the problems are also designed to enhance lifelong learning by requiring students to seek out physical parameters and actual equipment specifications from online resources and manufacturers. At the conclusion of the semester, students compile their findings into written reports and oral presentations that help them to relate all of the different projects from a process design perspective. Surveys given at the end of the semester indicated that the students enjoyed the experience of assimilating all of the various heat transfer topics into a single tangible product. In a student survey, all of the problems were rated highly ($\leq$ 2.5) on a 3-point scale that indicated whether the problems were ineffective (1 pt), needed some improvement (2 pts), or were effective "as is" (3 pts). Due to this positive feedback, we will be assigning this project again in future classes, perhaps with a few additional unit operations (e.g. a distillation step or refrigeration cycle).

I. Introduction

Project-based learning (PBL) is an intriguing approach to engineering education in which students are assigned projects that require them to apply the concepts learned in class towards solving relevant real world problems. PBL has been shown to have many significant benefits compared to traditional sets of isolated or unrelated homework problems. As might be expected, PBL helps students learn how to apply concepts from class[1] and helps them recall those skills after the end of the semester.[2] Since most PBL assignments require students to work in groups, this approach can also significantly improve communication and teamwork skills.[3] It is also interesting to note that PBL can increase student recruitment and overall retention rates when applied throughout an engineering curriculum.[4,5] This phenomenon may be attributed to the real world context that PBL provides to students. This context helps students to see exactly how core concepts are applied in the real world and helps to convince them that the material is important. Indeed, Felder et al note that students are motivated to study harder when they believe that they will actually need to use the course concepts later in their careers.[6]

While the benefits of PBL are easy to see, it is usually hard to find effective projects to implement PBL in engineering courses. There are some online resources with examples of project-based or problem-based learning assignments that focus on one or a few concepts[7,8], but it is much harder to find projects that utilize a majority of the concepts taught throughout a specific course. The purpose of this paper is to introduce a novel brewery design project for PBL in a heat transfer course. Each of the fundamental heat transfer concepts are addressed in this project (e.g. conduction, convection, and radiation) throughout multiple unit operations of a process that is similar to a commercial brewery. Students are required to design and optimize every step of their process (in the context of heat transfer) and then communicate their final designs in written and oral form. The overall goal of this project is to help students see how they may directly apply several course concepts to a real-world process that most college students find very intriguing and quite memorable. Finally, it is also important to mention that this project was developed for chemical engineering students, but most of the concepts should easily translate to other departments (e.g. mechanical or civil engineering).

II. Overview of the Brewery Process Design Project

While many industrial processes may require one or a few different heat transfer concepts (HXC), the traditional beer brewing process utilizes almost every mode of heat transfer (see Fig. 1). The brewing process begins with barley grains, which are "malted" by soaking them in water to initiate germination and the production of enzymes that convert complex sugars into simpler sugars for fermentation. However, germination must be stopped by drying the seeds in an oven (HXC = radiation, natural convection) before the seed consumes all of the available sugars. The dried grains are then pulverized and soaked in hot (40-65^{o}C) water in an insulated mash tun for 1-2 hours (HXC = insulation, unsteady state conduction) to extract sugars. The hot water for this step can be provided by a tank-less water heater that warms tap water to the desired temperature (HXC = forced internal convection). Once the sugars have been extracted from the barley grains, the liquid "wort" is sterilized by boiling it for 1 hour in a brew kettle that is heated by natural gas (HXC = boiling heat transfer). The sterilized wort must then be rapidly cooled with a plate and frame heat exchanger before yeast can be added for fermentation (HXC = heat exchanger design). The fermenter itself can also be sterilized with superheated steam (HXC = condensation heat transfer). After the fermentation step is complete, the product is packaged in one of several different types of containers with different dimensions and thermal conductivities – e.g. glass bottles or aluminum cans (HXC = conduction).

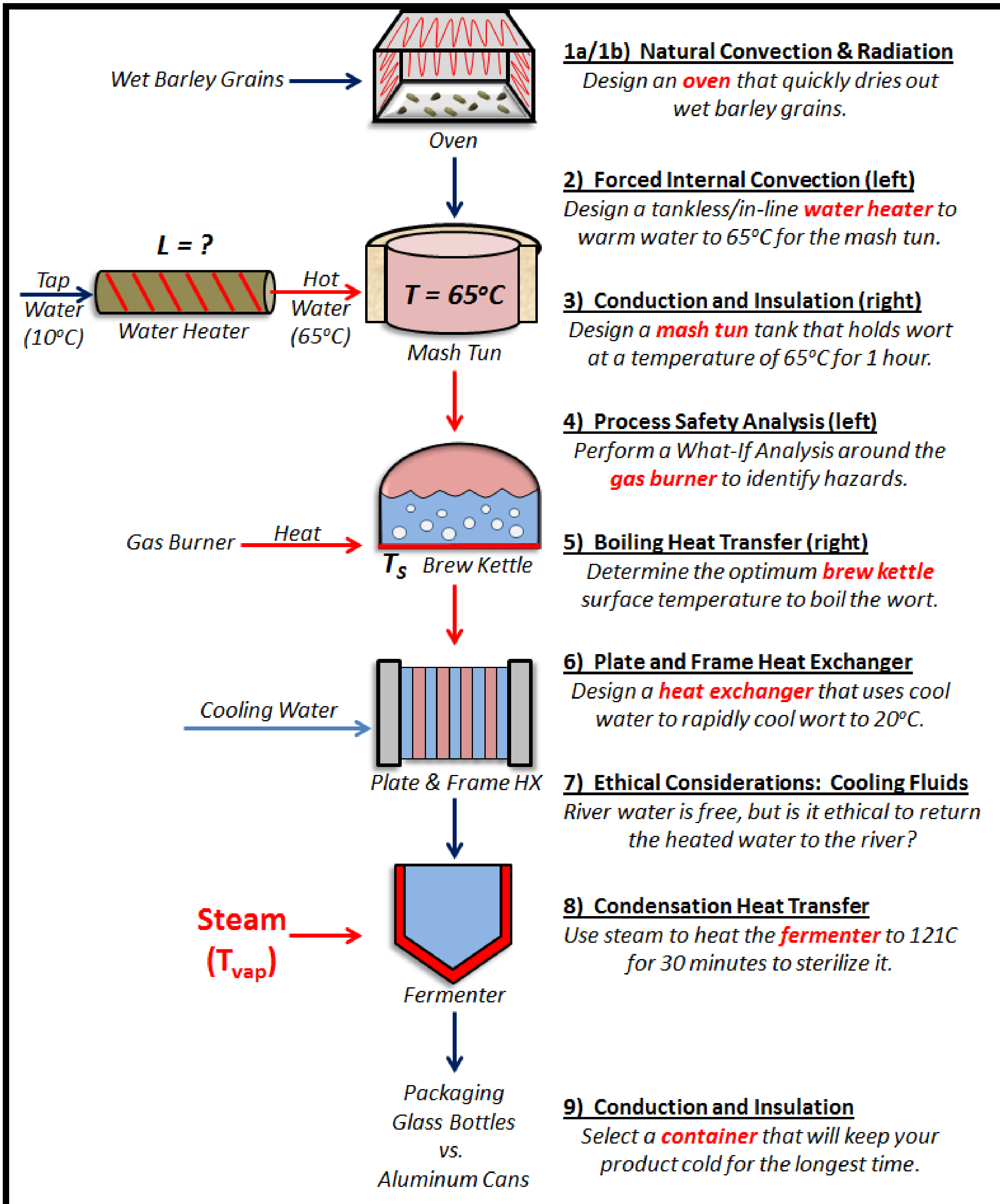


Figure 1 – Overview of the Brewery Process Design Project.

Overall, this process utilizes almost all (~75%) of the heat transfer concepts taught in our course, with a few minor exceptions (forced external convection, fin effects, and the NTU method). We also use this process to discuss process safety concerns pertaining to the natural gas burner in the brew kettle and the ethical considerations associated with using river water as a cooling fluid in the heat exchanger that chills the wort. Therefore, this project provides a very useful theme for our course which helps to validate and tie together most of the disparate concepts that are discussed. At the end of the course, the students prepare a written report that summarizes all of the equations, properties, and concepts that they used for their calculations. This report also helps students retain knowledge of heat transfer by serving as a detailed reference material that they can use later in their careers. Detailed explanations of each step in the process and the requirements for the report are discussed in detail in the following sections.

Natural Convection and Radiation in a Barley Oven

In this first step of the process, students are asked to design an oven that will provide the highest initial rate of heat transfer to moist barley grains (T_i = 20°C). The only restrictions are that the barley grains must rest on the bottom surface of the oven and there are only three possible configurations for the heating elements (T = 450°F) – two small elements on the left and right sides or one large element on the back side or top side (see Fig. 2). In each case, students are allowed to neglect heat transfer with the other non-heated surfaces. The overall dimensions of the oven (H = 3 ft, W = 6 ft, D = 3 ft) are also fixed such that the total area of each heating element configuration is constant (18 ft^2). Therefore, the difference in heat transfer between these configurations is determined by the rates of heat transfer by radiation from the elements to the grains (Eq. 1)[9] and natural convection to the air (T_b = 20°C) in the oven (Eq. 2)[9]. The objective of this problem is to force students to consider how they might calculate overall rates of heat transfer in a system with multiple modes of heat transfer.

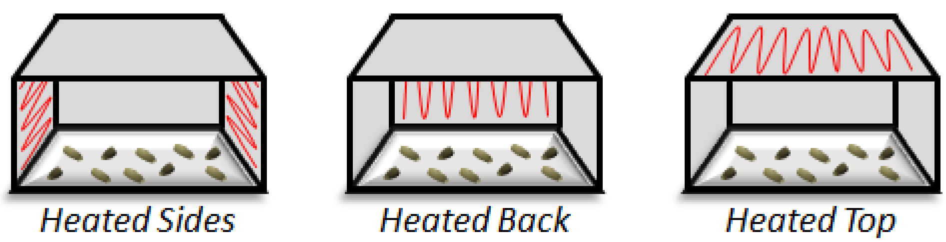


Figure 2 – Possible heating element configurations for the oven design problem.

$$\dot{Q}_{rad,1-2} = \frac{\sigma\left(T_1^4 - T_2^4\right)}{\frac{1-\varepsilon_1}{A_1\varepsilon_1} + \frac{1}{A_1F_{1-2}} + \frac{1-\varepsilon_2}{A_2\varepsilon_2}} \quad \text{(Eq. 1)}^{9}$$

$$\dot{Q}_{NC} = hA_1(T_b - T_1) = \frac{Nu \cdot k}{L_c}A_1(T_b - T_1) = \frac{CRa^m k}{L_c}A_1(T_b - T_1) \quad \text{(Eq. 2)}^{9}$$

In Eq. 1 and Eq. 2, the subscript 1 denotes properties for the heating element and 2 indicates properties for the barley grains. σ is the Stefan-Boltzmann constant (σ = 5.67 x 10^{-8} W/m^2K^4) and Ra is the Rayleigh number, while C, m, and L_c are constants that depend upon the geometry and orientation of the surface and Ra (only C and m). Students can find their own estimates for physical properties like emissivity and thermal conductivity or they can be provided (ε_1 = 0.5, ε_2 = 0.9, k_{air} = 0.033 W/mK).

With the existing constraints on the system, students should find that the rate of natural convection is highest from the vertical heating elements, while radiation heat transfer is highest from the horizontal element on the top surface. However, when the effects of radiation and natural convection are combined ($Q_{total} = Q_{rad} + Q_{NC}$), the total rates of heat transfer are almost identical. At this point the student must realize that summing radiation and natural convection rates is actually a flawed strategy, since Q_{NC} actually represents the rate of heat transfer to the air instead of to the barely grains. Consequently, there will be an additional resistance to convection heat transfer that is not considered in Eq. 2 and the actual rate of convective heat transfer to the barley grains will be lower than the value estimated by Eq. 2. Therefore, while vertical elements will heat the air in the oven at the fastest rate, a horizontal element on the top surface will provide the highest initial rate of heat transfer to the barley grains. Students can also be asked to consider how this system changes when the oven is preheated (T_b = 450^{o}F) or another type of metal is used for the heating elements (ε_1 = ?).

Forced Internal Convection in a Tankless Water Heater

After the barley grains have been dried and pulverized into grist, sugars are extracted from the grist with hot water (40-65^{o}C). In our hypothetical process, this hot water is supplied on demand by a tank-less water heater that heats tap water from an inlet temperature (T_{in}) to the specified outlet temperature (T_{out} = 65^{o}C) by varying the mass flow rate (m) of tap water through a pipe with a constant surface temperature (T_w = 100^{o}C) and length (L_P). Calculating the required mass flow rate for a given T_{in} and T_{out} is relatively difficult iterative process in this case, since m is a function of Nu and Re, which in turn are also functions of m. The type of equation used to calculate Nu is also dependent on m, since different equations are used to model Nu in laminar and turbulent flow. Consequently, students must perform iterative calculations with guess values for m until they converge on the actual value of m (see Fig. 3).

In addition to applying forced internal convection equations, the objective of this problem is to show students how to use software packages to solve complex iterative problems. Specifically, we use this problem to teach students about If statements and iterative loops, which are much easier to set up than performing successive calculations by hand. Once the program is set up, the students can be challenged further by asking them to repeat their calculations for different inlet temperatures or pipe dimensions (D_P, L_P).

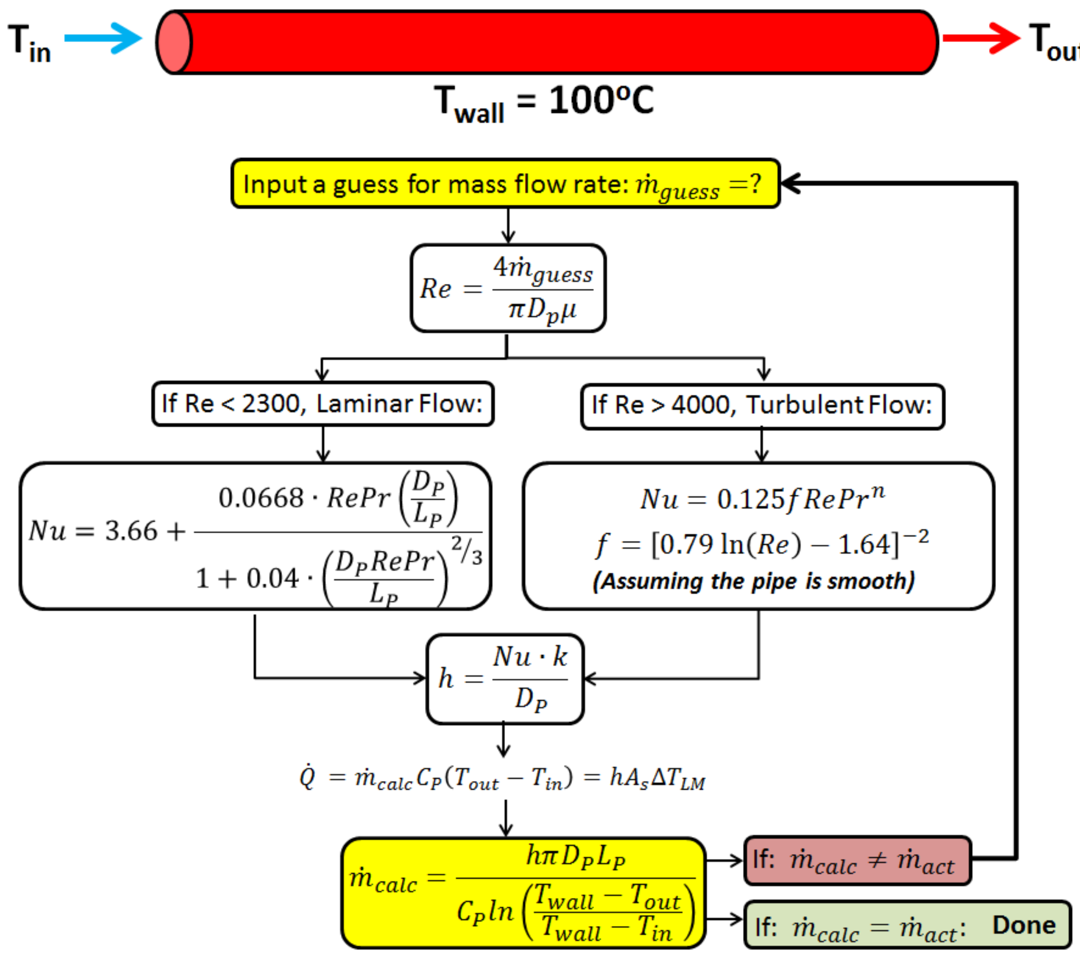


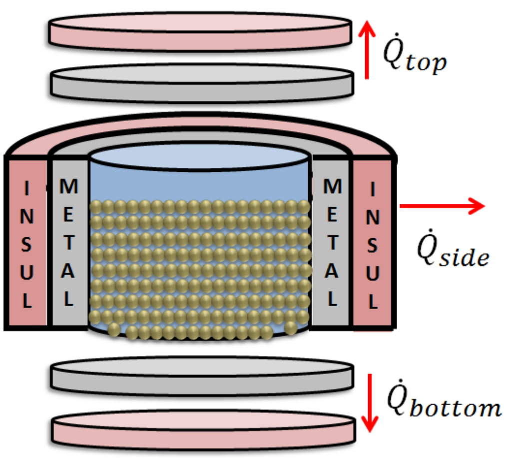
Figure 3 – Iterative process for determining the mass flow rate required to heat a fluid stream from a specified inlet temperature (T_{in}) to a desired outlet temperature (T_{out}) using a pipe with a constant wall temperature (T_{wall}). Additional variables and properties are inner pipe diameter (D_P), length of pipe (L_P), Prandtl number (Pr), thermal conductivity (k), and heat capacity (C_P). All equations are adapted from the course textbook.[9]

Unsteady State Conduction in an Insulated Mash Tun

Once the grist has been mixed with the hot water in the mash tun, it needs to stay at the same high temperature for a long time (e.g. 1-2 hrs). The temperature can be maintained by insulating the mash tun to minimize heat loss by convection to the surrounding air, which allows us to apply the concepts of insulation and series/parallel resistances. Although this is a very complicated system with a mixture of solids and liquids, it can be crudely modeled by assuming the liquid inside the tank is thoroughly mixed to provide a uniform temperature distribution within the tank. This allows us to "lump" the system and derive an equation for unsteady state heat loss based on Eq. 3 that predicts the temperature inside the tank (T_{tank}) over time (t): [9]

$$\dot{Q}_{total} = \frac{(T_{tank} - T_{bulk})}{R_{total}} = -\rho V C_p \frac{\partial T_{tank}}{\partial t} \qquad \text{(Eq. 3)}^{9}$$

Most of the variables in Eq. 3 can be easily estimated (ρ, V, C_P), but the total resistance to heat transfer (R_{total}) is a more complex term, since there are both series resistances (conduction through tank wall and insulation, then convection to outside air) and parallel resistances (heat transfer through the vertical wall and the top/bottom of the tank) as shown in Fig. 4.



$$R_{bot} = \frac{\Delta x_{metal}}{k_{metal} A_{bot}} + \frac{\Delta x_{ins}}{k_{ins} A_{bot}} + \frac{1}{h_{bot} A_{bot}}$$

$$\dot{R}_{side} = \frac{ln\left(\frac{r_2}{r_1}\right)}{2\pi k_{metal} H} + \frac{ln\left(\frac{r_3}{r_2}\right)}{2\pi k_{insul} H} + \frac{1}{h_{side} A_{out}}$$

$$R_{top} = \frac{\Delta x_{metal}}{k_{metal} A_{top}} + \frac{\Delta x_{ins}}{k_{ins} A_{top}} + \frac{1}{h_{top} A_{top}}$$

$$\frac{1}{R_{total}} = \frac{1}{R_{top}} + \frac{1}{R_{bot}} + \frac{1}{R_{side}}$$

Figure 4 – Modeling heat loss from an insulated tank (left) can be achieved by estimating the total series and parallel resistances to heat transfer with the equations shown above on the right. Additional variables include surface area (A), thermal conductivity (k), layer thicknesses (Δx), inner tank radius (r_1), outer tank radius (r_2), and outer insulation radius (r_3).

Once the students have derived an equation for the temperature inside the tank as a function of time, they are asked to determine a minimum insulation thickness (Δx_{ins}) that provides a temperature drop $\leq 2^{o}$C ($T_{initial} = 65^{o}$C) over a period of 1 hour. This can be easily done by plugging the necessary equations and variables into Mathcad and varying Δx_{ins} until the final temperature in the tank at t = 1 hr exceeds 63^{o}C.

Students can be further challenged by asking them to minimize heat transfer by optimizing the height of the tank, while keeping the volume constant. The goal in this case is to minimize Q by reducing surface area, which is a function of tank height (H) and radius (r_1), as shown in Eq. 4. Since tank volume is constant, Eq. 5 can be substituted into Eq. 4 for r_1 to obtain A_s as a function of H. The tank height that provides the minimum surface area can then be found by taking the derivative of $A_s(H)$ and setting it equal to zero. This optimum value of H can then be used to find the minimum insulation thickness.

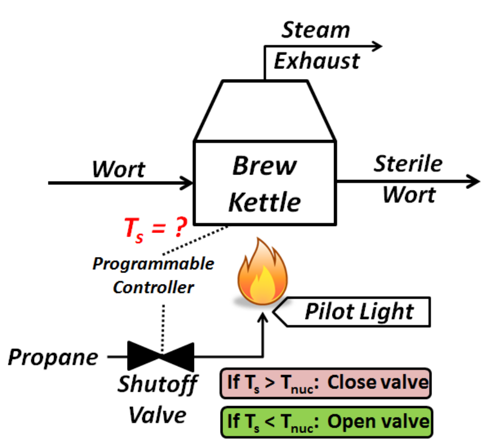
$$A_s = A_{side} + A_{bottom} + A_{top} = 2\pi r_1 H + \pi r_1^2 + \pi r_1^2 \quad \text{(Eq. 4)}$$

$$V = \pi r_1^2 H \quad \text{(Eq. 5)}$$

The objectives of this problem are (1) to give students an opportunity to apply equations for unsteady state conduction to a real-world system and (2) show them how to carefully use approximations and assumptions to simplify complex systems like the mash tun into an approachable (lumped) model system. Students are also forced to question the validity of their assumptions by asking them whether the lumping assumption used in Eq. 3 will overestimate or underestimate the actual temperature inside the tank (answer: underestimate).

Optimization of Boiling Heat Transfer in a Brew Kettle

After the sugars have been extracted from the grist into the water, the resulting wort must be sterilized to remove any bacterial contaminants that would otherwise ruin the fermentation. The wort is usually sterilized by boiling it for ~60 minutes in a brew kettle that is heated by a natural gas burner. Boiling the wort also has the additional benefit of precipitating several tannins and other undesirable molecules that would negatively affect the flavor of the finished product. In our process, students are asked to set up a feedback control loop (see Fig. 4) that maintains the surface of the brew kettle at an optimum temperature to ensure the system is in the nucleate boiling regime (T_{nuc}). Above this temperature, much less efficient film boiling would occur, thereby unnecessarily wasting energy from the natural gas. The optimum temperature for nucleate boiling can be found by combining the equations for maximum heat flux (q_{max}) and surface temperature in the nucleate boiling regime (T_{nuc}) shown in Fig. 5. [9]



$$q_{max} = \frac{\pi}{24} H_{fg}\left[\sigma g \rho_v^2 (\rho_l - \rho_v)\right]^{1/4}\left(1 + \frac{\rho_v}{\rho_l}\right)^{1/2}$$

$$T_{nuc} = T_{sat} + \left(\frac{q_{max}}{\mu_l H_{fg}}\right)^{1/3}\left(\frac{\sigma}{g(\rho_l - \rho_v)}\right)^{1/6}\frac{C_{sf} H_{fg} Pr_l^s}{C_{P,l}}$$

Figure 5 – Feedback control loop for a propane burner that heats a brew kettle to boil wort. When the surface temperature (T_s) of the kettle exceeds the optimum temperature (T_{nuc},

estimated with the equations on the right), the burner is shut off. Vapor properties are denoted with a subscript v, while liquid properties are denoted with a subscript l. C_{sf} is the surface factor constant, while s is a constant that depends on the type of fluid being boiled.

In this section of the project, students are asked to do some research to determine what type of surface (e.g. type of metal with or without treatment) will provide the most efficient boiling heat transfer. Students can determine the best surface material by retrieving and testing different values for the surface factor constant (C_{sf}), which directly influences T_{nuc}. In this case, it is quite obvious that we would want a surface with the lowest possible C_{sf}, thereby making T_{nuc} as low as possible and reducing the amount of propane needed to heat the brew kettle. Nonetheless, students are still asked to calculate T_{nuc} for at least 3 different surfaces and discuss the magnitude of the differences in T_{nuc}, which can be several degrees Celsius. The objective of this problem is to force students to retrieve real-world physical parameters and compare the significant effects that different materials can have on heat transfer phenomena.

Process Safety: A What-If Analysis for the Brew Kettle

In addition to the calculations of T_{nuc} for boiling heat transfer in the brew kettle, students are also asked to perform a "What-If" style hazard identification analysis on the whole system shown in Fig. 5. The What-If analysis requires students to brainstorm possibly hazardous events, then predict the consequences of that event and (if necessary) suggest ways to prevent any hazardous events from occurring. For example, one possible event is that the pilot light that ignites the propane may malfunction. This would be a serious hazard, since propane would continue to flow out of the valve and could accumulate inside the brewery to hazardous or explosive levels. To prevent this from happening, a thermocouple could be installed near the pilot light to detect combustion of the propane. If the pilot light malfunctions, then the thermocouple would measure a relatively low temperature and trigger an alarm and/or a controller that shuts off the gas valve. Several other hypothetical hazards can also be imagined in this system, but the students are only required to come up with at least three hazardous scenarios and solutions. The objective of this problem is to give students a practical example of an easily overlooked hazard in a process and have them consider possible preventative measures.

Designing a Heat Exchanger to Chill the Wort

The wort chiller is designed to be the most challenging section of the brewery design project, since heat exchangers are commonly used by chemical engineers in industry. Students are asked to design a heat exchanger that can quickly cool 250 gallons of hot wort ($T = 100^{o}C$) down to $20^{o}C$ within 30 minutes. Students are given absolute freedom to define all of the other variables in this system by selecting their own coolant fluid, heat exchanger, and pumps. However, all of their decisions must be carefully justified. For example, students can choose to use river water as a coolant, but they must account for fouling in their calculations and provide some proof of the available river water temperature. Alternative cooling fluids include tap water (available at high pressure, but has a cost) and refrigerants (highly effective, but can also be highly toxic). Students are also required to select a commercially available heat exchanger for this step of the process. To do so, they must calculate the required heat duty (Q_{req}, Eq. 6) and make sure that the maximum heat duty (Q_{max}, Eq. 7) of the selected heat exchanger exceeds that value.

(Eq. 6) [9] $$\dot{Q} = \dot{m}C_p\Delta T \qquad < \qquad \dot{Q} = UA_S\Delta T_{LM}$$ (Eq. 7) [9]

In Eq. 7 above, there are many different ways to calculate the overall heat transfer coefficient (U), depending on the type of heat exchanger that the students choose to use (shell and tube, plate and frame, double-pipe, etc.). They should be able to predict that a plate and frame heat exchanger is the best choice for this application, since it provides a relatively high surface area for heat transfer, but we let them pick whichever design they wish. Either way, once the coolant and heat exchanger have been chosen, students are also required to select pumps that can provide the required mass flow rates for the coolant and wort streams and to estimate annual operating costs (e.g. water and electricity fees). Overall, this section of the project is meant to give students the opportunity to select a real-world device for our hypothetical scenario and give them a sense of all of the costs associated with heat exchangers (e.g. coolant and utility costs).

Ethical Considerations: Using River Water as a Coolant

The coolant that leaves the wort chiller can easily get very hot (>40^{o}C). Therefore, disposing of the coolant in a drain or the environment can have some serious implications. Indeed, the Environmental Protection Agency (EPA) enforces several regulations that indicate the maximum temperature of a fluid that can be drained into a lake or river. Students are reminded to consider these regulations while they are designing selecting their heat exchangers and developing a strategy to discard or recycle their coolant streams. We also lead an in-class discussion that focuses on a hypothetical scenario in which a plant supervisor instructs an operator to dump a hot coolant stream into a river, even though the temperature of the stream exceeds the maximum temperature recommended by the EPA. We begin by discussing ways to alter process variables to reduce the outlet coolant temperature, but also discuss strategies to handle the situation if the outlet temperature cannot be lowered. For example, the operator might show attempt to persuade the manager by showing them a copy of the EPA regulations or magazine articles about companies that were fined for similar offenses. Contacting the manager's boss and whistle blowing are also discussed as last resorts. This discussion gives students the opportunity to discuss important environmental and ethical issues.

Using Condensation Heat Transfer to Sterilize a Jacketed Fermenter

Just like the wort stream, the fermenter must also be sterilized before each fermentation. While there are many different ways to sterilize a fermenter, our hypothetical process includes a fermenter with an exterior jacket that can be filled with steam for sterilization. While this may not be the most efficient design, it is an opportunity for the students to apply their equations for condensation heat transfer. Specifically, the fermenter can be modeled as a vertical cylinder, allowing us to use Eq. 8 & Eq. 9 to calculate an initial heat transfer coefficient and rate of heat transfer (g is gravitational acceleration and H is fermenter height). [9]

$$h = 0.935\left[\frac{g\rho_l(\rho_l-\rho_v)H_{fg}^{*}k_l^3}{\mu_l(T_{sat}-T_s)H}\right]^{1/4} \quad \text{(Eq. 8)}$$ [9]

$$\dot{Q} = hA_s(T_{sat}-T_s) \quad \text{(Eq. 9)}$$ [9]

Once the initial rate of heat transfer is calculated, the mass flow rate of condensate leaving the jacket can also be calculated by dividing the rate of heat transfer by the modified enthalpy of vaporization ($m_{condensate} = Q/H_{fg}^*$). Students can be challenged further by asking them how the heat transfer and condensate mass flow rates will change after t = 0.

Selection of Packaging Material – Influences of Geometry and Thermal Conductivity

The last step of the process is to package the product into one of the many different available packages – bottles (glass, aluminum, or plastic) or cans (aluminum). Each one of these materials has its own advantages and disadvantages that may influence a company's decision. For example, aluminum is relatively cheap and stable, but it has a high thermal conductivity (i.e. it loses heat quickly). In contrast, glass has a relatively low thermal conductivity, but it is more expensive, heavy, and fragile. In this assignment, however, the students are asked to choose a packaging material that minimizes the initial rate of heat transfer from the cold fluid inside ($T_i = 4^oC$) to the hand holding the bottle or can ($T_o = 37^oC$). If we assume that the hand completely covers the sides of the cylindrical container and neglect heat transfer through the other surfaces, then the initial rate of heat transfer into the fluid can be calculated with Eq. 10.

$$\dot{Q} = \frac{2\pi kH(T_o-T_i)}{ln\left(\frac{r_2}{r_1}\right)} \quad \text{(Eq. 10)}$$

In this equation, H is the height of the container, while r_1 and r_2 are the inner and outer radii of the container wall, respectively. After retrieving the container dimensions (H, r_1, and r_2) and thermal conductivities (k) for various containers, students should find that glass bottles provide the lowest initial rate of heat transfer, indicating that they will keep a the product colder than the other packaging options. The students may also be asked which material will allow the product to be chilled as fast as possible, as one may desire when bringing it home from the store. In that case, aluminum cans provide the highest rate of heat transfer and will allow the product to be cooled much faster than glass bottles. Students can also be challenged further by asking them to design a coozie that reduces the rate of heat transfer through an aluminum can to a level that is comparable to a glass bottle. This scenario requires students to modify Eq. 10 by adding an additional series resistance term to account for the extra coozie layer.

Written Reports and Oral Presentation

While answers to some of the sections of this brewery design project may be collected, graded, and corrected for feedback throughout the semester, the ultimate deliverable for the project is the written report and oral presentation that are collected at the end of the semester. The written report requires students to organize and communicate their findings in a professional format that includes the following items:

- A process flow sheet that shows all of the steps in the process, along with important design variables that were calculated by the students (e.g. temperatures, flow rates, etc.)
- A 1-page executive summary that concisely describes the process and its optimization.
- A project narrative that thoroughly describes each step of the process and clearly shows:
    - Equations that were used in each step
    - Physical properties that were used and their sources
    - Tables showing key data for comparison
- An appendix containing any other useful references, such as price quotes for heat exchangers, any derivations of complex equations, and copies of Mathcad worksheets.

The goal of the written report is to provide students with a permanent resource that they can refer to later in their careers. Since many of the problems are open-ended, the report is primarily graded on the correctness of the approach, equations, and assumptions used in each problem. The organization, structure, and overall quality of the report can also be graded to give students feedback on the quality of their writing. The content of the oral presentation is very similar to the written report, but it requires students to practice their oral communication skills. We also leave 5 minutes at the end of each presentation for questions from the instructor or other students. These presentations also give the students a chance to see the alternative strategies used by other students to achieve the same goals. In contrast to the written reports, the oral presentations are graded for completion (including all required aspects of the process), clarity of communication, and the ability to accurately answer questions from the audience and instructor.

III. Feedback from Student Surveys

Surveys given at the end of the semester indicated that the students enjoyed the experience of assimilating all of the various heat transfer topics into a single tangible product. As shown in Table 1, each section of the project was rated highly on a 3-point scale ($\leq$ 2.4 average) that scored problems as ineffective/needing replacement (1 pt), needed some improvement (2 pts), or were effective "as is" (3 pts).

Table 1 – Results of Student Feedback Surveys (n = 47 students)

Oven Design	Water Heater	Mash Tun	Brew Kettle	Safety Analysis	Wort Chiller	Jacketed Fermenter	Product Packaging
2.98$\pm$0.15	2.91$\pm$0.28	2.79$\pm$0.41	2.91$\pm$0.28	2.83$\pm$0.43	**2.47$\pm$0.58**	2.94$\pm$0.25	2.98$\pm$0.15

We may slightly modify the wort chiller section of the project, since it received the lowest scores on the student surveys (2.47 $\pm$ 0.58). Comments from the student surveys suggested that the wort chiller project could be improved by providing a list of companies that sell heat exchangers and pumps to help students start their search (the current problem statement simply suggests that students search the internet to find companies). Aside from this minor change, the rest of the sections received excellent scores so we will continue assigning (and improving) this project in future classes.

IV. Conclusion

Overall, this brewery design project seems to be an effective way to link several disparate heat transfer concepts in a single assignment. The project includes all of the major heat transfer modes (conduction, convection, and radiation) and student feedback on the project was positive overall. In response to student comments, we will give students more guidance/supervision on the more open-ended parts of the project (e.g. heat exchanger design). We may also expand the project to include additional unit operations that utilize new heat transfer concepts. For example, we may also consider adding a distillation step to purify the ethanol for liquors or a refrigeration cycle to cool the fermenter/finished product. We may also make some problems more complex to mimic what actually happens in a real brewing process. For example, some fermentations require wort to be chilled down to 5-15^{o}C, instead of the 20^{o}C used in our current problem. Since river and tap water aren't available at these low temperatures, reducing the target outlet temperature of the wort in the problem statement would require students to consider using chilled ethylene glycol as a coolant. This strategy would also require students to utilize refrigeration concepts to design a chiller for the ethylene glycol.

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