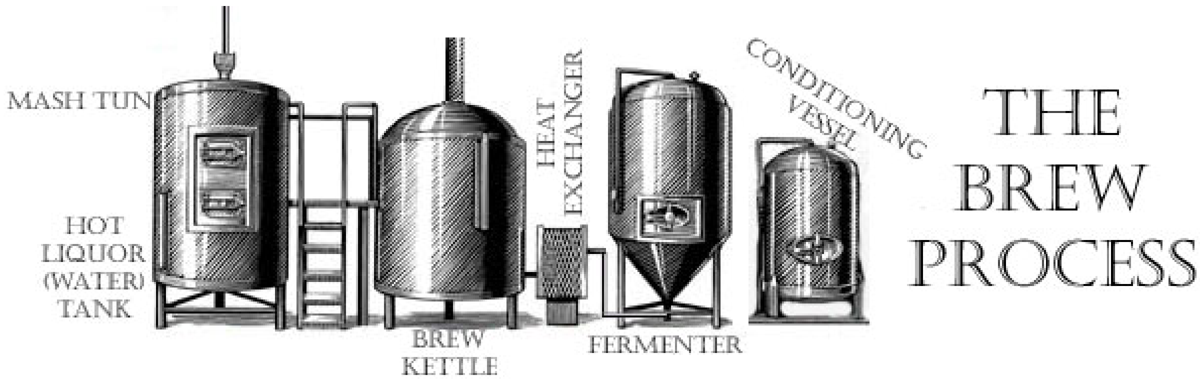
ChE 3031: Heat Transfer

Brewery Design Project



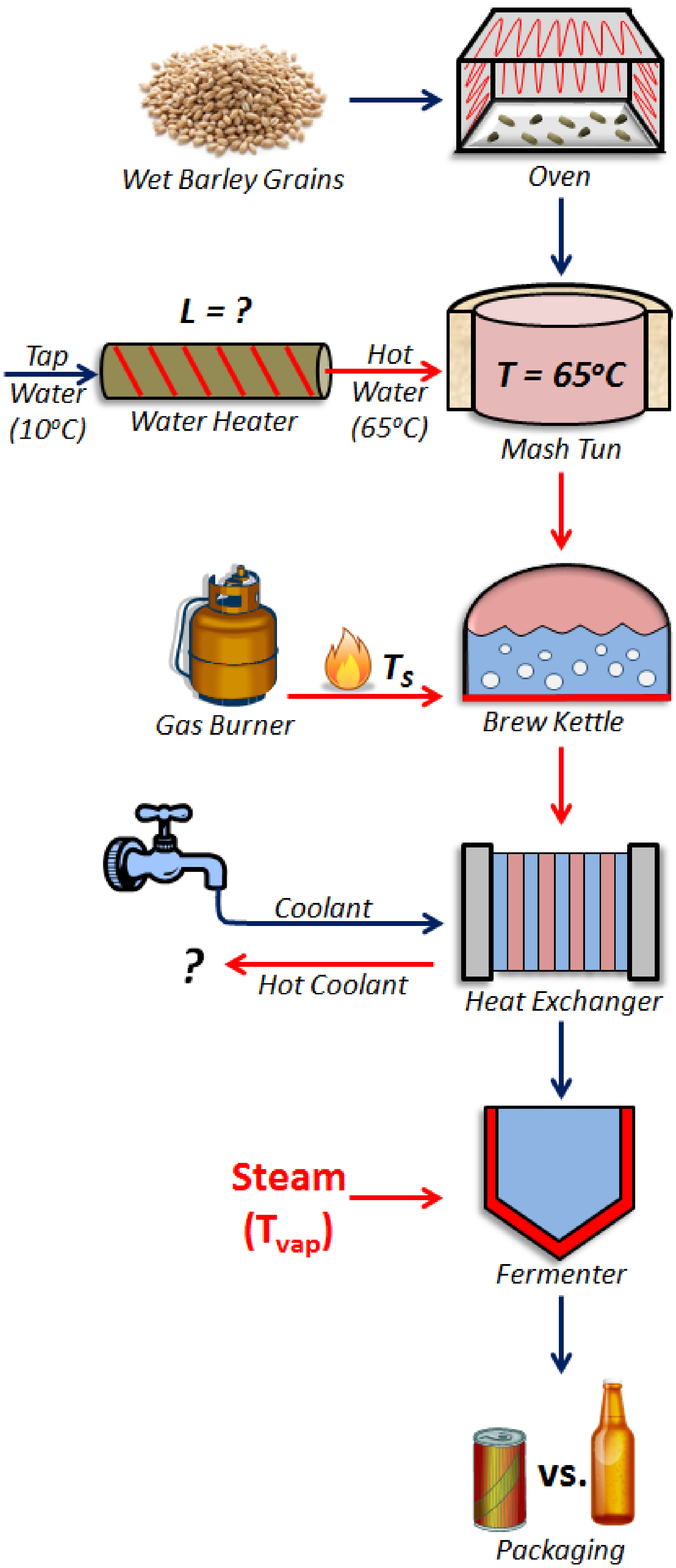
Project Description:

In addition to homework assignments, you will be required to complete a semester-long brewery design project. The goal of this assignment is to use heat transfer concepts and equations to design and optimize several pieces of brewery process equipment, including ovens, water heaters, kettles, and a wort chiller (heat exchanger). At the end of the semester, you will submit a written report and oral presentation that describe your findings.

General Guidelines for this Project:

1. ***All calculations must be done in Excel or MathCad. No hand calculations.***
   - Performing calculations *in silico* will help you rapidly optimize each piece of equipment.
   - Your worksheets will be included in the appendix of your final report.
2. ***You can make any assumptions and changes that you like, as long as they are valid and justified.***
   - This guide provides *an example* of a traditional brewing process. You are encouraged to innovate by changing the process and any of the given variables, but you must dry the barley, soak it in hot (65°C) water for 1 hour, boil wort for 1 hour, and chill wort to 20°C before adding yeast.
   - FYI, the "Journal of the Institute of Brewing" is a scientific journal devoted to brewery science…
3. ***You will be required to select real pieces of equipment for the following steps of the process:***
   - Mash Tun (tank), Brew Kettle (tank), Tankless Water Heater (heat exchanger), Wort Chiller (heat exchanger), Fermenter (tank), and any pumps that are necessary.
   - Examples of brewing equipment suppliers are provided at the end of this guide.
   - You must also consider utility costs and the disposal (or use/recycling) of waste streams.
   - Quotes for the equipment will be included in the appendix of your final report (highlight prices).
4. ***You will pitch your company at the end of the semester in a Shark-Tank-style presentation.***
   - Find a way to make your product stand out – will you be the "environmentally friendly", "local", "quirky", or "just-plain-oddball" brewery?
   - Total costs, efficiency, sustainability, safety, and novelty will be used to judge the final oral presentations and select the "best" design.
5. ***Your grade on this project, which is based on the written report (80%) and oralpresentation (20%), will account for 15% of your final grade.***
6. ***The team with the best design/presentation will receive 1% extra credit on their final course grade.***

Brewery Design Project Overview



1) Natural Convection & Radiation

*Design an **oven** that quickly dries out wet barley grains.*

2) Forced Internal Convection (left)

*Design a tankless/in-line **water heater** to warm water to 65°C for the mash tun.*

3) Conduction and Insulation (right)

*Design a **mash tun** tank that holds wort at a temperature of 65°C for 1 hour.*

4) Process Safety Analysis (left)

*Perform a What-If Analysis around the **gas burner** to identify hazards.*

5) Boiling Heat Transfer (right)

*Determine the optimum **brew kettle** surface temperature to boil the wort.*

6) Heat Exchanger/Wort Chiller (right)

*Design a **heat exchanger** that uses any coolant to rapidly cool the wort to 20°C.*

7) Disposal of Heated Coolant (left)

Determine how you will recycle/cool/ dispose of the heated coolant.

8) Condensation Heat Transfer

*Use steam to heat the **fermenter** to 121C to sterilize it.*

9) Conduction and Insulation (left)

*Select a **container** that will keep your product cold for the longest time.*

An Introduction to Brewing

Millennia of trial-and-error brewing experiments have yielded the conventional brewery process is described below, but there are many variations on this process. You can modify this process in any way, as long as you justify it appropriately.

Drying Grain in the Malt Kiln

The brewery process begins with barley grains (seeds), which are wetted to initiate germination and promote the breakdown of complex sugars (e.g. starch) into simpler sugars (e.g. glucose and maltose) for fermentation. However, since complete germination (i.e. sprouting) would deplete these simple sugars, germination is halted at a specific time by drying the grains in an oven. The resulting sugar-laden dry seeds are referred to as malt.

Extraction of Sugars into the Liquor in the Mash Tun

Simple sugars, flavor compounds, and other molecules are extracted from the malt by soaking them in batches of hot (65^{o}C) water for 1-2 hours in a special tank called a "mash tun." A tankless water heater is typically used to heat tap water from 10^{o}C to 65^{o}C for the mash tun, which is insulated to minimize heat loss during the malt soaking process. The resulting high-sugar liquid is called a "liquor".

Sterilization of the Wort in the Brew Kettle

The liquor from the mash tun must be boiled to remove contaminants (i.e. bacteria, fungi) prior to the yeast fermentation step. Boiling the liquor also removes undesirable volatile chemicals with unpleasant aromas (e.g. dimethyl sulfide). The boiling step is performed in a brew kettle, which is heated to a constant surface temperature (Ts) by a natural gas burner that is controlled by a thermocouple. Since natural gas is flammable and steam is generated in the kettle, this is the most hazardous step of the brewery process.

Heat Exchange in the Wort Chiller

Before yeast can be added to the sterile wort, it must be cooled to 20^{o}C (otherwise the yeast will be killed). Wort chilling is typically done with some sort of heat exchanger, which cools the hot wort with some sort of coolant. This step must be done as quickly as possible to preserve beneficial sugars and flavors in the wort that are lost when the wort is heated for too long.

Sterilization of the Fermenter

In between batches, the fermenter must be sterilized to prevent microbial contamination. Jacketed fermenters can be quickly sterilized by filling the vessel with water and flowing superheated steam through the jacket. As the steam condenses on the fermenter, it heats the water inside to 121^{o}C for at least 30 minutes and sterilizes the fermenter.

Packaging of the Final Product

After fermentation, the final product is chilled to 4^{o}C and stored for different amounts of time for to "condition" the brew. It may then be packaged for sale in either aluminum cans or glass bottles, depending on the manufacturer's preference. The choice of packaging can have significant effects on the taste, appearance, stability, and insulation of the product.

<u>The Rules:</u>

Your process must meet all of the following requirements:

1. **Each step of the process must be able to accommodate 100 gallons of liquid (wort/liquor/beer).**
   a. You must mix 400 lbs. of malt (V ~ 80 gal) with 100 gallons of hot water in the mash tun.
   b. You may neglect volume losses due to straining, boiling, etc. in later steps.

2. **With the exception of the malt kiln (oven), you must select commercial equipment for every step of your process and include quotes/list prices for each item in the appendix of the written report.**
   a. Malt kilns are cheaper to build on site than to order from a supplier, so you can neglect the costs of the malt kiln in your final analysis and focus primarily on its design (heating element positions).

3. **You must achieve the following process setpoints:**
   a. 100 gallons of tap **(<u>not river!</u>)** water must be heated to 65C for the barley.
   b. Barley must be steeped in that hot water ($T_{initial}$ = 70C, T_{final} = 65C) for 1 hour to make the liquor
   c. The liquor must be boiled to sterilize it (filtration is not acceptable)
   d. The wort must be chilled to 20C before adding yeast
   e. The fermenter must be sterilized before adding the wort or yeast
   f. You must select some sort of packaging for your product and provide a justification for it

4. **You must select a location for your brewery.**
   a. The location of your brewery will be used to determine utility (e.g. electricity and water) costs.

5. **A rationale for all fluid flow must be provided**
   a. **<u>Appropriate</u>** pumps or gravity may be used to move fluids between pieces of equipment.
   b. You must provide calculations that show how you will achieve the required flow rates

If you would like to change any part of the traditional brewery process, fill out a process modification form and meet with me to discuss your potential changes. Deviations from the traditional process are encouraged, but must be justified.

<u>Specific Process Guidelines:</u>

All of the process steps and conceptual questions listed in the following pages must be addressed in your written report.

You can only omit steps in the final report if you submit a process modification form and the instructor approves it.

Step 1: Malt Kiln/Barley Drying Oven

Task: Dry 400 lbs (~80 gallons) of barley grains inside an oven.
Goal: Heat the barley as quickly as possible (maximize initial rate of heat transfer)

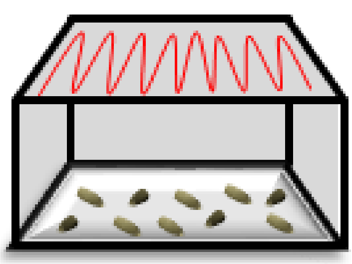
Restrictions/Variables:

- The grains must be spread into a layer that is 5 cm thick and all of the barley must fit into the kiln.
  - Otherwise, you may vary the dimensions of the kiln however you wish.
- You may only use a single heating element with a maximum surface temperature of 200°C.
  - In other words, only one wall of the kiln can be covered by a heating element.
  - The heating element can be horizontal or vertical.

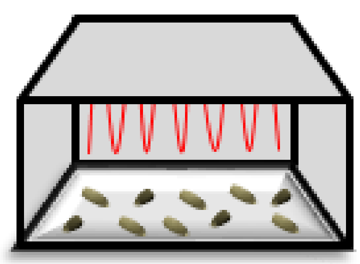
Questions to address in the Written Report:

1. Report the initial total rate of heat transfer (Q_{total}) for 2 different kiln designs (complete the table below).
   a. One of the designs must have a horizontal element, while the other must be vertical.
2. Which of the two designs is better? Justify your answer in terms of radiation and natural convection.
   a. How can you maximize radiation heat transfer? …convection heat transfer?
3. Which mode of heat transfer will dominate if the oven is preheated (i.e. the air is heated to 200°C)?
   a. Does this answer influence your kiln design?

	Kiln Dimensions			**Heating Elements**		**Heat Transfer Rates (W)**	
	Width (m)	**Length (m)**	**Height (m)**	**Orientation**	**Area (m^2)**	$Q_{convection}$	$Q_{radiation}$
Design #1				**Horizontal**			
Design #2				**Vertical**			



Kiln – Horizontal Element



Kiln – Vertical Element

<u>**Step 2: Heating Tap Water to 70C with a Tankless Water Heater**</u>

Task: Heat local tap water to 70C for steeping the barley in the mash tun.
Goal: Calculate the mass flow rate required to provide the desired temperature with a fixed system.

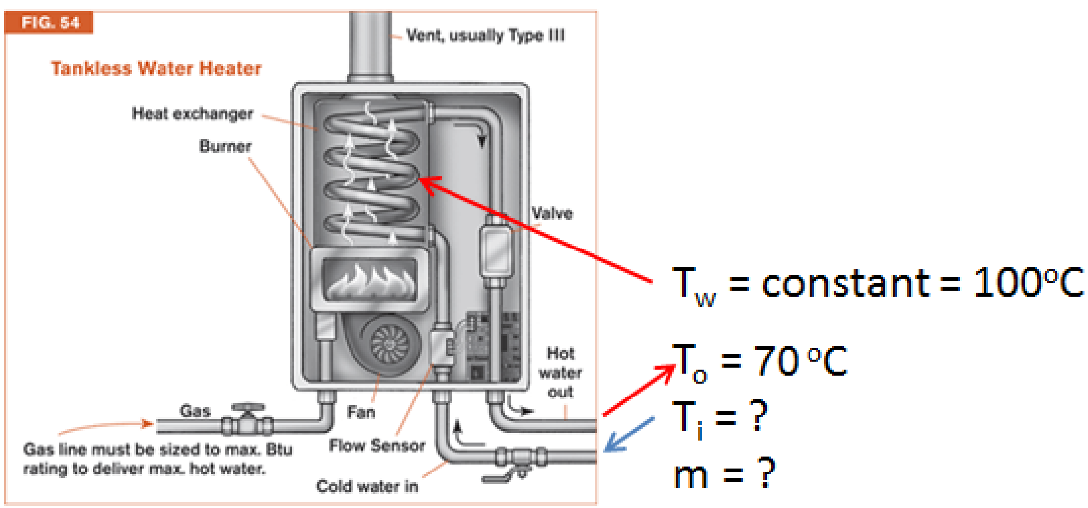
Restrictions:

- You must select a real tankless water heater and use its physical dimensions for your calculations.
- The location of your brewery will determine your inlet tap water temperature.
- You may assume that the wall temperature is a constant 100^{o}C.

Questions to address in the Written Report:

1. Derive an equation for mass flow rate that depends on heat transfer coefficient and inlet/outlet temperatures.
2. What type of flow do you have? Is this type of flow ideal for heat transfer?
3. How would you model a system in which transitional flow occurs (2,300<Re<4,000)?
4. Calculate how long it will take to deliver 100 gallons of hot water and complete the table below:

Heater Dimensions		**Fluid Properties**		**Time to Deliver 100 gallons (min)**
Pipe Diameter (m)	**Pipe Length (m)**	**Inlet Temperature (C)**	**Mass Flow Rate**	



Step 3: Transient Conduction in the Mash Tun

Task: Extract sugars from barley grains using hot water that is initially at 70C.
Goal: Design the mash tun tank such that the temperature of the liquid does not decrease below 65C in 1 hour.

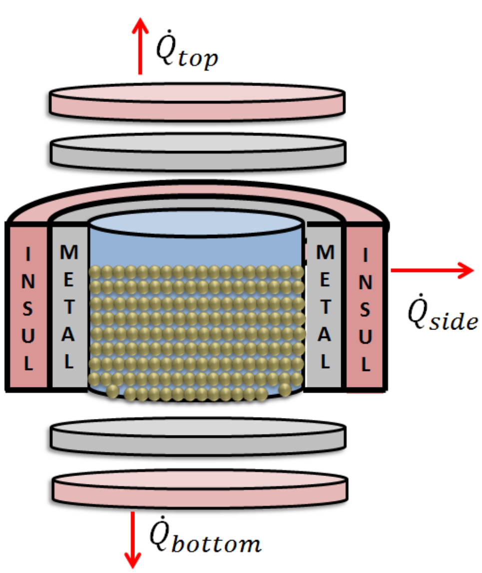
Restrictions/Variables:

- The mash tun/tank must be able to fit both the liquid (100 gallons) and the barley grains.
  - Remember that any excess space will be filled with air and you must account for it in your calculations.
- You must select a real tank for this step, which will determine the dimensions used for your calculations.
- You can insulate the tank however you wish. Insulation costs can be neglected in the final report.
- You may assume the following:
  - The brewery is maintained at a constant temperature of 20C
  - External Heat Transfer Coefficients: h_{top} = 50 W/m^{2}K, h_{bot} = 5 W/m^{2}K, h_{side} = 25 W/m^{2}K
  - Properties of Barley: Density = 650 kg/m^3, Cp = 1.6 kJ/kgK
  - Heat transfer is negligible through the corners of the cylindrical tank

Questions to address in the Written Report:

1. What would the ideal height:diameter ratio be for minimizing conduction through a cylindrical tank?
   a. Are your tank's dimensions (e.g. height:diameter ratio) optimal or sub-optimal?
2. Derive an equation that describes the temperature inside the tank as a function of time [T(t)].
   a. Determine the insulation thickness required to keep the tank above 65C for 1 hour.
   b. Plot the temperature inside the tank over the course of 1 hour. Include the plot in your report.
   c. Will this plot over- or under-estimate the actual temperature inside the tank?
3. Aside from tank height and insulation thickness, describe and justify 3 other ways to minimize heat transfer from the tank.

Properties of the Mash Tun				Insulation Properties		Final Temp (C)
Height (m)	**Diameter (m)**	**Wall Thickness (cm)**	**k (W/mK)**	**Thickness (cm)**	**K (W/mK)**	



Step 4: Boiling the Wort in the Brew Kettle

Task: Sterilize the wort by boiling it in the brew kettle, which is heated by natural gas

Goal: Optimize boiling heat transfer while also reducing the amount of gas burned to heat the kettle (i.e. minimize T_s).

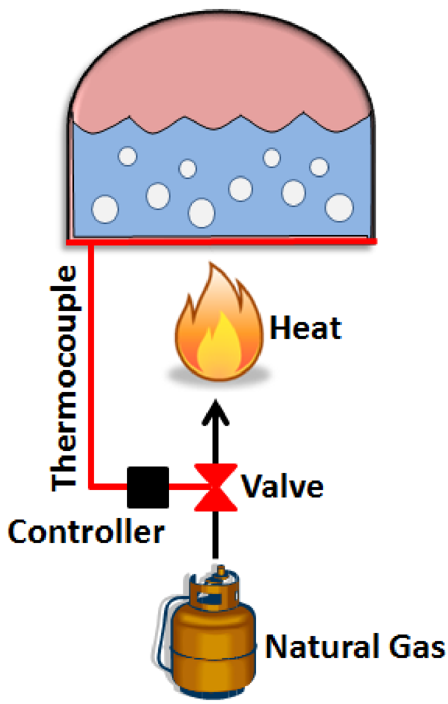
Restrictions/Variables:

- Brew kettles are usually heated by burning natural gas. A thermostat measures the surface temperature (T_s) of the brew kettle and keeps the gas on if T_s is too low or turns the gas off if T_s reaches/exceeds the setpoint.
  - You can use this feedback loop to maintain any T_s you wish.
- You must select a real brew kettle (tank) and use its properties for your calculations.

Questions to address in the Written Report:

1. What type of boiling is most efficient?
2. Compare the optimum T_s values of at least 2 materials. What types of materials provide the lowest T_s?
3. What potential hazards are associated with this system? Perform a What-If analysis and describe at least 2 safety measures that can be implemented to prevent such hazards.
4. Complete the table below:

	Maximum Heat Flux (q_{max})	Brew Kettle Properties		
		Material	C_{sf}	Optimum Surface Temp (T_s)
Brew Kettle #1				
Brew Kettle #2				



Step 5: Cooling the Wort to 20C

Task: The wort must be chilled from 100°C to 20°C before yeast can be added for fermentation.

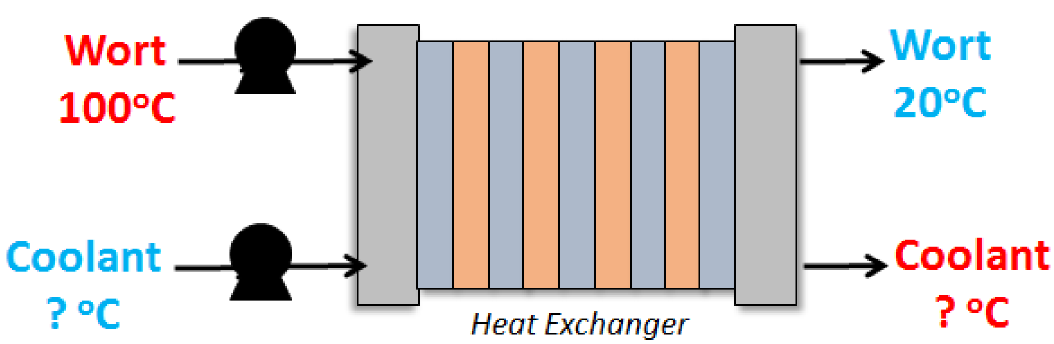
Goal: Cool the wort as quickly (and cheaply) as possible.

Restrictions/Variables:

- The wort must be chilled in 10 minutes or less.
- You must select a real heat exchanger and use its dimensions to perform calculations that verify it can cool the required amount of wort (100 gal) in the specified amount of time (10 min).
- You must select a coolant to use in the heat exchanger. Common choices include:
  - Tap water: must be purchased, but available at pressure
  - River water: free, but must be pumped from nearby source
  - Coolants (e.g. ethylene glycol): expensive, but may have unique beneficial heat transfer properties
  - These are just examples – you are free to choose any coolant you wish as long as it is justified.
- You must use either gravity or pumps to provide the required flow rates for your heat exchanger.
  - Begin by calculating the flow rates and pressure drops for each stream.
  - If you don't use pumps, you must use fluid flow equations to prove that you will have the required flow rates/pressures for the streams in your heat exchanger.
  - If you do use pumps, you must prove that the pump can deliver the required flow rate/pressure (e.g. with product specs). You must also estimate how much electricity the pump will require.

Questions to address in Written Report:

1. Calculate the required heat duty for the wort stream ($Q = mC_p\Delta T$).
2. What type of heat exchanger did you select? Why? Prepare a diagram that shows all of the relevant dimensions of your heat exchanger, along with the mass flow rates, temperatures, and pressures of all streams.
   a. Include a picture of the heat exchanger in the main body of the report.
3. Describe the coolant that you selected and how you will dispose of it (if necessary). How much will it cost?
   a. Explain how you will dispose of your heated coolant. Keep in mind that the Environmental Protection Agency prohibits the dumping of water above 100°F into sewers, rivers, or lakes.
4. Describe the pumps that you will use for your process. How did you select them? How much will they cost?
   a. Include a picture of the pumps in the main body of the report.
   b. If you are not using pumps, provide a detailed explanation for why your approach will work. All statements must be validated with calculations in the main body of the report.



Step 6: Sterilizing the Fermenter

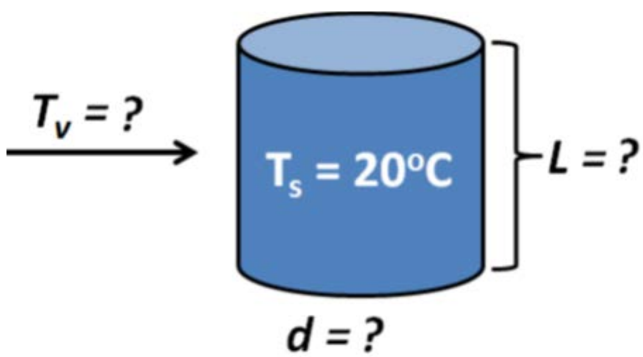
Task: The fermenter must be sterilized by keeping it at 121C for 20 minutes before wort and yeast can be added.
Goal: Determine the effects of superheating steam on the initial rate of heat transfer to the fermenter.

Variables/Restrictions:

- You must find a real fermenter and use its dimensions for your calculations.
  - You can assume that a jacket can be added to any fermenter for a 20% increase in the list price.
  - For conical fermenters, you can assume that a jacket will only cover the cylindrical portion.
- The steam is available at 1 atm (H_{fg} = 2255 kJ/kg, T_{sat} = 100C, C_{pvapor} = 1.9 kJ/kgK).
- The fermenter is initially at equilibrium with the surrounding air (T_s = 20°C).
- You will evaluate the effects of 5 different steam temperatures (Including T_{sat}) on the initial rate of heat transfer to the fermenter and the initial condensate mass flow rate. Present your results in two graphs (T_v vs. Q and m).

Questions to address in the Written Report:

1. How does the initial rate of heat transfer vary with the steam temperature? Prepare a plot of Q vs. T.
2. How does the initial condensate flow rate vary with the steam temperature? Prepare a plot of m vs. T.
3. What temperature of steam would you recommend for the process?
4. How will both of these values change after t = 0?
5. Besides varying the temperature of the steam, describe two ways in which you could further increase condensation heat transfer in this system.



Step 7: Packaging the Final Product

Task: Select a packaging material for your product based on heat transfer concepts.
Goal: Either prevent heat loss while the consumer is holding/enjoying the product or choose a material that allows the consumer to chill the product quickly in a refrigerator after purchasing it at room temperature.

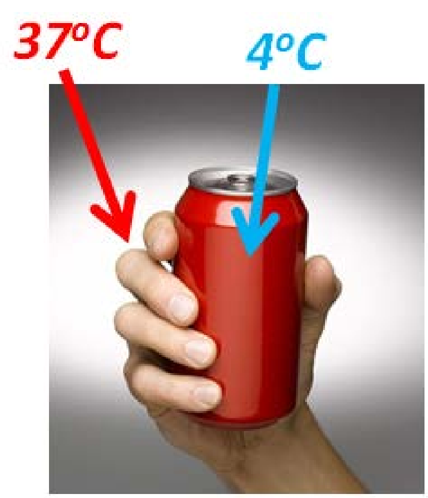
Restrictions/Variables:

- You may either use packaging materials that are currently used for beer (e.g. glass or aluminum) or you can propose an alternative packaging material, as long as it is feasible.
  - Common dimensions for cans, bottles, etc. can also be found online, but you are free to suggest novel geometries (as long as they are feasible).
- You may assume that the majority of heat transfer occurs where the consumer holds the product with a hand at a constant temperature of 37C. Therefore, you can neglect heat transfer from the top, bottom, and anywhere else the consumer is not touching the package.

Questions to address in the Written Report:

1. Estimate the initial rate of heat transfer for an aluminum can, glass bottle, and a 3rd material.
   a. Discuss the differences between these materials/dimensions in the context of heat transfer.
2. Which material will keep the product cool as long as possible?
3. Which material will allow you to cool the product as quickly as possible from room temperature?
4. Select a packaging material (coozie is optional) for your product and rationalize your choice.
5. Design a coozie (you can use any material you like) to insulate your chosen packaging material. How does your coozie influence the rate of heat transfer (e.g. Does it increase/decrease? By how much?).

	Thermal Conductivity (k)	Wall Thickness (mm)	Outer Diameter (cm)	Height (cm)	Initial Heat Transfer Rate
Aluminum Can					
Glass Bottle					
Material #3					
Coozie					(material+coozie)



Deliverable: Written Report/Professional Summary

You must summarize your design optimization in a written report (due on the same day as your oral presentation).

The written report will include the following sections:

Title Page

- Include the following information: Name of Brewery, Location of Brewery, Company Logo, and team names

Executive Summary

- Page limit = 1 page
- Provide a summary of how your process works from start to finish. Briefly explain how you optimized each step and your final recommendations for each step of the process.

Process Diagram

- Page limit = 1 page
- Show every piece of equipment in your process (tanks, pumps, etc.) and any relevant dimensions.
- Show and label all inlet outlet streams – indicate all temperatures and pressures (when appropriate).

Balance Sheet

- See Excel template file on blackboard. Fill in all of the blank fields and **use the indicated units**.

Detailed Process Description

- Page limit = 5-10 pages.
- The purpose and optimization of each unit operation should be discussed in detail.
- Address all of the questions listed in the project guide and include all of the requested tables and figures.
- All of your important assumptions and answers should be **bold and underlined**.

Appendix

- Section 1: Calculations (Excel/Mathcad worksheets)
- Section 2: Quotes for Equipment- Highlight all prices and relevant dimensions. Shipping costs not required.
- Section 3: Approved Process Modification Forms (if any) – see the template at the end of this guide.

Grading of the Final Memo

Your memo will be graded according to the following criteria:

- **Title Page = 10%**
- **Executive Summary/Process Diagram = 10%**
- **Balance Sheet = 30%**
- **Detailed Process Description = 30%**
- **Appendices = 20%**

Submission and Deadline

You must email me your completed memo (jacob.elmer@villanova.edu) as a single PDF document before the class session in which you present. MathCad sheets, Excel workbooks, and Word documents should be saved as PDF files in an organized and neat format (points will be deducted for sloppily printed worksheets). You may merge separate PDF files with PDF modification software (e.g. Adobe or PDFillFree) or you may choose to print off all of your documents and scan them as a single file.

Deliverable: Oral Presentation/Business Pitch

In addition to the written report, you will also deliver an oral presentation to the class that describes your brewery. The presentations will be in the format of a new business pitch – you will be trying to convince the instructor to invest in your new brewery. The team with the best design will receive 1% extra credit on their final course grade as a bonus.

Several criteria (e.g. total costs, efficiency, sustainability, creativity, novelty, and safety) will be used to judge the final designs and assign extra credit. Emphasize the novelty/value/attractiveness of your brewery by addressing the following topics in your presentation:

- **Marketing/Novelty – Why should I buy your product?**
    - Prompts: Who is your target customer? What makes your product different? What feedstocks will you use? How will you sell your product? How do you make your product? How will it be profitable? Do you have plans to scale up your business?
- **Efficiency/Creativity – How have you improved your brewery process?**
    - Prompts: Did you modify the traditional process? If so, what are the advantages and disadvantages of the change? How have you minimized costs? Can you create new revenue streams by utilizing waste streams or energy?
- **Sustainability/Safety/Ethics – Is the process feasible?**
    - Prompts: Is the process feasible in both the short and long term? What feedstocks are you using? Are they renewable? Have you recycled any waste streams or energy? Are there any potential hazards or ethical dilemmas associated with your proposed process?

Grading Criteria:

- **20% = Time**
    - Presentations should be 8-10 minutes long, with $\leq$ 5 minutes for questions afterwards.

- **20% = Participation**
    - All members should participate. If you don't talk, you don't get these points.

- **40% = Content**
    - At a minimum, the presentations should include the following slides:
        - Introduction – Company Name, **Logo**, and Location, Team Member Names
        - Process Overview – Show a diagram of your process and give a brief overview
        - Fluid Flows – Explain how each fluid stream will be moved from point A to point B
        - Unit Operations – Select $\geq$ 3 steps of the process and explain how you optimized each one
        - Economic Analysis – Show equipment and utility costs for a single batch and 52 batches/yr

- **20% = Audience/Instructor Questions**
    - You must satisfactorily answer 2 questions from the instructor and/or audience

Process Modification Form

Please complete this form and bring it with you to meet with the instructor to discuss your modification(s).

Team Names:

Provide a brief description of how you wish to modify the traditional brewery process:

Provide a flowsheet or illustration that shows how your modified process will work:

Approved by Instructor? Yes No

Instructor Signature: ____________________________________ Date: _______________________

Include this completed form in the Appendix of your final written report.

Recommended Websites for finding Equipment:

You are free to use any supplier that you wish (even Amazon or Ebay) as long as you include quotes for all equipment in the Appendix of your report. Previous classes have also found it very helpful to call local breweries (e.g. Victory, Troeg's, etc.) and ask where they get their equipment. A few potential suppliers are listed below to get you started:

Bubba's Barrels:

http://www.bubbasbarrels.com/

Home Depot:

http://www.homedepot.com/b/Plumbing-Water-Heaters-Tankless-Gas/N-5yc1vZc1u0

SS BrewTech:

http://www.ssbrewtech.com/

Sprinkman:

http://www.sprinkman.com/products/craft-brewing-systems/tanks-and-vessels

Brazetek:

http://www.brazetek.com/

Northern Brewer Homebrew Supply:

http://www.northernbrewer.com/shop/brewing/brewing-equipment/

Midwest Supplies:

http://www.midwestsupplies.com/