food for thought

"Food for Thought" explores the relationship between food/drink and chemical engineering processes/concepts.

SIP YOUR MASS BALANCES

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I'd like to introduce a co-author for this column — Seth, a 2023 graduate of our program! He's here because he did a nifty undergraduate project with my colleague Jim Maneval that I want to share with you. It provides a great example for students pondering mass balances and the bigger picture of where our raw materials come from.

If I had to pick a small set of key words someone would have to use to convince a stranger they were a chemical engineer, "mass balance" would be right up there on my list (along with "PFD," "Reynolds number," and "fugacity"). I once used the term "mass balance" in conversation with a physics undergraduate student. She asked, "What does that mean? Isn't it just that mass is conserved?" Sort of. Our students figured out object permanence around their second birthday[1] and conservation of mass somewhere between 6-8th grade.[2] But mass balances don't come at them until the first or second years of their undergraduate careers! Even though this idea rests upon the conservation of mass, it's not quite the same thing. To me, it centers on the idea that you are almost never measuring *everything*. Or, more accurately, that the things that are convenient, easy, or possible to measure are seldom the same as the things you need to know to characterize the chemical and physical changes in a process.

For example: If I make a cake from a box of cake mix, I've got two volume measurements (water, oil), one item-based measurement (egg), and the original box of mix. Everyone agrees that "one cake" is what results, but what *mass* of cake results is actually not the same as the mass of ingredients that went in, because some water and part of the baking soda vaporized (and I licked the spatula). What makes mass balances college-level material is lining up all the measured quantities on whatever basis they started, converting them to mass-basis, then figuring out how much cake there is to share. It's not so straightforward. But starting with cake is a great stepping stone for our mass-and-energy-balance students as they move towards larger processes.

Which brings us to Seth's project. Seth took the Fermentation Technology course with Jim, which discusses all sorts of fermentation processes but mostly the production of beer. It is, as you might imagine, a popular course. For folks less familiar with beer production, the base process for generic "beer" starts with dried, toasted, malted grains soaked in water to make a sugar-rich extract. You concentrate this extract through a boiling step, which sanitizes your extract and also provides an opportunity to add other elements for flavor extraction, such as hops. This liquid is cooled and placed in a clean air-locked vessel, and yeast are added. The yeast grow, eat the sugar, and burp out carbon dioxide and ethanol (and some other flavorful chemicals). After some time — hours to weeks — the yeast are done and we have a beer![3]

This is a lovely process to ask students to draft a mass balance around because it captures many tricky transformation points — phase change, reaction, dissolution — in a relatable process that's pretty easy to see in real life on a field trip to a local microbrewery. Another nice element of this process as a case study for mass balances is how well it works through an environmental sustainability lens, particularly considering the water use throughout the process. Students are commonly surprised through this process to discover just how little of the water used throughout the beer making process ends up in bottles as, y'know, *beer*.

Drawing the box around the process beginning with water and malted grains is a common approach. Seth used his own unique background to take this mass balance one step further. Seth, you see, is a farmer, who grew up on a farm in rural central Pennsylvania. What, thought Seth, would happen if I moved the box around the process to start in the soil? Seth set himself the goal, as an independent student project, to brew beer starting with grains he grew himself. Here's the breakdown in his own words:

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> *My family and I set aside a field by our home, 3.7 acres in a near square field on a mostly uniform semicircle hill running east to west to be planted with a common cultivar of '6-row' barley capable of growing in our central Pennsylvania Susquehanna valley climate. The more common '2-row" varieties of barley used in most beer are mostly incompatible with PA growing conditions. In these 3.7 acres, 400 pounds of barley were planted, with an initial market value of ~$250. Over the course of the summer, only five tractor-based operations were performed to work the field, totaling 23 hours of tractor-based labor, 89 gallons of diesel fuel, and approximately 7.3 tons of organic chicken manure. Only organic chemical fertilizers were used because this field is in the process of attaining organic certification. Operations to prepare the field started in mid-March, and planting took four hours and 14 gallons of diesel in early May, a late start to planting barley in PA but necessary due to extenuating circumstances. The final harvest occurred in August shortly before the semester started. The entire process took 10 hours and 26 gallons of diesel to harvest and take the majority to a local granary. This harvest yielded ~8,400 pounds of barley, unrefined thus including many stalk fragments, small rocks, and field debris. Much of the barley was sold immediately to recover capital investments and due to a lack of storage. No additional water beyond rain (and 75% of manure by weight) was used for irrigation, limiting the yield of plants but drastically reducing the impact of farming.*

I'm popping in to explain the additional step that takes us from the harvested grain to brewing — recall from earlier, the grains used to make beer are "malted." Grains are seeds, and malting is the process of letting the seeds *just* start to sprout. Chemically, this means the enzymes in the seed start turning its stored starches into sugars, upping the sugar content significantly. This sounds straightforward — how many of us have started a seedling and watched it grow, as it cracks open and puts forth a cute first tiny stem or root? I thought this was a simple thing until I watched Seth work in the lab. Timing is crucial — the grains need to develop far enough to be sweet but not so far to be actual seedlings. The cutoff between not-far-enough and too-far along this process can be a matter of hours. And, because the dried grains need to be soaked for this to go forward, mold becomes an issue. And access to air. And having enough space. It was a little like Seth suddenly had a puppy that he couldn't leave alone for more than a few hours or it would destroy the lab.

> *If we begin by retrieving 1 kg of uncleaned barley from the grain bin so that it may be converted into beer, many preparatory steps are needed to conduct a clean and repeatable process. About 13% of the barley is water by mass, and 1% by mass is large debris that can be sifted out easily such as rocks, other plants, insects, and trash. Several washes with water would now be conducted, using a total of 8 to 12 kg of water to rinse the kernels until the water would remain clean. At this point the interior moisture content of the barley was still 13%, even though the mass of the clean grains was 1.5 kg due to retained interstitial water between the grains. Now the grains would be steeped in- and out- of water for three days, alternating soaking and air resting so that the grain takes up water at the right pace, not drowning and allowed to breathe. At this point the kernel would be 44 - 48% moisture, the original 0.99 kg was now 2.5 kg, with 4.4 kg of water used over the course of steeping. Following the steep, the kernels would be germinated so that the kernels would break open the outer hull and release the enzymes needed to break down the starch. This process will have to be stopped before the plant fully starts to sprout. After another three days, the 2.5 kg would have evaporated down to 2.375 kg of kernels at 42 - 44% moisture. The kernels would then be dehydrated down to 0.92-0.95 kg over a course of 16 hours, a moisture content of 5 - 8%, which would be finally kilned down to 0.9-0.93 kg at a higher temperature, imparting the flavors and colors of caramelization reactions. Thus by the end of the malting process, one kilogram of harvested barley resulted in about 0.9 kg of malt, with about 75% viability, meaning 75% of the kernels germinated, potentially lowering the efficiency of the starch degenerating enzymes. One kg of the malt produced about 0.31 kg of sugar at a mash efficiency of 70% and 0.95 gallons of finished beer according to the recipe we were using.* ***A single 12 oz bottle of beer represents 42.3 square feet of farmland, 0.33 gallons (42 oz) of municipal water, and 0.825 hours of labor (farming to bottling).***

What can we all use from this in the classroom? It can be tricky enough to take early students through a beer production mass balance with the traditional boundaries on the process. But it can be even more impactful if we bring the sourcing into the problem and use some of the values Seth shares with us. I've worked with engineering students who, at the start of class, cannot conceive that farming isn't trivial — that corn, soybeans, etc. don't just pop out of the ground and into trucks with minimal human effort. As chemical engineering educators, we should help our students see where the raw materials we turn into food, cosmetics, and pharmaceuticals come from. Seth and I agree if more ChE students appreciated that the beer in their red cup represents nearly an hour of aggregated effort as well as a king-sized-bed worth of field, they should be more likely to show respect for their drink and perhaps their processes' raw materials in general.

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