food for thought

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

LIGHTEN UP!

Margot Vigeant
Bucknell University • Lewisburg, PA 17837

Bubbles are both loved and loathed by chemical engineers. We seek them in order to boost contact surface area between liquid/vapor phases in distillation and stripping, and we dread their unexpected occurrence in pipes or tanks. Bubbles turn out to be key to the structure and flavor of foods, from angel food cake to zwieback. The incorporation of bubbles into baked goods is leavening, which consists of three parts. First, there's the incorporation of nucleation sites into the dough. Then there's the generation (or further incorporation) of gas to grow the nucleated bubbles. Finally, there's the thermal expansion of the bubbles to give us airy and flavorful breads and cakes. Let's take a brief tour through the chemical engineering of tasty bubbles!

Ironically, it always seems like desirable bubbles are difficult to come by and are terribly fragile, while undesirable bubbles never go away. An excellent example of this issue can be found in baked goods, where most of the effort in preparation goes into the creation and maintenance of bubbles. The first step is nucleation. Due to surface tension, smaller bubbles require more energy to make per unit volume than do larger bubbles, and going from no bubble to a tiny bubble takes the most energy of all. This is why the abrupt creation and subsequent demise of bubbles through cavitation is so destructive to impellers or propellers — tiny bubbles can literally *chew through steel*![1] Your average reaction takes the more energetically accommodating route of expanding an existing bubble (heterogeneous nucleation). This is why you see bubbles in Champagne or in a pot of boiling water emerge preferentially from tiny scratches in the surface of the glass or pot — the vapor is expanding tiny bubbles that are already present in that crevasse rather than initiating a totally new bubble. In fact, if you try to boil water in a perfectly smooth vessel, temperatures may reach in excess of 200ºC before bubbles emerge![2] Thus, if anyone's ever told you they are a bad cook by saying, "I can't even boil water," you should cut them some slack because it's more difficult than it seems!

Clearly, a simple increase in temperature isn't going to generate bubbles in bread or cake, so instead we perform mechanical work to create the initial bubbles through mixing and/or kneading. This can be quite a lot of work! Imagine an angel food cake, where the leavening is provided exclusively by beaten egg whites. A typical starting point for such a cake is 12 egg whites, or about 700 mL of fluid. These eggs are beaten until their volume more than doubles and the color shifts from clear to white, indicating the presence of colloidal-size light-scattering bubbles. If we assume that we are capturing 1 L of air in 1 μm diameter bubbles, that means we have about $2x10^{15}$ bubbles with a total surface area of over 6000 m^2! Warning, thermodynamics ahead: approximating the egg whites as having the surface tension of water, we need to do at least 460 J of (reversible) work to create all this new surface area. That sounds like it ought to be a couple of seconds of effort for my 300 W stand mixer, but given that not all of the electrical work going into the motor translates into surface-creation work in the bowl, it actually takes several minutes to generate the bubbles we seek.

Now that bubbles exist, it's time to enlarge them. There are three main sources of additional gas in baked goods. We can add yeast, which burps out carbon dioxide as it consumes

Margot Vigeant *is Rooke Professor of Chemical Engineering at Bucknell University. She teaches chemical engineering thermodynamics, applied food science and engineering, and capstone design. Margot's broad research area is effective pedagogy in engineering, including approaches to conceptual learning and inquiry-based activities for thermodynamics and heat transfer. She is also interested in "making"in engineering and using technology to broaden engagement and access. Margot completed her doctorate at the University of Virginia. She is an ASEE Fellow, Apple Distinguished Educator, and chair of the 2022 ASEE Chemical Engineering Summer School.*

sugars in our dough. We can add a chemical leavener, which reacts or decomposes to generate gas. Or some of the water in our batter or dough may vaporize, expanding the bubbles due to steam. In practice, usually at least two of these are in play when baking.

Breads are typically leavened by yeast or chemicals, while cakes cannot readily be leavened by yeast. Why not? Gas production by yeast is slow relative to gas production from sodium bicarbonate. A glutenous polymeric texture aids in bread-trapping yeast-produced CO_2. The higher proportion of fat and sugar in cake, relative to bread, means that cake does not develop the stretchy texture that comes from gluten. The airy structure in this case comes more from the freeze-frame of bubbles during the "phase change"* from batter to cake than from the patient work of burping yeast.

You may be familiar with two commercial chemical leaveners — baking soda (sodium bicarbonate) and baking powder (composition varies by manufacturer). Sodium bicarbonate can generate CO_2 either by reaction with acid or, at high enough temperatures, from decomposition. Baking powder typically relies on the same fundamental reaction while incorporating a sort of thermal-fuse that releases an acid to react with sodium bicarbonate only at elevated temperatures. Any convenient gas-generating reaction will work, and ammonium bicarbonate was once a popular alternative. On the plus side, since both decomposition products (ammonia and CO_2) are gasses, ammonium bicarbonate leaves no flavor residue unlike the "soapy" taste that baking soda produces. On the rather significant minus side, ammonium bicarbonate produces a poisonous gas and has therefore fallen out of favor for home use.

Steam generation happens in any dough or batter that has free water. For most applications, this is a welcome boost to leavening, but in the case of strictly unleavened bread such as kosher matzoh, it must be avoided. This isn't easy! Wheat is monitored from field to cooking for excess moisture, and water used in the dough is monitored to eliminate possible fermentable elements. Once dough is mixed, matzoh are baked within 18 minutes so that fermentation doesn't have sufficient time to occur.[3] What about steam? While the water content is minimized, it's not zero, so steam is unavoidable. But the matzoh dough is rolled thinly and "docked" — covered in tiny holes — so that any steam that does form escapes rather than creating bubbles within the dough.

Returning to leavened breads and cakes, after we've created nuclei and gas generation, it's time to turn to the thermal expansion of gases. Baking catalyzes the changes needed to turn liquid-like dough or batter to solid-like bread or cake. But there's another thing the increased temperature of the oven has up its sleeve — warm gas occupies a larger volume than cool gas. This was first published by Jacques Charles, balloonist and inventor, which is fitting as steam-leavened baked goods are the special province of the French. Charles's law suggests that the change from room temperature to a hot oven (20ºC → 177ºC) results in about a 50% increase in bubble volume. This doesn't happen, however, because we typically don't cook baked goods until they reach equilibrium with the oven. We have a name for when we do — burnt! The internal temperature of well-cooked baked goods tends to be below boiling. Another factor that stops baked goods from realizing their full expansion under Charles's law is that the resistance to expansion increases as cooking proceeds. You can see this in a pound cake, where the characteristic crack down the middle of the cake results because the interior bubbles keep right on expanding after the edges and surface of the cake are effectively solid. The buildup of pressure has nowhere to go, so the surface of the cake ends up fracturing.

Any way you slice it, all of that bubble nucleation, growth, and expansion leaves us a masterpiece of thermodynamics ready for jam or frosting! Enjoy!

*In this case the "phase change" is not a true chemical phase change; cake batter doesn't go from liquid to solid because it crystallizes. It's more analogous to what happens when paint dries. But that's a detail for another column!

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