ENGINEERING PERFECT PUFFED SNACKS

A Cornell research team supports the food industry with mathematical models of rice puffing.

by **LEXI CARVER**

FIGURE 1. Parboiled rice, unpuffed (top) and puffed (bottom).

A common snack in parts of Asia for centuries, puffed grains have become a staple in mass-produced cereals and snacks on grocery store shelves around the world. The delightful crunch of rice cakes, varieties of puffed corn, and crispy bites in chocolate desserts is familiar (and delicious) for many.

Also familiar is the less desirable sensation of biting into a puffed snack and discovering that it is too soft, too chewy, too dry, or slightly soggy straight out of the bag. What causes these abrupt mishaps?

What happens inside a rice kernel during puffing, for instance? To a casual observer watching the process, a single piece would heat up and then suddenly and explosively changes shape, like popcorn (Figure 1).

But the physics of rice puffing involves an incredibly complex interplay of mass, momentum, and energy transport; rapid water evaporation; material phase transition; pressure buildup; and plastic deformation.

Food companies have put in many hours working to achieve the right moisture and texture in puffed food that will keep customers happy. They've worked to create reliable processing conditions so that the occasional rubbery piece is an anomaly and not the norm. For scaling up puffing methods for production, food companies need to optimize processing for consistent texture, flavor, moisture content, and in some cases, food safety.

⇨ RESEARCHING OPTIMAL PROCESSING CONDITIONS

Using a research grant from the United States Department of Agriculture (USDA) Agriculture and Food Research Initiative (AFRI) program, Cornell University has performed a study of the transport processes in deformable porous media with phase-dependent properties, with a focus on food. Prof. Ashim Datta, from the Department of Biological and Environmental Engineering, led a team to model the dynamics and material behavior during the puffing of parboiled rice[1].

In addition to studying the intricacies of phase change, energy transfer, and mechanical behavior during puffing, their extensive investigations looked into the effects of salt preconditioning, temperature, and initial moisture levels to facilitate the desired final texture.

At the core of their research was the need for a modeling methodology that would be transferrable to many scenarios. "We built a framework for studying the physics of food processes and made it applicable to different problems; for example, frying incorporates a certain set of physical phenomena, while baking involves a somewhat different set but within the same framework," explains Prof. Datta. He elaborates on the particular concerns of the food industry: "Consumers want the texture of fried food, but without the health cost; the same quality, but not the same method.

"So food companies looked into baking and 'popping' as an alternative to frying. They are constantly updating products and processes. When they change something, they have to know the new optimal conditions. The framework we developed allows us to swap conditions more easily to test the effects of different processes on the final food product.

"Once we know how various combinations of temperature and moisture for one way of processing lead

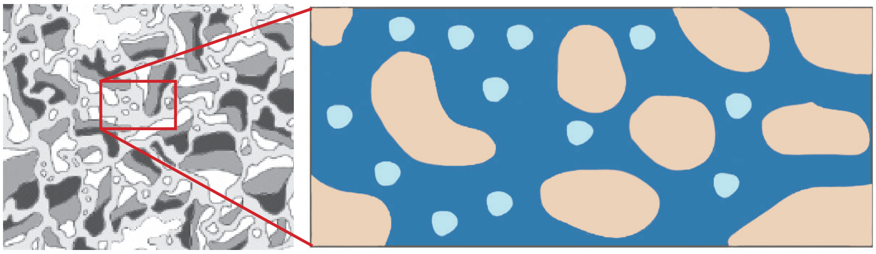

FIGURE 2. Depiction of rice as a porous, elastoplastic solid. The kernel contains liquid water subject to capillary diffusion, convection, and phase change (dark blue); gas composed of water vapor and air, subject to bulk flow, binary diffusion, and phase change (light blue); and a solid starch skeleton that undergoes large deformations (beige).

to certain mechanical properties, we can see whether other processing routes will produce the same food quality. We wanted to determine how different processes affect texture, water or oil content, and even the corresponding health implications.”

One of the biggest challenges facing the research team was the fact that so many different factors influence the final state of the food. Heating a parboiled rice kernel to temperatures of 200°C leads to the rapid evaporation of liquid water, resulting in large gas pressure buildup and a phase transformation in the grain. It transitions quickly from a rigid, glassy state to a soft, compliant (rubbery) one that allows the kernel to balloon into its final shape. Heating time and initial water and salt content also play a deciding role.

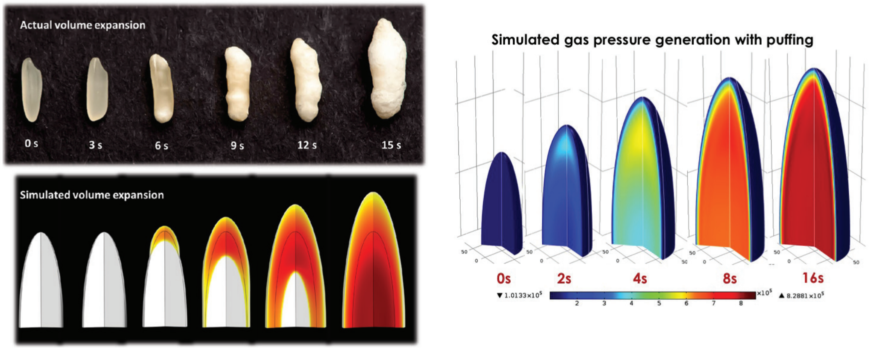

FIGURE 3. Left: Measured volume expansion and simulated volume expansion during a 15-second puffing sequence. Right: Simulation showing gas pressure generation.

⇨ MODELING INTERCONNECTED PHYSICS

In order to understand how these factors work together and hone in on the ideal processing conditions, Tushar Gulati, (a student of Prof. Datta at the time), headed up the work to break down the mysteries of rice puffing.

He used the COMSOL Multiphysics® software to analyze the interconnected mechanical, thermal, material, and fluid behavior within a puffing parboiled rice grain.

“Numerically, this is a very challenging problem,” Prof. Datta commented. “The team studied flow through the porous medium, multiphase transport, solid mechanics, heat transfer, and in other situations incorporated the electromagnetic behavior involved in microwave heating.”

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> — PROF. ASHIM K. DATTA, CORNELL UNIVERSITY

Gulati built a multiphase porous media model to study the mass and momentum changes, energy transport, and large volumetric expansion. The model analyzed the different phases of solid rice, liquid and gas water, and moisture transport modes such as capillary flow, binary diffusion, and pressure-driven flow. He assumed the rice to be an elastoplastic material and obtained mechanical displacement and expansion.

The corresponding simulation revealed the spatial and temporal distributions of temperature, moisture, pressure, evaporation rates, volumetric strain, porosity, and stress levels at different times during puffing (Figures 3 and 4).

The team validated the computational model using a reconstruction of micro-CT images used to determine the expansion ratio and visualize the microstructure development. Gulati also found that the expansion ratio was sensitive to evaporation rates and the intrinsic permeability of the modeled solid matrix.

By the end of his work, they had a fully coupled model that linked the different behaviors occurring during puffing, including the phase change. Gulati coupled the transport model to the large deformation, and also tested how different levels of salt affected volumetric expansion, evaporation, and material properties. Salt lowers the glass transition temperature, meaning that the rice puffs more quickly and at lower temperatures.

“The simulation illustrated how properties vary within the rice grain initially, as well as how they change over time during heating,” Prof. Datta adds. “This would be impossible to measure experimentally. The model tells how the

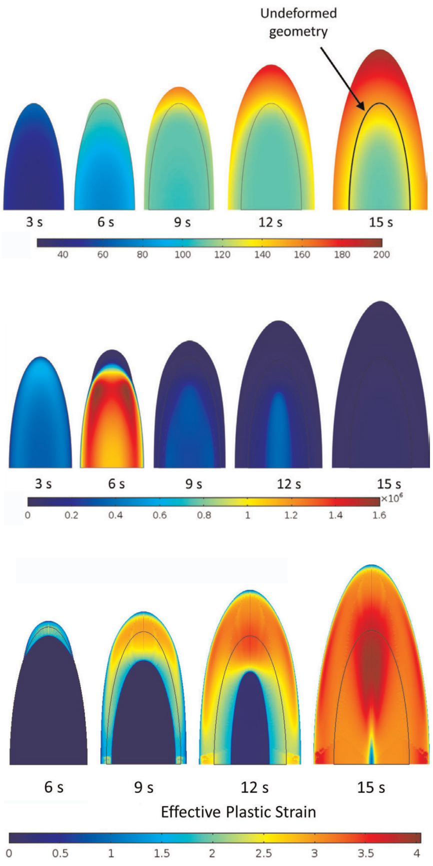


FIGURE 4. Temperature (top, shown in degrees Celsius); first principal tensile stress (center, shown in Pa); and effective plastic strain (bottom) during puffing.

rice grain expands, dries, and shrinks."

The model also provided an understanding of how the porosity developed, illustrating pore formation beginning at the kernel tip and progressing inward (Figure 5).

Based on the results, they determined the optimal amount of salt, moisture content, temperature, and heating time to produce the ideal puffed rice grain. The simulation also showed the conditions needed to maximize the expansion ratio.

⇨ LOOKING FORWARD IN FOOD ENGINEERING

In addition to this model framework, Prof. Datta's research team has extended their simulation practices to studies of food safety. This has big implications for food companies that need to predict the health benefits of certain foods, know when they will expire, and ensure that their processes are safe.

Prof. Datta is currently the PI on a USDA NIFA-funded project where his students are using COMSOL to not only build simulations, but also construct computational apps that extend the analyses to nonengineers. At Cornell University apps are deployed on a large scale via the COMSOL Server™. Apps are beneficial for students and teachers because they don't need to invest in the software or hardware directly.

"Simulation apps bring new opportunities to education," he remarks. "In a food safety class, apps enable multidisciplinary learning where students can simulate many what-if scenarios realistically." The app developed at Cornell is used by several universities around the US.

They have provided food scientists with an app that covers canned food, for analyzing how the necessary heating time for sterilization varies with different container sizes (Figure 6). The app user can adjust the temperature and calculate how long it will take to heat food to a safe temperature for a given can. It also provides an adjusted rate of bacteria dying, to confirm whether or not the final product will be safe for consumption.

Prof. Datta says that, while puffed rice was the starting point, their work is easily transferrable to other biomaterials such as corn — or even to completely different applications. "The physics and modeling knowledge is useful in other industries," he says. "For example, one of my students later studied microwave drying of molds for cars' catalytic convertors, using simulation techniques similar to those we developed here." While he teaches the next generation of engineers about the fundamentals of physics modeling, he looks forward to seeing what comes next for the food industry. ❖

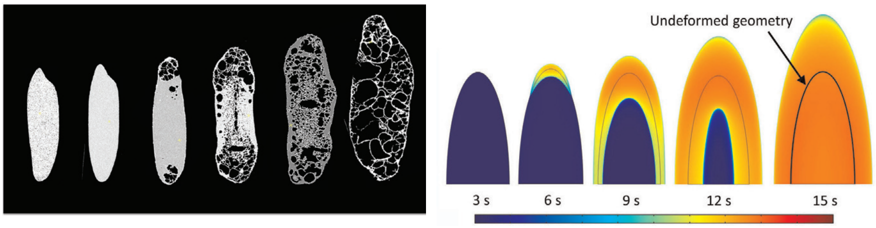
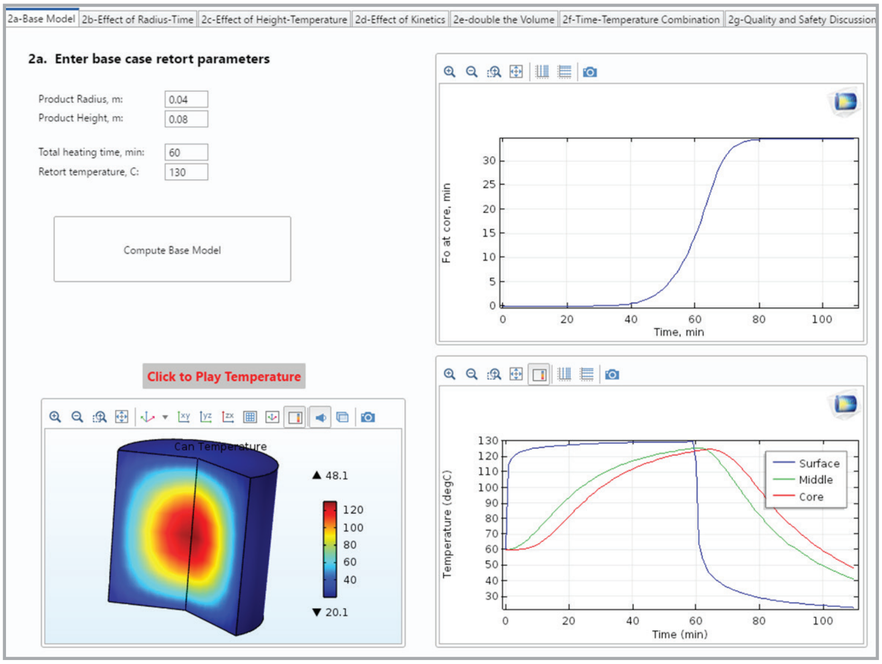


FIGURE 5. Left: CT scan of rice at different times during puffing. Right: Simulation showing predicted porosity profiles.



2a. Enter base case retort parameters

Product Radius, m: 0.04
Product Height, m: 0.08

Total heating time, min: 60
Retort temperature, C: 130

FIGURE 6. The computational app created by Prof. Datta's students for studying canned food. Users can change parameters such as the can dimensions and heating time.

REFERENCES

1. *Gulati, Tushar and Datta, Ashim K. "Coupled multiphase transport, large deformation and phase transition during rice puffing," Chemical Engineering Science 139 (2016) 75–98.*

One of Prof. Datta's favorite parts of his work is teaching a course at Cornell that introduces students to using COMSOL for biomedical process modeling. Because of the software's ability to fully couple integrated multiphysics phenomena, such as those present in rice puffing, he finds COMSOL to be a powerful tool for students to learn about simulation and the underlying physics in different applications of biomedical science.

This year Datta will also present at a workshop at The International School on Modeling and Simulation, a short-term international school that is the outcome of a special interest group for virtualization in food engineering.