QUICK STUDY

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Engineering puffed rice

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Sophisticated materials science lies behind the fabrication of the crunchy, low-fat food enjoyed in cereals and snacks worldwide.

Who wouldn't like to eat something nice and crispy that doesn't have the calories of fried food? Puffed food products, enjoyed all around the world, can provide the crunch without the oil. In the West, puffed products are consumed as breakfast cereals and other ready-to-eat foods. In Asian countries, puffed rice is the main ingredient in some of the most popular snacks.

Puffing rice is similar to popping corn. In an initial pretreatment, the rice grains are soaked in heated salt water, where they absorb moisture; then they are dried. During the puffing stage, the kernels are exposed to intense heat that causes rapid evaporation of the water inside them and creates high internal pressure due to the generated steam. At the same time, the grains, mostly made of starch, soften and expand as pressure builds up. The enlarged grains dry quickly and harden; the result is crispy, puffed rice.

For large-scale manufacturers, delivering a consistently high-quality product, improving on that quality, and using energy efficiently all have enormous financial implications. To achieve those ends, the manufacturers need to understand their processes comprehensively and quantitatively.

Mechanistic model-based simulations can help. Such simulations are based on physical models that have identified the underlying mechanisms responsible for a process; for example, one of the processes underlying the puffing of rice is pressure buildup associated with evaporation. This Quick Study describes a simulation developed by two of us (Gulati, under the supervision of Datta). With that simulation, we were able to show how various process parameters, such as heat input, affect the temporal and spatial evolution of the rice grain and could provide quantitative insight not possible experimentally. The simulation approach also allows for easy, virtual testing of what-if scenarios and helps reduce the time needed to improve on a process or to develop a new process altogether.

Inside the grain

Untreated rice kernels are made of crystalline starch—that is, an orderly arrangement of starch molecules. When rice is puffed without pretreatment, the starch reacts with water and undergoes a process, called gelatinization, that enables it to hold a large amount of water. As a result, only limited water evaporates during puffing, and the rice does not expand as it should to a crunchy final product. When the rice is pretreated, the gelatinization step occurs before puffing, and the orderly structure of the starch converts to an ill-organized form. Because of the transformation in the starch structure, the rice can expand more fully during the puffing process.

The high temperature associated with the puffing process also affects the starch, which changes from a glassy, hard state to one that is rubbery. When the moisture in the grain starts to evaporate, the pressure generated expands the soft and rubbery kernel. The increased porosity (ratio of fluid volume to total volume), due to the kernel's expansion, becomes permanent as the material dries and hardens.

In our simulations, the starch skeleton of the expanding rice grain is modeled as an elastoplastic material. If such substances are not deformed too much, stress (applied force per unit area) and strain (deformation per unit length) are proportional; that's the elastic part of the elastoplastic behavior. But once the so-called yield stress is surpassed, stress in an elastoplastic material is proportional to the strain rate—plastic behavior. Assuming that the rice skeleton is elastoplastic allows us to capture not only the elastic and inelastic expansion of the rice but also its setting into a fixed final state after it has entered the plastic regime and stress is removed.

In the case of rice puffing, the deformation-inducing forces are internal forces arising from intense heating. But a lot is going on in that small grain. As the sketch in figure 1 shows, rice kernels include multiple phases—solid starch, liquid water, and air and water vapor—all distributed nonuniformly within the grain. Various forces described by well-known equations transport the fluid components across the solid starch skeleton. Those include capillarity and gas pressure that drive water, and gas pressure that drives air and water vapor. In addition, in the rice grain, gas diffuses and heat is conducted. In our simulations, we do not attempt to include temperatures, mass concentrations, and the like at every point in

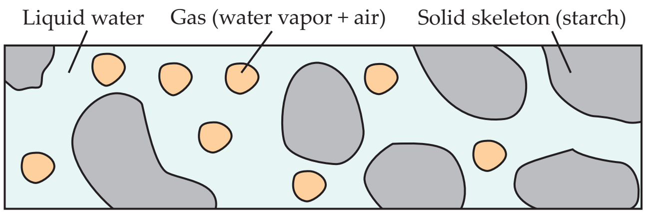

FIGURE 1. MULTIPLE PHASES coexist in a rice kernel: solid starch, liquid water, and gaseous air and water vapor. (Adapted from T. Gulati, A. K. Datta, *Chem. Eng. Sci.* **139**, 75, 2016.)

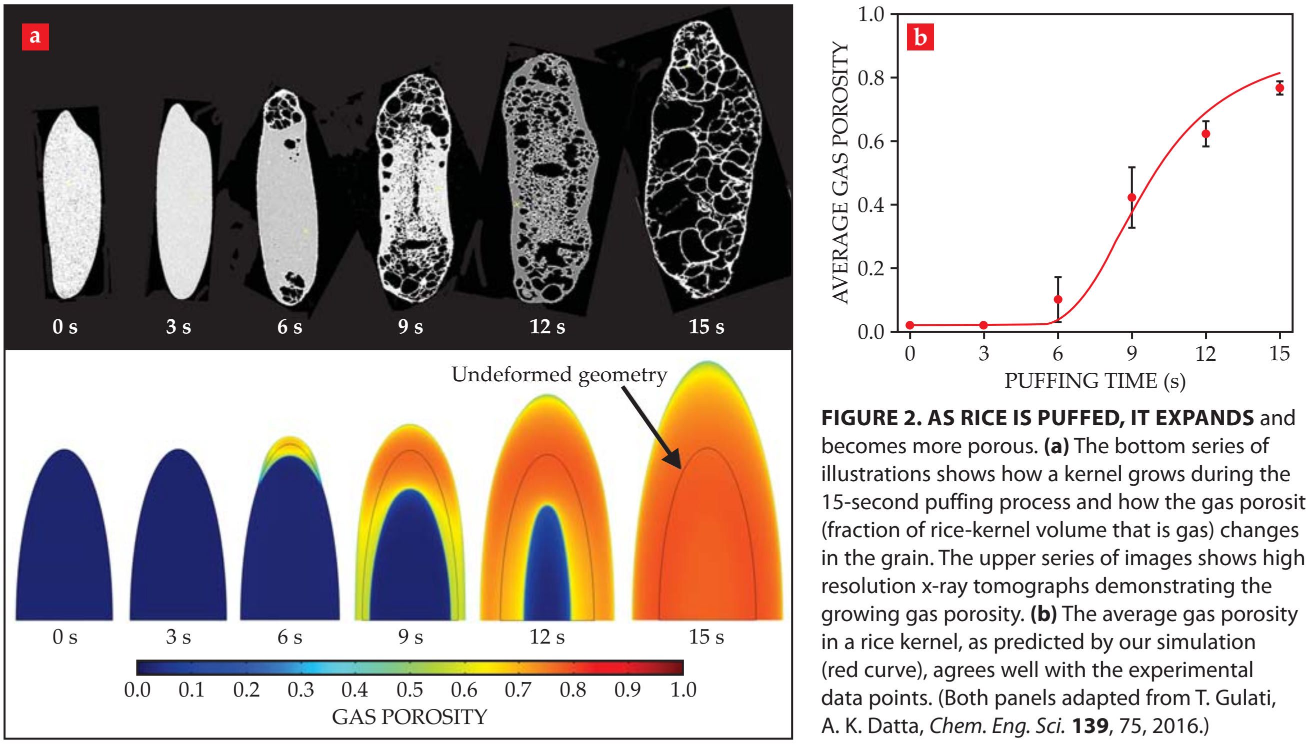

FIGURE 2. AS RICE IS PUFFED, IT EXPANDS and becomes more porous. **(a)** The bottom series of illustrations shows how a kernel grows during the 15-second puffing process and how the gas porosity (fraction of rice-kernel volume that is gas) changes in the grain. The upper series of images shows high-resolution x-ray tomographs demonstrating the growing gas porosity. **(b)** The average gas porosity in a rice kernel, as predicted by our simulation (red curve), agrees well with the experimental data points. (Both panels adapted from T. Gulati, A. K. Datta, *Chem. Eng. Sci.* **139**, 75, 2016.)

the rice grain. Instead, all variables in our equations are averages over a representative elementary volume, defined as the smallest volume over which averaged quantities are representative of the material as a whole. Determining a representative elementary volume is a challenge in itself that is beyond the scope of this brief tutorial.

As the rice grain warms up and water evaporates, the parameters governing diffusion, heat conduction, stress–strain relations, and so forth change. In particular, the mechanical properties of starch are drastically changed to capture the effect of the material transitioning from glassy to rubbery. Having incorporated all those complications in our model, we can probe the effects of individual transport mechanisms on the final puffed product.

Results and future directions

Figure 2 shows representative findings. The illustrations in panel a show how the rice grain grows and the gas porosity (volume of water vapor and air as a fraction of the whole) changes during the 15-second puffing period. Panel b presents the gas porosity information graphically. Our simulations show that the tip of the grain is always the hottest part. Thus the change in starch from glassy to rubbery initiates at the tip, and that is where grain expansion starts. As the grain expands, the stresses drop at the tip, but with time the grain's interior also transitions to the rubbery state and expansion continues to the core.

We in the Datta group have used our model-based simulation to track spatial variation and temporal evolution of temperature, moisture, porosity, and mechanical stress during the rapid puffing process. We have also explored volume change and the transport of liquid and vapor phases. Experimentation alone would not yield such detailed knowledge of the process.

Our model can help manufacturers to significantly reduce trial-and-error experimentation by predicting optimum conditions such as salt concentration during pretreatment, moisture content after pretreatment, and puffing temperature. With an extended version of our original model, we have looked at gun puffing, a more intensive process in which a large pressure differential is created between the inside and outside of the grain and then is rapidly released. We have shown that decreasing the pressure release time increases the final volume of the puffed kernel.

Datta is currently leading an effort to develop a comprehensive framework for predicting the changes that a food material undergoes during processing; the simulation of rice puffing, with its complex and coupled physics of multiphase transport, solid mechanics, phase transition, and plasticity, is a step in that more general development. In the future, we hope, models will account for additional complex processes—for example, electromagnetic effects in microwave puffing, reactions such as those leading to color development, and additional mechanical behaviors in materials. As part of the new effort, we also plan to incorporate our simulation models in applications that can be used by people with no simulation background. Industrial producers and students alike can then apply their creativity to explore food products and process designs.

Additional resources

▶ R. Chinnaswamy, K. R. Bhattacharya, "Studies on expanded rice. Optimum processing conditions," *J. Food Sci.* **48**, 1604 (1983).

▶ T. Gulati, A. K. Datta, "Coupled multiphase transport, large deformation and phase transition during rice puffing," *Chem. Eng. Sci.* **139**, 75 (2016).

▶ R. G. M. van der Sman, J. Broeze, "Structuring of indirectly expanded snacks based on potato ingredients: A review," *J. Food Eng.* **114**, 413 (2013).

▶ A. K. Datta, "Toward computer-aided food engineering: Mechanistic frameworks for evolution of product, quality and safety during processing," *J. Food Eng.* **176**, 9 (2016).