Modeling Flow and Deformation During Salt-Assisted Puffing of Rice Kernels

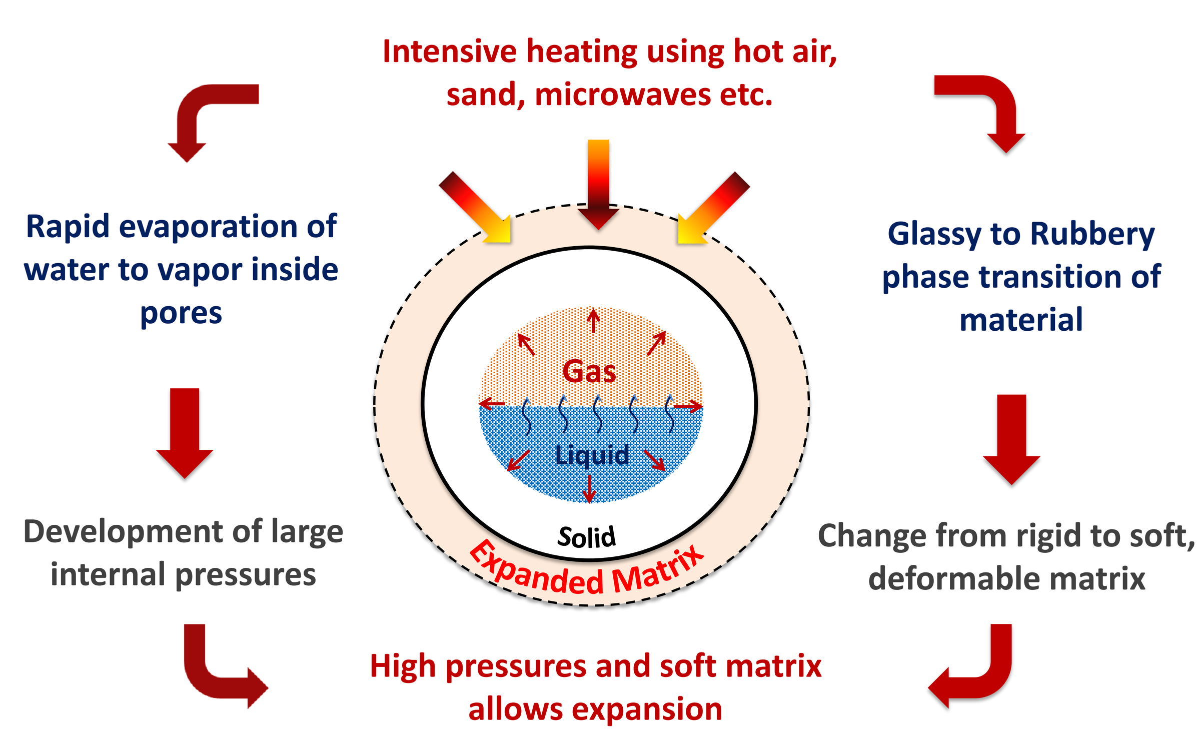
T. Gulati & A. K Datta

Department of Biological & Environmental Engineering, Cornell University, Ithaca, NY, USA

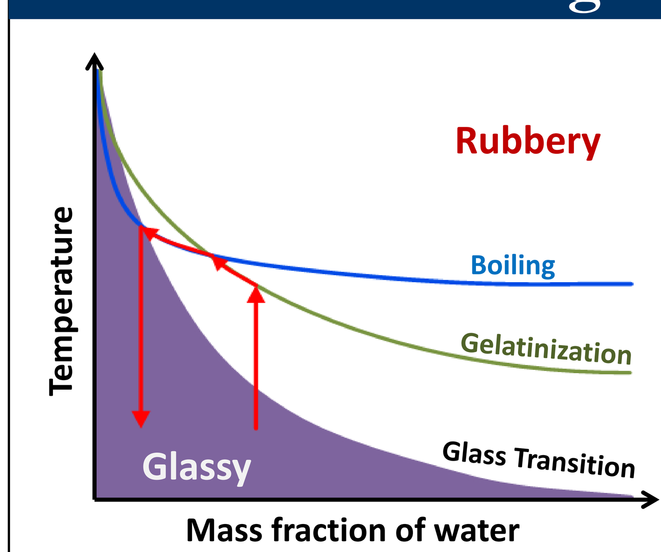
Overview

- Rice puffing is studied using numerical and experimental methods to explain puffing of biomaterials when subjected to intense heat
- High pressures (due to intense heating) and a soft matrix (due to glass transition) allows for large volumetric expansion of the kernel
- Under suitable puffing conditions, the ratio of initial volume to volume of rice could be as high as 6; a higher expansion ratio indicates a better quality product
- By treating rice as a porous material, a fundamentals-based model of rice puffing process that can describe heat and moisture transport, rapid evaporation and large deformations of the solid matrix is presented to understand the factors affecting the puffing process

Physics of Expansion



Rice Puffing Phenomenon



Pathway for rice puffing process

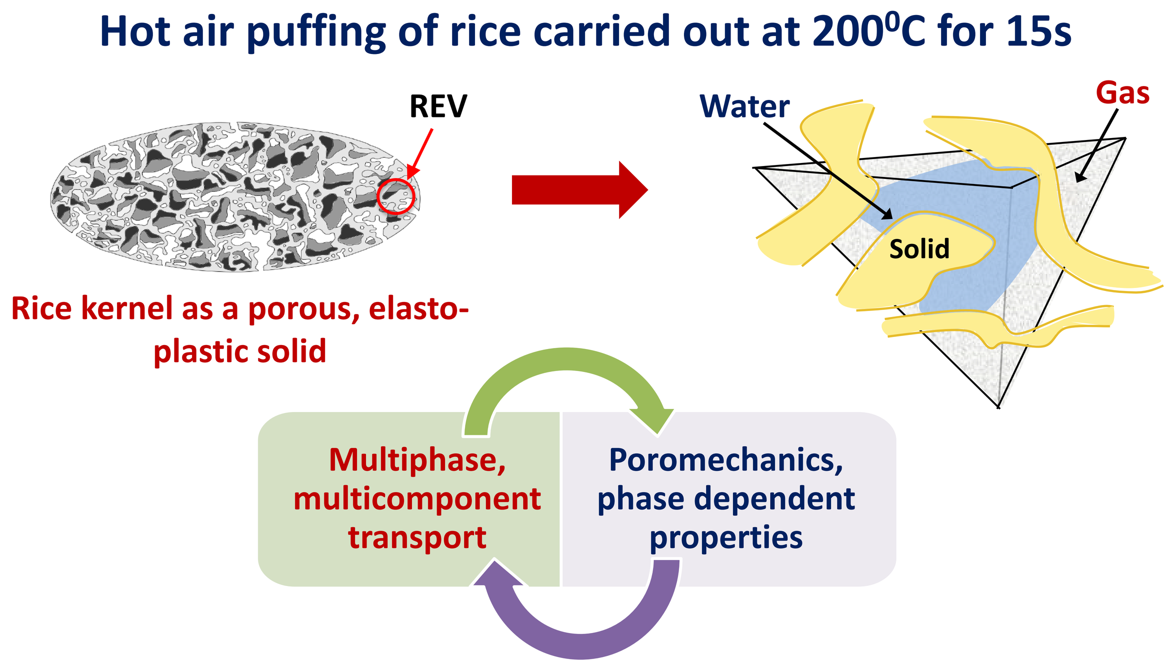
Parboiled rice puffs better than raw rice due to a low glass transition temperature and less crystalline starch

High temperatures and salt pretreatment lead to high expansion ratio of the puffed product

Initial moisture content of about 10%-11% (wet basis) is found ideal for puffing

Modeling Framework

Hot air puffing of rice carried out at 200°C for 15s



Prediction of Key Quality Attributes

Porosity | Final Moisture | Degree of volumetric expansion

Heat & Mass Transport Model

Mass conservation of different species:

Liquid Water:

$$\frac{\partial c_w}{\partial t} + \nabla\cdot\underbrace{\left(\rho_w \mathbf{v_w}\right)}_{\text{bulk flow}} = \nabla\cdot\underbrace{\left(D_w \nabla c_w\right)}_{\text{capillary flow}} - \overbrace{\dot{I}}^{\text{phase change}}$$

Water Vapor:

$$\frac{\partial c_v}{\partial t} + \nabla\cdot\underbrace{\left(\rho_g \omega_v \mathbf{v_g}\right)}_{\text{bulk flow}} = \nabla\cdot\underbrace{\left(\varphi S_g \frac{C^2}{\rho_g} M_a M_v D_{eff,g} \nabla x_v\right)}_{\text{binary diffusion}} + \dot{I}$$

Air:

$$\underbrace{\omega_v + \omega_a}_{\text{Mass Fraction}} = 1$$

Energy balance:

$$\rho_{eff} C_{p,eff} \frac{\partial T}{\partial t} + \nabla\cdot\left[\underbrace{\sum_{i=w,v,a}\left(c_{p,i}\mathbf{n_i}T\right)}_{\text{convection}}\right] = \nabla\underbrace{\left(k_{eff}\nabla T\right)}_{\text{conduction}} - \overbrace{\lambda\dot{I}}^{\text{Evaporative Cooling}}$$

Momentum balance:

$$\frac{\partial c_g}{\partial t} + \nabla\cdot\left(\mathbf{n_{g,G}}\right) = \dot{I} \qquad \mathbf{n_{g,s}} = -\rho_g \frac{k_g k_{r,g}}{\mu_g}\underbrace{\nabla P}_{\text{gas pressure gradient}}$$

Darcy (convective) Velocity

$$\mathbf{v_i} = -\frac{k_i k_{r,i}}{\mu_i}\nabla P$$

Phase Change:

$$\dot{I} = K\frac{M_v}{RT}\underbrace{\left(p_{v,eq} - p_v\right)}_{\text{Non-Equilibrium Formulation}}$$

Flux due to material deformation:

$$\mathbf{n_{i,G}} = \mathbf{n_{i,s}} + \underbrace{c_i \mathbf{v_{s,G}}}_{\text{Solid Velocity}}$$

Solid Mechanics Model

Solid Momentum Balance:

$$\nabla.\sigma = \underbrace{\nabla P}_{\text{Gas pressure gradient drives deformation}}$$

Stresses:

$$\underbrace{\sigma}_{\text{Cauchy Stress}} = J^{-1}\underbrace{\mathbf{F}}_{\text{Deformation Gradient}}.\mathbf{S}.\mathbf{F}^T, \qquad \mathbf{F} = \underbrace{\mathbf{F_{el}}}_{\text{Elastic Deformation}}\overbrace{\mathbf{F_{pl}}}^{\text{Plastic Deformation}} \qquad \underbrace{\mathbf{S}}_{\text{2nd PK Stress}} = \frac{\partial W_s}{\partial \mathbf{E}}$$

Large Strains:

$$\mathbf{E} = \frac{1}{2}\left[(\nabla.\underbrace{\mathbf{u}}_{\text{Solid displacement}})^T + \nabla.\mathbf{u} + (\nabla.\mathbf{u})^T\nabla.\mathbf{u}\right]$$

Constitutive Law:

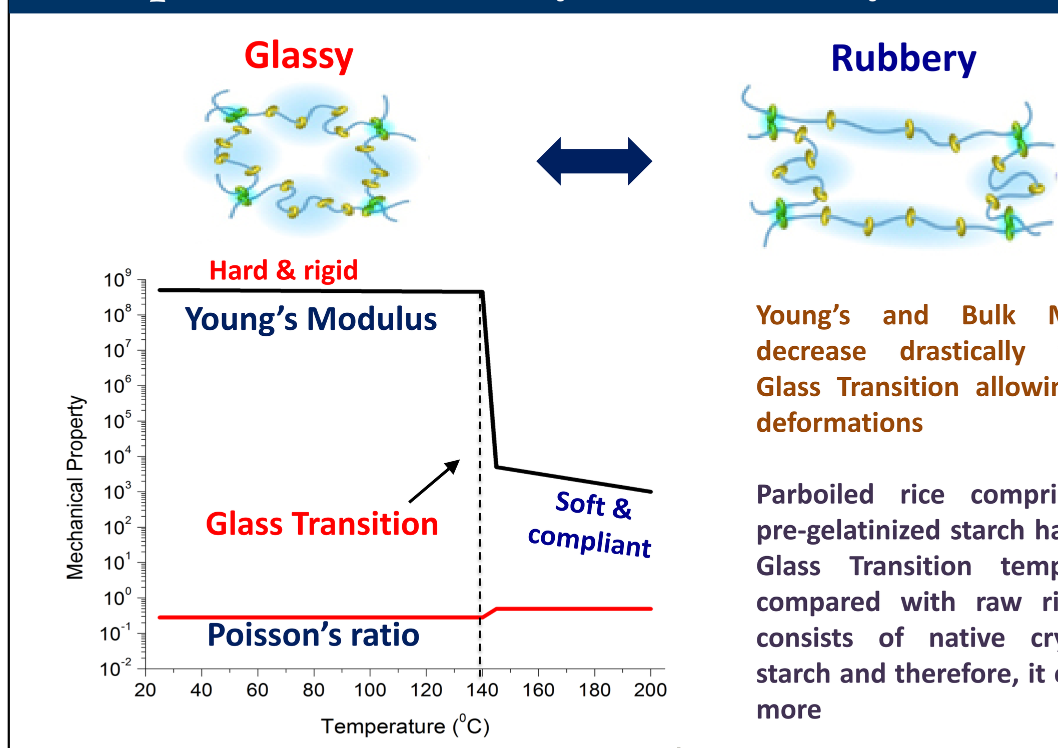
$$W_s = C_{10}(\bar{I}_1 - 3) + C_{01}(\bar{I}_2 - 3) + \frac{1}{2}\kappa(J_{el} - 1)^2$$

Mooney-Rivlin Hyperelastic Material

Material Flow:

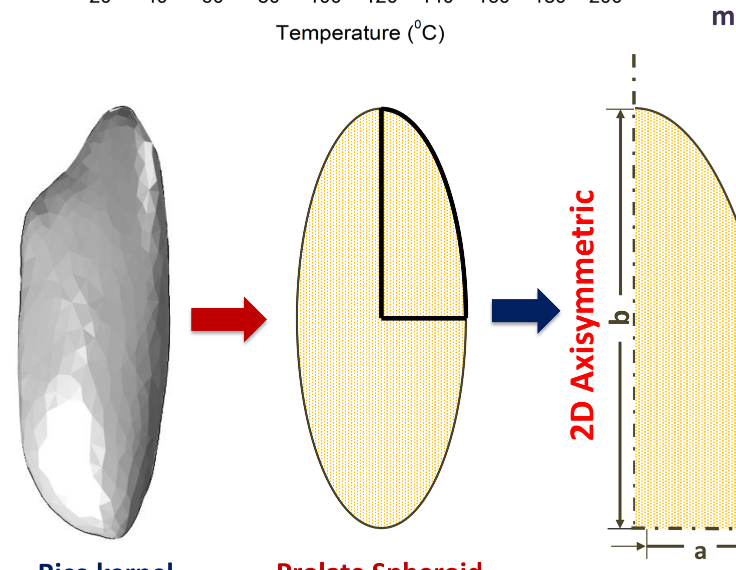
$$F = \underbrace{\sigma_{mises} - \sigma_{YS}}_{\text{Von-Mises Yield Criterion}} \qquad \underbrace{\sigma_{YS} = \sigma_{YS0}}_{\text{Perfectly-Plastic Material}}$$

Properties, Geometry & Boundary Conditions



Young's and Bulk Modulus decrease drastically through Glass Transition allowing large deformations

Parboiled rice comprising of pre-gelatinized starch has lower Glass Transition temperature compared with raw rice that consists of native crystalline starch and therefore, it expands more



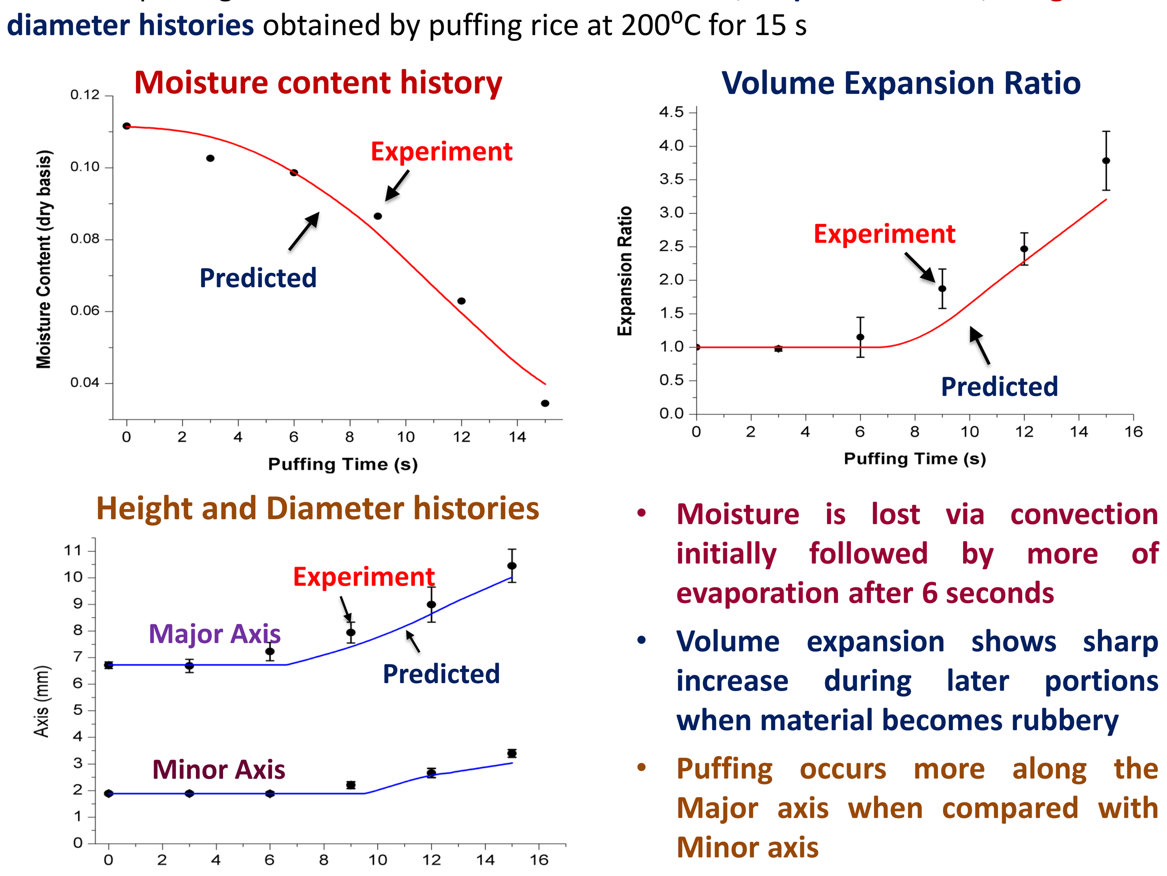
- Forced convection heat transfer
- Moisture Loss through evaporation
- Free surface for expansion

a = 0.94 mm
b = 3.35 mm

- No axial displacement
- Insulated for energy and moisture transfer

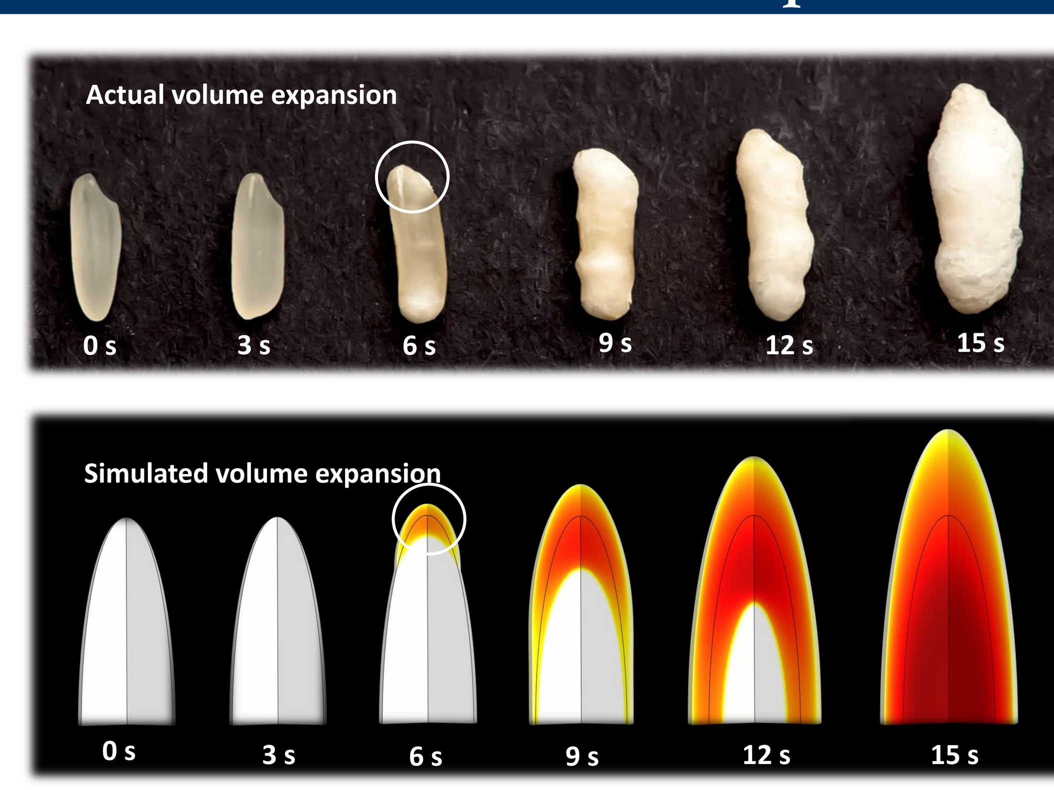
Results: Model Validation

The rice puffing model was validated for **moisture**, **expansion ratio**, **height** and **diameter histories** obtained by puffing rice at 200°C for 15 s



- Moisture is lost via convection initially followed by more of evaporation after 6 seconds
- Volume expansion shows sharp increase during later portions when material becomes rubbery
- Puffing occurs more along the Major axis when compared with Minor axis

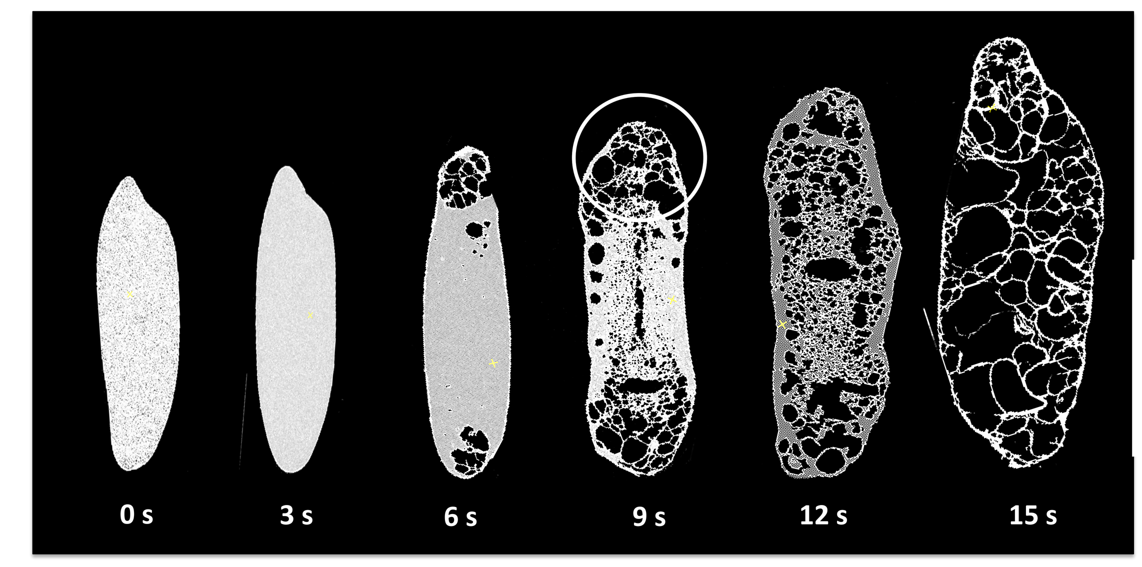
Actual and Simulated Expansion



Rice begins to puff from the tip and the developed model can simulate this phenomena reasonably well

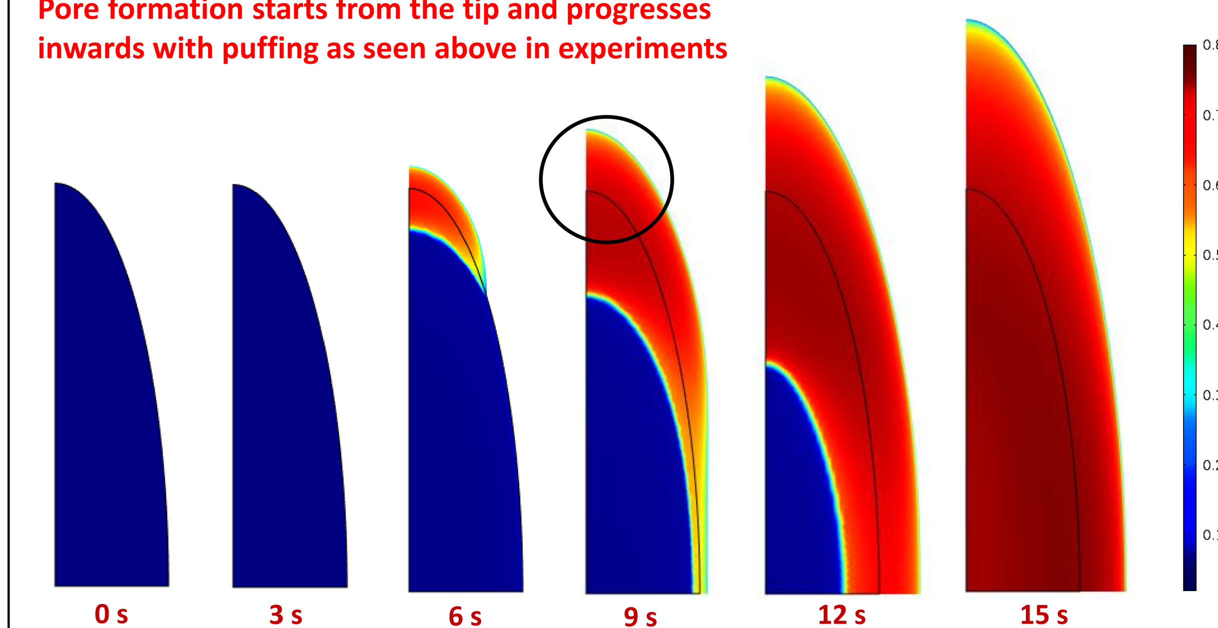
Microstructure Development

Micro-CT of rice at different puffing times



Porosity as predicted by the model

Pore formation starts from the tip and progresses inwards with puffing as seen above in experiments

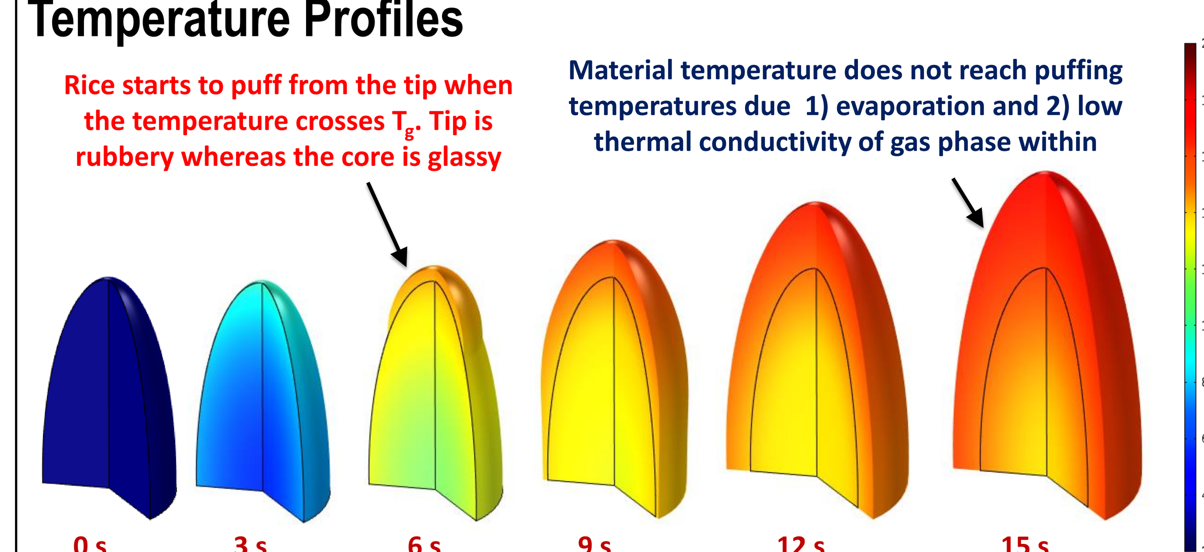


Temperature & Pressure Profiles

Temperature Profiles

Rice starts to puff from the tip when the temperature crosses T_g. Tip is rubbery whereas the core is glassy

Material temperature does not reach puffing temperatures due 1) evaporation and 2) low thermal conductivity of gas phase within



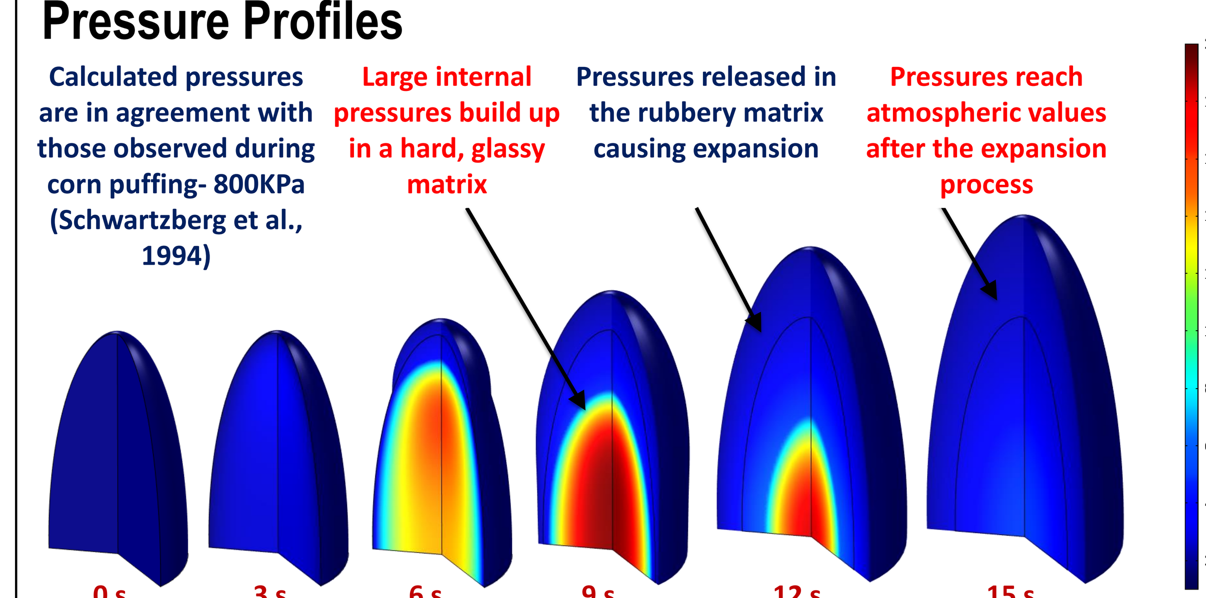
Pressure Profiles

Calculated pressures are in agreement with those observed during corn puffing- 800KPa (Schwartzberg et al., 1994)

Large internal pressures build up in a hard, glassy matrix

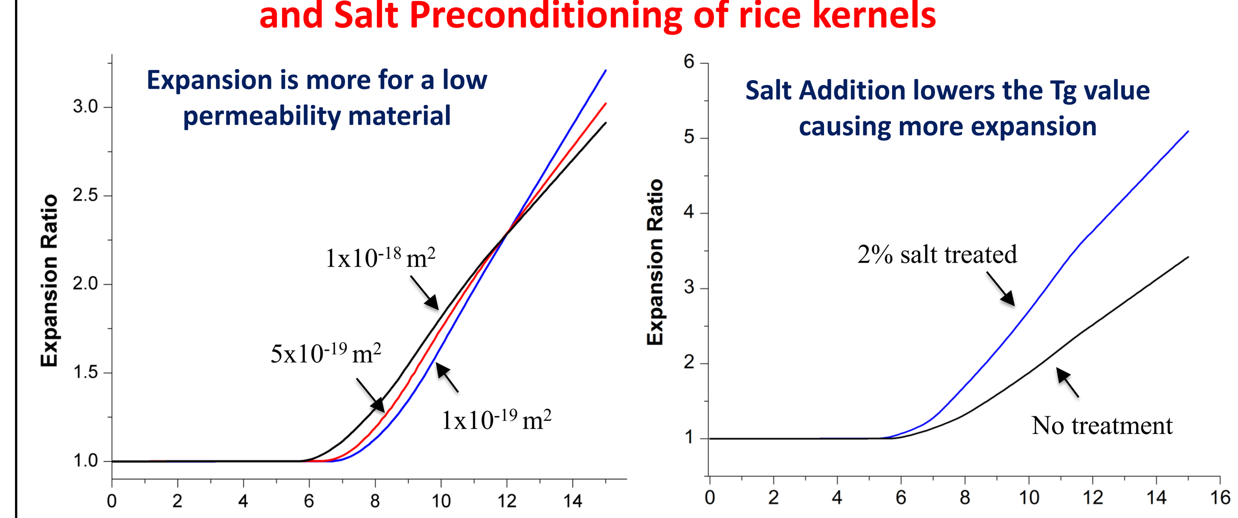
Pressures released in the rubbery matrix causing expansion

Pressures reach atmospheric values after the expansion process



Expansion Ratio as Quality Parameter

Volume Expansion Ratio as affected by Intrinsic Permeability and Salt Preconditioning of rice kernels



Summary & Potential Applications

A **fully coupled model** for multiphase transport and large deformation during **rice puffing** was formulated, solved using finite elements and validated using experimental measurements.

- **High temperatures** are required to generate pressures and glass transition to puff the grain
- Rice starts to **puff from the tip** where it becomes rubbery. **Pore formation** within the kernels follows a similar trend.
- **Large pressures are developed** in the glassy regions near the core that are subsequently released when the material transitions to the rubbery state and puffs

The model developed for rice puffing can be extended to many other **puffing type processes** and products e.g., using **hot oil, gun puffing, extrusion, microwave puffing** and **starch based-foamed plastics in the chemical process industry.**

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