Stress Crack Formation During Drying of Corn Kernels

Pawan S. Takhar * and Srivikorn Dit-u-dompo

Department of Animal and Food Sciences, Texas Tech University, TX 79409 E-mail: pawan.takhar@ttu.edu

Abstract

Three-scale fluid transport equation of Singh et al. [3] was coupled with viscoelastic stress equation to predict crack initiation in corn kernels. A relation between the strain tensor and shrinkage of kernels was developed. The corn was assumed to undergo uniform volume change, with the shape of kernel remaining geometrically similar to its initial shape. The diffusive properties and the coefficient relating viscoelastic stress to moisture diffusion were estimated using the inverse method. Micro computed tomography (micro-CT) experiments were conducted to capture the internal structural components of corn kernels. The 2D CT-scan images were converted to 3D geometry using Avizo software. The 3D geometry was imported in Comsol Software where the solution of equations was obtained. The equations were solved in stationary Lagrangian coordinates. After obtaining the solution, the data was exported to Matlab for converting it back to the moving Euerian coordinates and calculation of stresses. Simulations were performed for various temperature and humidity conditions for both continuous and intermittent drying. The conditions causing the least amount of stress-cracks were identified.

Keywords: CT Scan; Geometry Reconstruction; Image to Simulation; Multiscale Multiphysics Transport

1. Introduction

Food materials often develop stress-cracks during fluid transport processes (e.g. drying and sorption) due to interaction of several factors. Identifying critical regions, where cracks may develop, is a tedious task because of multiscale nature of stresses; presence of multiphases; non-homogeneous structure; and phase transitions (e.g. glass transition) caused by heat and moisture transport.

In this paper, corn kernel geometries with different components are reconstructed from 3D imaging experiments using MicroCT. The resulting geometry, containing all the details with real-world fidelity, is then meshed and simulated with multiphysics, multiscale numerical model. By performing simulations with various combinations of drying air and temperature, optimum drying conditions causing sufficient moisture loss and minimal crack formation can be obtained.

The paper is organized in the following way. Section 2 details the experimental setup and volume visualization of the acquired data. Section 3 demonstrates the reconstruction of corn kernel geometry. Section 4 discusses the governing equations and Comsol simulation. Section 5 presents the results. A conclusion summarizing the image to simulation workflow is presented as section 6.

2. MicroCT Experiments and Volume Visualization

To create the corn's 3D geometry, a micro-CT (computed tomography [5]) scan was performed at a resolution of 2.7392 micrometer in x, y and z directions. The CT scan results are stored as a stack of 253 tif images. Each image has 398 pixels in x direction and 454 pixels in y direction. The 2D slices obtained using micro CT were reconstructed into a 3D volumetric dataset using Avizo software [1].

In Figure 1, the volume data is sample at three orthogonal planes. The scanning direction is along Z axis. XY and XZ planes are colored with grey scale, while YZ plane is displayed using the colormap at the top of Figure 1. Opacity is applied in proportion to intensity, to make low intensity pixels transparent. Note the three components, hard endosperm, soft endosperm and germ are illustrated with fonts color coded corresponding to later segmentation results. Figure 2 shows hardware accelerated direct volume rendering of the full data.

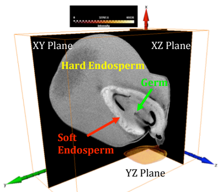

Figure 1. MicroCT image reconstruction: plane cuts. Note YZ plane is color contoured with the colormap shown at the top of the image.

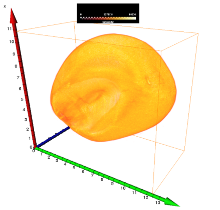

Figure 2. Direct volume rendering of MicroCT image data. Colormap is the same as Figure 1.

3. Geometry Reconstruction

After appropriate filtering, automatic and interaction segmentation algorithms were adopted to segment the corn kernel into various components such as hard endosperm, soft endosperm and germ. Figure 3 demonstrates the user interface for completing this task. The voxels of interest can be selected automatically, using thresholds or magic wand for example, or interactively using methods such as growing contour. The segmentation is a two-pass workflow, separating voxel selection and voxel assignment, to ensure greatest flexibility in creating, modifying, and managing different materials. In both voxel selection and assignment, automatic and interactive tools can be used in combination.

Furthermore, surface with triangular facets can be reconstructed automatically. The surface will be cleaned up to ensure that it is simulation ready, as shown in Figure 3. Avizo 6.1 can then be used to generate tetrahedron volume mesh in Nastran format as illustrated in Figure 4, which can be imported to Comsol. Alternatively, STL surface can be used to communicate with Comsol directly or via a third-party mesher such as gmesh.

To optimize the consumption of the computational resources, the reconstructed surface are simplified. The kernel is also dissected into half as shown in Figure 3.

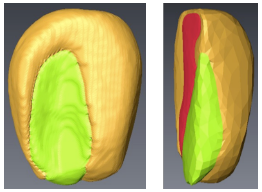

Figure 3. Geometry reconstruction with Avizo. Left: full geometry. Right: half of the geometry.

4. Simulations

Multiscale fluid transport model of Singh, Maier et al [3] was used to model moisture diffusion in corn kernels.

$$\dot{\varepsilon}^f - (1-\varepsilon^f)\nabla_E \cdot (D\nabla_E \varepsilon^f) + (1-\varepsilon^f)\nabla_E \cdot \left[\int_0^t B_\nu(t-\tau)\nabla_E \dot{\varepsilon}^f(\tau)d\tau\right] = 0,$$

$$B_\nu(t) = B_c G(T, \varepsilon^f; t)$$

where, $B_\nu(t)$ Memory function
B_c Coefficient multiplying G(t) to convert it into force term.
D Darcian (Fickian) diffusion coefficient
$G(t)$ Stress relaxation function
t Time
T Temperature
ε^f Total volume fraction of interacting fluid (water) in the macroscale REV (Sum of volume fractions of adsorbed fluid and bulk fluid)
∇_E Del operator in Eulerian coordinates

The equation couples the effect of viscoelastic relaxation given by the time integral to moisture diffusion. This makes the equation predict non-Fickian transport in the vicinity of glass transition. Corn kernels exhibit glass transition in drying temperature and moisture content range used in the industry [2]. On the half-face, symmetry boundary condition was used. On the remaining kernel a Neumann type boundary condition was imposed by introducing a mass flux driven by the water vapor pressure difference between the kernel and the drying air. The diffusivity of corn was obtained estimated using the inverse method as discussed in [6], the stress relaxation function value was obtained from [7]. To estimate the coefficient B_c, two types of approaches were used. In the first approach it was estimated using the inverse method. In the second approach it was estimated using an asymptotic technique involving plotting the change in the ratio D/G(t) as a function of low values of moisture content in the glassy state.

Acknowledgements

Thanks to USDA-CSREES for providing the financial support under the award number 2003-35503-13963.

5. Results

The following two figures show the distribution of moisture content at two drying conditions (figure 4 at 29^{o}C temperature and 48% relative humidity and figure 5 at 85^{o}C temperature and 14% relative humidity). The figures show that greater moisture gradient is observed between germ and endosperm. This makes corn prone to formation of cracks near the germ. At higher temperature higher gradient is observed. These results agree with that of Song and Litchfield [4] who made similar observation using magnetic resonance imaging. At both temperatures the germ is tending to retain moisture at its inner regions, which is expected due to its low moisture diffusivity in comparison to the remaining corn components. Toward the bottom of the kernel, the moisture is migrating at a faster rate due to narrow region.

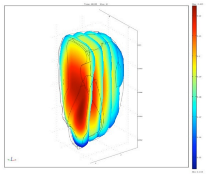

Figure 4. Low temperature moisture content distribution after 5 hrs of drying.

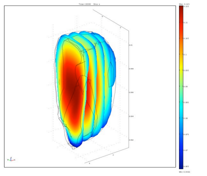

Figure 5. High temperature moisture content distribution after 5 hrs of drying.

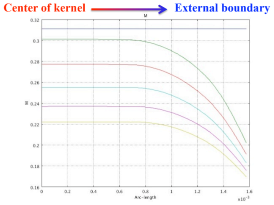

Figure 6. Moisture distribution at 29^{o}C and 48%RH

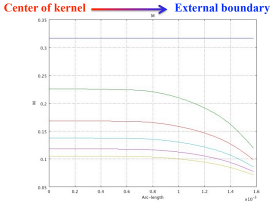

Figure 7. Moisture distribution at 85^{o}C and 14%RH

At high temperature greater reduction in moisture is caused in the same time, which causes faster drying. However, greater moisture gradients are developed which may make corn prone to cracking. By performing simulations with various combinations of drying air and temperature, optimum drying conditions causing sufficient moisture loss and minimal crack formation can be obtained.

6. Conclusions

The availability of advanced techniques like micro computed tomography has made it feasible to capture internal details of complex food structures. The hybrid mixture theory of porous media modeling the physics of transport processes coupled with stresses in complex food systems. The 3D reconstruction software packages can be used along with finite element software to solve porous media equations for complex 3D geometries.

References

[1] Avizo software website, http://www.vsg3d.com, 2009.
[2] J. Hundal and P. S. Takhar. "Dynamic viscoelastic properties and glass transition behavior of corn kernels." *International Journal of Food Properties* **12**(2): 295 - 307 (2009).
[3] P. P. Singh, D. E. Maier, et al. "Effect of viscoelastic relaxation on moisture transport in foods. Part I: Solution of general transport equation." *Journal of Mathematical Biology* **49**(1): 1-19 (2004).
[4] H. P. Song and J. B. Litchfield. "Measurement of stress cracking in maize kernels by magnetic-resonance-imaging." *Journal of Agricultural Engineering Research* **57**(2): 109-118 (1994).
[5] S. Zhang, P. Barthelemy, et al. "Advanced 3D Data Analysis and Visualization in Aluminum Die Casting using Computed Tompgraphy". *Proceedings of Materials Science & Technology2009*, Pittsburg, PA, October 2009.
[6] Chen, G., D. E. Maier, O. H. Campanella and P. S. Takhar. "Modeling of Moisture Diffusivities for Components of Yellow–dent Corn Kernels." *Journal of Cereal Science* **50** (2009).
[7] Waananen, K. M. and M. R. Okos. "Stress-relaxation properties of yellow-dent corn kernels under uniaxial loading." *Transactions of the ASAE* **35**(4): 1249-1258 (1992).