Drying of Corn Kernels: From Experimental Images to Multiscale Multiphysics Modeling

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Abstract: This work demonstrated the importance and feasibility of experimental image to simulation workflow. The workflow is successfully applied to a food processing study, where multiphysics and multiscale modeling based on 3D experimental image reconstruction contributes to the preservation of corn, one of the major food sources for the world population.

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

1. Introduction

Corn kernels have a complex structure as they are composed of a pericarp layer outside and contain hard and soft endosperm and germ components. Corn kernels are harvested around 30% moisture content on dry basis and dried to about 12% moisture content using heated air. Drying helps to lower the water activity to increase their shelf life. If the drying is not controlled properly, the kernels develop stress cracks, which makes them prone to insect and microbial damage.

To study and control the drying process, multiscale and multiphysics simulation conducted on the real corn kernel geometry is necessary. While the complex corn kernel structure make it extremely challenging to model accurately, this paper adapted an *experimental image to simulation* workflow.

3D imaging, such as computerized tomography (CT), is a proven technology in the medical industry due to its non-destructive nature. When applied to material research and industrial production, it can provide a unique opportunity for scientists to acquire the details of the subject material. In the meanwhile, the advances in such data acquisition capability lead to an explosion of data. The capacity in efficiently managing this data, intuitively visualize these data, and accurately analyze these data became vital to extract insight out of these large amount of numbers. When CT imaging is combined with state-of-art data analysis and visualization software algorithms, the fully digitized workflow will not only unveil the material characteristics to the finest possible scale, but also allows advanced modeling to be applied directly on the real-world geometry.

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® [1]. Figure 1 and 2 shows the reconstructed volumetric dataset.

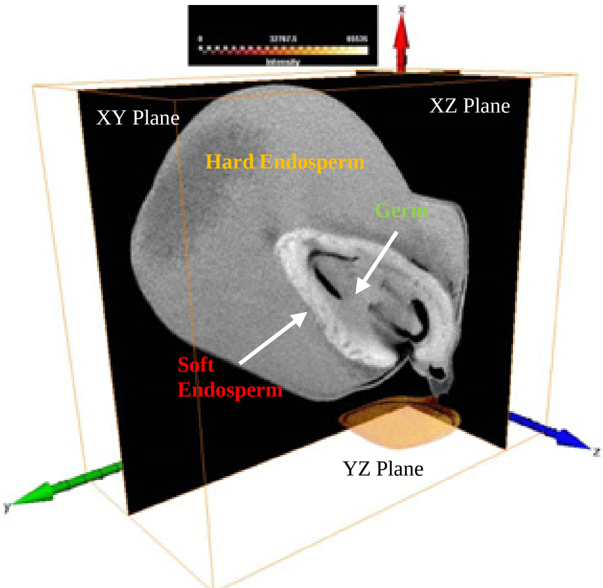

Figure 1. MicroCT image reconstruction: plane cuts. Note YZ plane is color contoured with the colormap shown at the top of the image.

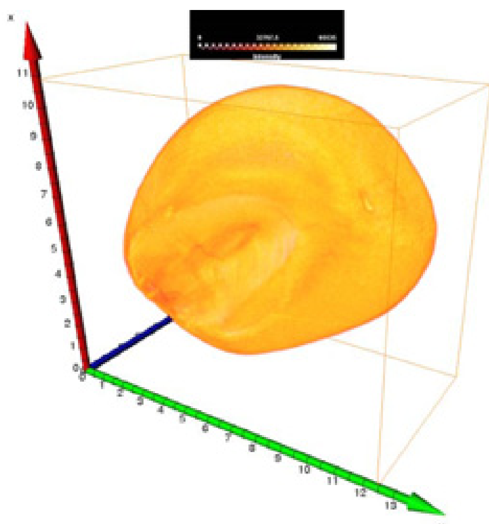

Figure 2. Direct volume rendering of MicroCT image data. Colormap is the same as Figure 1.

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, software 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. A multi-resolution algorithm is used by Avizo to ensure the best quality and performance that are supported by available resources on various display hardware.

The visualization of experimental images reveals the full detail of the corn kernel geometry and material composition, hence provides importance guidance to reconstruct real-world geometry, as well as template for future experiment-simulation comparison.

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 Avizo 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. Avizo also provided semi-automatic tools such as interpolation and warping to ensure the right balance of user interactivity and automation.

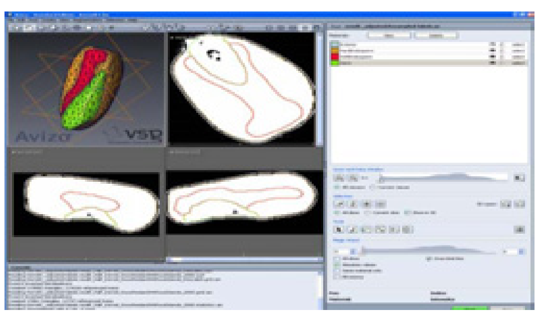

Figure 3. Segmentation interface.

Quantitative information such as volume fraction can be achieved, as shown in Table 1 below, after all the three materials are segmented.

Material	Volume Fraction
Hard Endosperm	68.9%
Soft Endosperm	22.9%
Germ	8.2%

Table 1. Volume fraction of different material components in the corn kernel.

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 4. Avizo 6.1 can then be used to generate tetrahedron volume mesh in Nastran format as illustrated in Figure 5, 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 4.

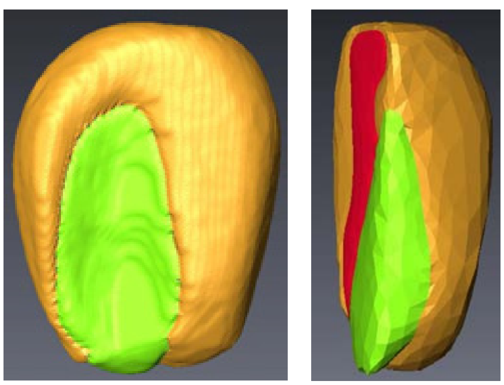

Figure 4. Geometry reconstruction with Avizo. Left: full geometry. Right: half of the geometry.

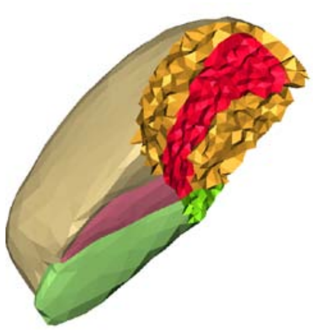

Figure 5. Volumetric mesh generated by Avizo

Figure 5 shows the volumetric mesh generated by Avizo. The center top of the corn kernel model is opened up to reveal internal mesh topology.

4. Simulation

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

$$\dot{\varepsilon}^f - \left(1-\varepsilon^f\right)\nabla_{\mathbf{E}} \cdot \left(D\nabla_{\mathbf{E}}\varepsilon^f\right) + \left(1-\varepsilon^f\right)\nabla_{\mathbf{E}} \cdot \left[\int_0^t B_v(t-\tau)\nabla_{\mathbf{E}}\dot{\varepsilon}^f(\tau)d\tau\right] = 0,$$

$$B_v(t) = B_c G(T, \varepsilon^f; t).$$

where, various symbols are given as

$B_v(t)$ 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)

$\nabla_{\mathbf{E}}$ 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 from [6], the stress relaxation function value was obtained from [7].

5. Results

The following two figures show the distribution of moisture content at two drying conditions (figure 6 at 29 C temperature and 48% relative humidity and figure 7 at 85C 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.

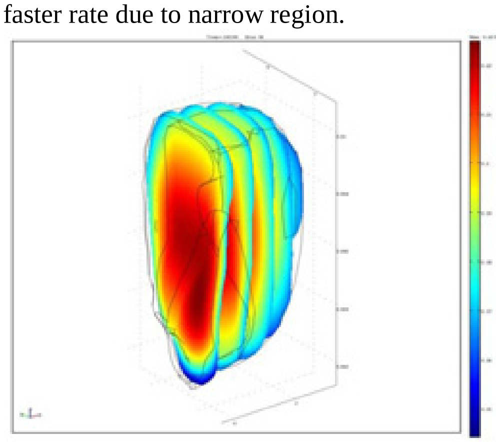

Figure 6. Low temperature moisture content distribution after 5 hrs of drying.

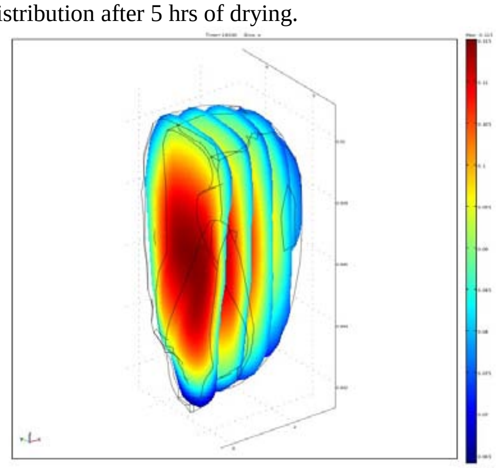

Figure 7. High temperature moisture content distribution after 5 hrs of drying.

Figure 8 and 9 shows moisture distribution across cross-section. In both figures, the profiles from top toward bottom are at intervals of 1 hr from 0 to 5 hrs. Left of the figure is the center of kernel, right is the external boundary.

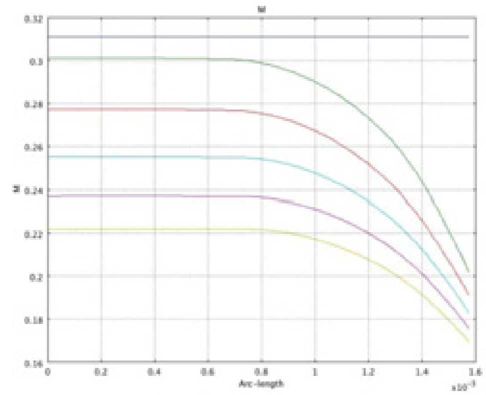

Figure 8.Moisture distribution at 29C temp and 48% RH.

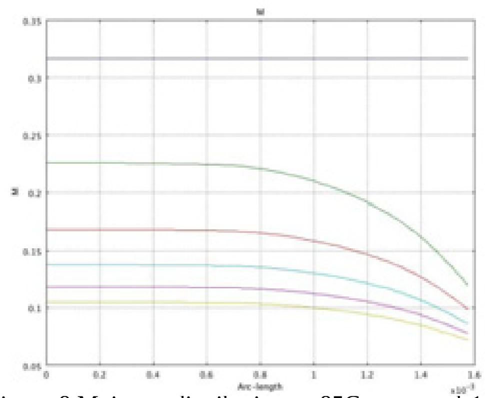

Figure 9.Moisture distribution at 85C temp and 14% RH.

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

This work demonstrated the importance and feasibility of experimental image to simulation workflow, which opens the door to vast number of applications requiring the real world geometry. Moreover, the workflow is successfully applied to a food processing study, where multiphysics and multiscale modeling based on 3D experimental image reconstruction contributes to the preservation of corn, one of the major food sources for the world population.

7. References

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8. Acknowledgements

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