Simulation and Experimental Analysis of Mass Transfer Drying of Corn Kernels (Postprint)

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Abstract

To understand the moisture diffusion process within corn kernels during drying and optimize drying process parameters, this study employs simulation and experimental research methods to analyze the temporal variation of internal moisture distribution in corn kernels during the drying process. Corn kernels are composed of four components: seed coat, horny endosperm, floury endosperm, and embryo, with each component possessing distinct moisture diffusion coefficients. This paper respectively assumes corn kernels as single-component homogeneous bodies and multi-component heterogeneous bodies, and establishes corresponding mathematical drying models. The moisture variation within corn kernels is simulated using the COMSOL Multiphysics module, and experimental validation is performed through thin-layer drying experiments of corn kernels. The results demonstrate that both established models can effectively simulate the thin-layer drying process of corn kernels; the discrepancy between simulated and experimental values is smaller at 80°C than at 70°C; the accuracy of the multi-component model for corn kernels is superior to that of the single-component model.

Full Text

Preamble

Simulation and Experimental Analysis of Mass Transfer in Drying a Single Corn Kernel

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Abstract: To understand the moisture diffusion process within corn kernels during drying and optimize drying process parameters, this study employs both simulation and experimental methods to analyze the temporal variation of internal moisture distribution. A corn kernel comprises four components—seed coat, horny endosperm, farinaceous endosperm, and embryo—each with distinct moisture diffusion coefficients. This paper establishes drying mathematical models based on two hypotheses: (1) the corn kernel as an isotropic monocomponent body, and (2) the corn kernel as a multicomponent heterogeneous body. The internal moisture changes were simulated using the COMSOL Multiphysics module and validated through thin-layer drying experiments. Results demonstrate that both models effectively simulate the thin-layer drying process of corn kernels, with smaller deviations between simulated and experimental values at 80°C compared to 70°C. The multicomponent model exhibits higher accuracy than the monocomponent model.

Keywords: corn kernel; multicomponent; monocomponent; thin-layer drying; mass transfer

0 Introduction

Appropriate drying processes are crucial for the drying industry. For corn, drying parameters affect cracking rate, storage duration, and overall product quality while also influencing energy consumption. Increasingly, drying processes are being developed through model simulation followed by experimental validation to refine the models and improve both product quality and energy efficiency.

Corn kernels have irregular shapes and complex internal structures, with moisture distribution varying across different cross-sections and drying stages. Techniques such as nuclear magnetic resonance and CT scanning can only determine moisture distribution at specific moments and sections. Since moisture diffuses at different rates through various kernel structures, a layered analysis of corn is necessary. Takhar considered the heterogeneity of corn kernels and investigated diffusion coefficients for different components. During drying, the varying textures of different kernel components result in different moisture diffusion rates. The internal moisture gradient is closely related to kernel structure, which can be viewed as an assembly of four parts—seed coat, horny endosperm, farinaceous endosperm, and embryo—with different diffusion coefficients that depend on both temperature and moisture content. Chen separated each component based on corn' s complex structure, measured their individual drying curves, and solved Fick' s second law using COMSOL Multiphysics to derive relationships between diffusion coefficients, drying temperature, and moisture content, providing a theoretical basis for diffusion coefficient selection in this study.

Zhang Shiwei conducted theoretical analysis and simulation studies on the internal heat and mass transfer processes of corn kernels under hot air conditions. By scanning corn kernels with medical CT, high-precision images were optimized using MIMICS and ANSYS software to establish a three-dimensional geometric model, which was then imported into COMSOL Multiphysics for solution. This approach better describes the internal mass transfer process and moisture variation during drying. Therefore, this study constructs both multicomponent and monocomponent physical models of corn kernel structure, comparing COMSOL Multiphysics simulations with thin-layer drying experiments to evaluate the simulation accuracy of different component models.

1.1.1 Multicomponent Geometric Model

Assuming structural symmetry of the corn kernel in the width direction, only one-half of the kernel needs to be calculated. The physical model is shown in [Figure 1: see original paper], which illustrates the seed coat, horny endosperm, farinaceous endosperm, and embryo constructed using PRO/E. The volumes of the four components are presented in . Taking the kernel' s center of gravity as the coordinate origin, the x- and y-axes represent the width and thickness directions, respectively.

1.1.2 Monocomponent Geometric Model

Assuming structural symmetry in both width and thickness directions, only one-quarter of the corn kernel needs to be calculated. The physical model is shown in [Figure 2: see original paper]. The overall dimensions of the monocomponent geometric model are identical to those of the multicomponent model.

1.2.1 Hot Air Drying Mathematical Model for Multicomponent Corn Kernels

Model Assumptions: 1. Uniform temperature and moisture distribution inside the kernel at the initial drying stage 2. Negligible shrinkage and deformation during drying 3. Each kernel component is an isotropic homogeneous body 4. Moisture diffuses to the external boundary in liquid form and vaporizes at the kernel surface

The internal mass transfer equation during drying is described as: MATH_1

Initial condition: MATH_2

Boundary condition: MATH_3

where: t is drying time (s); X is dry basis moisture content (kg/kg); h is convective mass transfer coefficient (m/s); Sh is Sherwood number; d is equivalent particle diameter (mm); X is equilibrium moisture content (kg/kg); D is effective moisture diffusion coefficient for different components (i = 1, 2, 3, 4) (m^2/s).

1.2.2 Hot Air Drying Mathematical Model for Monocomponent Corn Kernels

Model Assumptions: 1. Uniform temperature and moisture distribution inside the kernel at the initial drying stage 2. Negligible shrinkage and deformation during drying 3. The corn kernel is an isotropic homogeneous body 4.

Moisture diffuses to the external boundary in liquid form and vaporizes at the kernel surface

The initial and boundary conditions are consistent with Section 1.2.1. The internal mass transfer equation during drying is described as: MATH_4

where: D is effective moisture diffusion coefficient (m^2/s).

1.2.3 Heat Transfer Mathematical Model for Hot Air Drying of Corn Kernels

The internal heat transfer equation during drying is described as: MATH_5

Initial condition: MATH_6

Boundary condition: MATH_7

where: T is corn kernel temperature (K); T_0 is initial kernel temperature (K); T is hot air temperature (K); k is thermal conductivity of corn kernel ($W/(m \cdot K)$); $T/\ n$ is the derivative of internal temperature along the outer normal direction; h is convective heat transfer coefficient ($W/(m^2 \cdot K)$); $C\ = 2010\ J/(kg \cdot K)$ is specific heat capacity; $\ = 1150\ kg/m^3$ is kernel density; hfg is latent heat of vaporization (J/kg); V is kernel volume (m^3); A is kernel surface area (m^2).

2.1 Experimental Materials

Corn (Demaiya No. 1) kernels without damage or mold, with normal color and odor were used. The initial moisture content at harvest was 0.38 ± 0.02 (d.b.) kg/kg. After harvest, the kernels were sealed in plastic bags and stored in a refrigerator at (5 ± 1)°C, then removed and cooled to room temperature before experiments.

2.2 Main Experimental Apparatus

The digital tunnel drying experimental apparatus (Zhejiang Zhongke Teaching Equipment Co., Ltd.) included: a blower (BYF7122) rated at 370 W; an electric heater rated at 4.5 kW; a drying chamber measuring 180 mm × 180 mm × 1250 mm; and CZ500 load cells (0–300 g). Additional equipment comprised a DHG-9140A electric thermostatic blast drying oven (Shanghai Jinghong Experimental Equipment Co., Ltd.), an FB224 electronic balance (Shanghai Shunyu Hengping Scientific Instrument Co., Ltd.), and an HM70 temperature-humidity meter (Vaisala, Finland).

2.3.1 Hot Air Thin-Layer Drying Experiment for Corn Kernels

Experimental conditions were set as follows: initial uniform moisture and temperature distribution, initial moisture content of 39.33% (d.b.), initial surface temperature of 25°C, hot air temperatures of 70°C and 80°C (thin-layer drying experiments show that higher temperatures increase drying rate but do not necessarily improve drying effectiveness, hence 70°C and 80°C were selected), air velocity of 1.2 m/s, and relative humidity of 12 ± 2%. Kernels were dried to a safe moisture content of 14%, with drying curves measured accordingly. The experimental setup is schematically shown in [Figure 3: see original paper].

2.3.2 Computer Simulation Experiment

Numerical solution of the model employed the convection-diffusion and heat transfer modules in COMSOL Multiphysics (4.3a) with custom governing equations based on the heat and mass transfer mathematical models. Simulation conditions matched experimental conditions. During COMSOL setup, after importing the physical model, the mesh calibration selected normal physics mesh standards. Mesh independence verification confirmed that normal physics mesh met accuracy requirements. Parameters for the heat and mass transfer process are listed in .

2.4 Experimental Parameter Acquisition

The dry basis moisture content was calculated using: MATH_8

where: W is total mass at any drying time t (g); W_G is dry matter mass (g).

3 Results and Discussion

After 5 minutes of simulated drying, temperature differences within the kernel were minimal with negligible temperature gradients; thereafter, only moisture gradient effects on diffusion were considered. As shown in [Figure 4: see original paper], at 70°C hot air temperature and 12 minutes drying time, the maximum difference between simulated and experimental average moisture content for the monocomponent model was 0.0389, corresponding to a relative error of 11.39%. This discrepancy likely stems from differences between actual material properties and simulation assumptions. The model employed empirical effective moisture diffusion coefficients from a one-dimensional spherical diffusion model and simplified the kernel as a homogeneous body, whereas actual kernels comprise multiple components (seed coat, embryo, horny endosperm, farinaceous endosperm) with different diffusion coefficients, inevitably introducing deviation. In contrast, the multicomponent model showed higher agreement with experimental values, with a maximum difference of 0.0138 and relative error of 4.56%.

During the final drying stage, as kernel moisture content decreased, the difference between simulated and experimental values gradually increased, with simulated moisture changing more slowly than measured values. This may be attributed to kernel cracking after prolonged high-temperature drying, which eliminates pericarp resistance and exposes internal tissues directly to hot air, accelerating moisture transfer. Additionally, kernel shrinkage shortens internal moisture transfer distances, increasing transfer rate. Since the simulation model did not account for cracking or shrinkage, larger deviations occurred in the final drying stage.

As shown in [Figure 5: see original paper], higher hot air temperatures reduced the time required to reach safe moisture content. Notably, at 80°C, differences between simulated and experimental values for both monocomponent and multicomponent models were smaller than at 70°C. This may occur because higher temperatures increase diffusion coefficients while reducing differences between component coefficients, bringing them closer to actual values. However, considering the energy required for temperature elevation and potential quality degradation at high temperatures, excessively high drying temperatures are not recommended for energy savings. Moreover, even at 70°C, the multicomponent model showed minimal deviation from experimental values, demonstrating its superior accuracy and reliability over the monocomponent model. The variation of kernel moisture content X with drying time t (min) under different temperatures is presented in .

Moisture distribution patterns from the multicomponent model are visualized in [Figure 6: see original paper] (left: 70°C, right: 80°C) at 600 s, 1800 s, and 3600 s. Results show that average moisture content decreases with drying time, external moisture is lower than internal moisture, and kernels dried at 80°C exhibit lower moisture content than those at 70°C at all stages, confirming faster drying at higher temperatures.

Conclusions

1. Both multicomponent and monocomponent geometric models and drying mathematical models were established for corn kernels. Simulation and thin-layer drying experiments demonstrate that both models effectively reflect drying curve trends, though the multicomponent model achieves higher simulation accuracy than the monocomponent model.
2. Increasing drying temperature reduces the difference between simulation and experimental results, but the reduction is limited. At 70°C hot air temperature, the multicomponent drying model maintains high accuracy, indicating practical applicability.

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