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

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Abstract

To understand the diffusion process of moisture inside corn kernels during drying and optimize drying process parameters, this study employs simulation and experimental research methods to analyze the temporal variation patterns of moisture distribution within corn kernels during the drying process. The corn kernel consists of four components: pericarp, horny endosperm, floury endosperm, and germ, each with distinct moisture diffusion coefficients. This study establishes drying mathematical models for corn kernels based on two assumptions: as a single-component homogeneous body and as a multi-component heterogeneous body. The moisture variation inside corn kernels is simulated using the COMSOL Multiphysics module, and experimental validation is performed through thin-layer drying experiments on corn kernels. The results demonstrate that both 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 multi-component model exhibits higher accuracy than the single-component model.

Full Text

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 two drying mathematical models based on different assumptions: one treating the corn kernel as an isotropic monocomponent homogeneous body, and the other as a multicomponent heterogeneous body. The internal moisture changes were simulated using the COMSOL Multiphysics module, and the models were validated through thin-layer drying experiments. The results demonstrate that both models effectively simulate the thin-layer drying process of corn kernels, with smaller discrepancies between simulated and experimental values at 80°C compared to 70°C. The multicomponent model exhibits higher accuracy than the monocomponent model.

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

0 Introduction

Rational drying processes are crucial for the drying industry. For corn, drying parameters affect cracking rate, storage duration, and overall product quality while also causing energy waste. Increasingly, drying processes can be modeled and simulated, followed by experimental validation to adjust and improve the process, ultimately enhancing product quality and achieving energy conservation.

Corn kernels have irregular shapes and complex tissue structures, with moisture distributions 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 different kernel structures, layered analysis is necessary. Takhar considered the heterogeneity of corn kernels and investigated diffusion coefficients for different components. During drying, the varying textures of different corn components result in different moisture diffusion rates. The internal moisture gradient is closely related to kernel structure, which can be viewed as a composite of four parts: seed coat, horny endosperm, farinaceous endosperm, and embryo, each with different diffusion coefficients that depend on kernel temperature and moisture content. Chen separated each component based on corn's complex structure, measured their individual drying curves, and used COMSOL Multiphysics to solve Fick' s second law, establishing relationships between diffusion coefficients, drying temperature, and moisture content for different components, 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 in corn kernels under hot-air conditions using a three-dimensional model. 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 and calculation. This approach better describes the internal mass transfer process and moisture changes during drying. Therefore, this paper constructs both multicomponent and monocomponent physical models of corn kernel structure, comparing simulation results from COMSOL Multiphysics with thin-layer drying experiments to evaluate the simulation accuracy of different component models.

1.1.1 Multi-component Geometric Model

Assuming structural symmetry of corn kernels 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], where the four components of the corn kernel are 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. The multicomponent geometric model shares the same overall dimensions as the single-component model.

1.1.2 Single-component 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].

1.2.1 Mathematical Model for Hot-air Drying of Multi-component Corn Kernels

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

The mass transfer equation inside the kernel during drying is described as:
The initial condition is:
The boundary condition is: h X X

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 corn components, $i = 1, 2, 3, 4$ (m^2/s).

1.2.2 Mathematical Model for Hot-air Drying of Single-component Corn Kernels

Model Assumptions: 1) Uniform temperature and moisture distribution inside the corn 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 mass transfer equation inside the kernel during drying is described as:

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 heat transfer equation inside the kernel during drying is described as:
(7)

The initial condition is:
The boundary condition is: C T T

Where: T is corn kernel temperature (K); T is initial kernel temperature (K); T is hot-air temperature (K); k is thermal conductivity of corn kernel (W/(m·K)); T/ n is the derivative of internal temperature along the outer normal direction; h is convective heat transfer coefficient (W/(m^2·K)); C = 2010 J/(kg·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 (Demeya 1 variety) without damage or mold, with normal color and odor. Initial moisture content at harvest was 0.38 ± 0.02 (d.b.) kg/kg. After harvest, kernels were sealed in bags and stored in a refrigerator at (5 ± 1)°C, then removed and cooled to room temperature before experiments.

2.2 Main Experimental Equipment

Digital tunnel drying experimental device (Zhejiang Zhongkong Science and Education Equipment Co., Ltd.): blower (BYF7122) rated at 370 W; electric heater rated at 4.5 kW; drying chamber dimensions 180 mm × 180 mm × 1250 mm; load cell model CZ500, 0–300 g.

Other equipment: DHG-9140A electric thermostatic blast drying oven (Shanghai Jinghong Experimental Equipment Co., Ltd.), FB224 electronic balance (Shanghai Shunyu Hengping Scientific Instrument Co., Ltd.), HM70 temperature and humidity meter (Vaisala, Finland).

2.3.1 Thin-layer Hot-air Drying Experiment of Corn Kernels

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

2.3.2 Computer Simulation Experiment

The numerical solution employed the convection-diffusion and heat transfer modules in COMSOL Multiphysics (4.3a). Custom governing equations based on the heat and mass transfer mathematical models were used for simulation experiments under conditions identical to the physical experiments. During COMSOL setup, after importing the physical model, the mesh calibration selected normal physics mesh standards. Grid independence verification demonstrated that normal physics mesh satisfied accuracy requirements. Parameters for the heat and mass transfer process are listed in .

2.4 Acquisition of Experimental Parameters

The dry basis moisture content is calculated as:

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

3 Results Analysis and Discussion

After 5 minutes of simulated drying, temperature differences within the kernel are minimal, with negligible temperature gradients. Thereafter, only the effect of moisture gradient on moisture diffusion is 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 is 0.0389, corresponding to a relative error of 11.39%. This discrepancy likely arises from differences between actual material properties and simulation assumptions. The model employs an empirical effective moisture diffusion coefficient from a one-dimensional spherical diffusion model and simplifies the corn kernel as a homogeneous body, whereas actual kernels consist of seed coat, embryo, horny endosperm, and farinaceous endosperm with different diffusion coefficients, inevitably introducing deviation. In contrast, the multicomponent model shows higher coincidence 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 decreases, the difference between simulated and experimental values gradually increases. Simulated moisture content changes more slowly than measured values, possibly because kernels dried at high temperature for extended periods develop cracks, losing pericarp resistance and allowing internal direct contact with hot air, accelerating moisture transfer. Additionally, kernel shrinkage shortens internal moisture transfer distances, increasing transfer rate per unit time. However, the simulation model does not account for cracking or shrinkage deformation, causing larger discrepancies in the final drying stage.

As shown in [Figure 5: see original paper], higher hot-air temperatures shorten the time required to reach safe moisture content. At 80°C, differences between both monocomponent and multicomponent simulated values and experimental values are smaller than at 70°C, likely because higher temperatures increase diffusion coefficients while reducing differences among component diffusion coefficients, bringing them closer to actual values. However, considering the energy required to increase temperature and the quality degradation at high temperatures, excessively high temperatures are not recommended for energy-saving purposes. Even at 70°C, the multicomponent model shows minimal deviation from experimental values, demonstrating higher accuracy than the monocomponent model and proving its reliability. The variation of corn kernel moisture content X with drying time t (min) under different temperatures is presented in .

Moisture distribution nephograms from the multicomponent model further illustrate internal moisture changes. [Figure 6: see original paper] shows moisture distribution at 600 s, 1800 s, and 3600 s under different temperatures (left: 70°C, right: 80°C). With increasing drying time, average moisture content gradually decreases, with lower moisture content at the exterior than interior. At all drying stages, moisture content is lower at 80°C than at 70°C, indicating faster drying at higher temperatures.

Conclusions

1) This study established multicomponent and monocomponent geometric models and drying mathematical models for corn kernels. Simulation and thin-layer drying experiments demonstrate that both models effectively reflect the drying curve trends, but 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 model maintains high accuracy and practical applicability.

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