Multiscale Multilayer Structure Heat and Mass Transfer Model and Simulation for Drying of Packed-Particle Porous Media (Postprint)

Authors: Yuan Yuejin, Tan Libin, Xu Yingying, Zhao Zhe, Bai Bofeng

Date: 2017-11-07T00:00:00+00:00

Abstract

To address the issue of multilayer physical structures in skeleton particles, a multiscale multilayer heat and mass transfer model for drying of packed particle porous media was developed by employing pore network methods, heat and mass transfer principles, and multiscale theory. Using rice grain piles as a typical representative case, hot-air drying experiments were performed for validation, and the effects of intra-particle tissue physical properties and other factors on the drying process were simulated and analyzed. The results indicate that the established model can effectively simulate the drying process of rice grain piles, and that significant moisture gradients exist within rice grains. The diffusion coefficient of the embryo exhibits the most pronounced influence on the drying process, followed by that of the husk, while the diffusion coefficient of the bran has the least impact; a smaller embryo diffusion coefficient can effectively "trap" moisture within the embryo.

Full Text

Multi-scale and Multi-layer Structural Modeling and Simulation of Heat and Mass Transfer Processes for Drying of Grain Packing Porous Media

Yuan Yuejin[1],[2]*, Tan Libin[1], Xu Yingying[1], Zhao Zhe[1], Bai Bofeng[2]
[1]College of Mechanical and Electrical Engineering, Shaanxi University of Science and Technology, Xi' an 710021, China
[2]State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi' an 710049, China

Abstract

Addressing the multi-layer physical structure of skeleton particles, a multi-scale and multi-layer structural model for heat and mass transfer during drying of grain packing porous media was established using pore network methods, heat and mass transfer principles, and multi-scale theory. Hot-air drying experiments on rice piles were conducted as a typical case for model validation, and simulations were performed to analyze the influence of physical characteristics of different tissues within particles on the drying process. The results demonstrate that the established model can effectively simulate the rice pile drying process, with significant moisture gradients existing within rice grains. The diffusion coefficient of the embryo exhibits the most pronounced effect on drying, followed by that of the hull, while the diffusion coefficient of the chaff has the minimal impact. A smaller embryo diffusion coefficient can effectively "trap" moisture within the embryo.

Keywords: grain packing porous media; drying; multi-layer structural model; multi-scale; diffusion coefficient

Drying of grain packing porous media is relevant to numerous fields including agriculture, food, light industry, chemical engineering, construction, and coal processing. Currently, research on the mechanisms and simulation of drying for agricultural product packing porous media primarily relies on the continuum approach, which treats such materials as virtual continuous wet solids. This method neglects the distinction between particle skeletons and pores within the material pile, as well as differences in internal tissue structures of particles, directly applying existing heat and mass transfer theories for modeling and solution [1-2]. However, agricultural product packing porous media possess complex structures that more closely resemble discrete media in most cases. Moreover, their skeleton particles contain a multi-layer physical structure including seed coat (hull), chaff, and embryo tissues. Obviously, ignoring these factors in drying process analysis does not reflect actual conditions.

Multi-scale theory investigates phenomena involving coupling across various spatial or temporal scales. After nearly three decades of development, it has become a core theory in fluid dynamics, materials science, environmental science, chemistry, meteorology, and high-energy physics [3]. Pore network drying theory emerged in the early 1990s when Daian and Saliba and Nowicki et al. first introduced the pore network method commonly used in percolation theory into porous media drying theory. It was subsequently refined through further research by Prat and Yortsos et al. [4-7]. This theory posits that moisture migration in porous media has significant advantages within pores, using a series of regularly arranged nodes and connecting throats to reproduce the geometric and topological structure of pore space, enabling direct investigation of heat and mass transfer during drying at the pore-throat level.

This paper introduces the fundamental concepts of multi-scale theory into the study of grain packing porous media drying, integrating interdisciplinary knowledge of pore network methods and heat and mass transfer principles to establish a multi-scale and multi-layer structural heat and mass transfer model for the drying process. Using rice piles as a typical representative of grain packing porous media, hot-air drying experiments were conducted for model validation, and simulations were performed to analyze how physical characteristics of different tissues within particles affect the drying process.

1.1 Physical Model

The ventilation drying process for agricultural product packing porous media primarily involves hot air driven by pressure entering the pore system from one or more directions, undergoing heat and mass exchange with skeleton particles, and exiting from another direction, as shown in Figure 1a [Figure 1: see original paper]. Clearly, pores serve as advantageous channels for heat and mass transfer during hot-air drying. To distinguish between particle skeletons and pores, this paper adopts the method from reference [6] to construct a pore network physical model, as shown in Figure 1b. The model consists of two main components: a "pore-throat-pore" network and the skeleton. Pores are spherical and throats are cylindrical, with diameters following certain probability distributions. A two-dimensional pore network physical model can be described by parameters including distribution laws, inter-node distance, model scale number, and coordination number [6]. Furthermore, to investigate how different tissue structures (hull, chaff, and embryo) within skeleton particles affect the drying process, the research object is divided into two distinct scales: particle scale and dryer scale.

At the particle scale, each skeleton particle possesses three different physical tissue structures: seed coat (hull), chaff, and embryo, as shown in Figure 1c.

1.2 Mathematical Model

To simplify the mathematical model, the following basic assumptions are made for the hot-air drying process of grain packing porous media: (1) At the particle scale, skeleton particles are assumed to be ellipsoidal with multi-layer physical structure, non-shrinking and non-deforming; internal moisture transfer is assumed to occur primarily through liquid or vapor diffusion; heat required for moisture phase change within skeleton particles is assumed to be supplied by the particles themselves. (2) At the dryer scale, convective heat transfer is dominant, neglecting heat conduction and radiation; convective mass transfer is dominant, neglecting diffusive mass transfer and any mass transfer involving liquid phase; the gas phase is assumed to be incompressible ideal gas.

1.2.1 Particle Scale

For each skeleton particle at the particle scale in the pore network physical model (Figure 1c), the Lykov theory [16] can be used to describe its internal heat and mass transfer processes. Based on the above assumptions, the simplified heat and mass transfer equations in cylindrical coordinates are:

Where: T_g is the temperature at a certain location within the particle at a given time, K; λ_g is the particle thermal conductivity, W/(m $\cdot$ K); ρ_g is the particle density, kg/m^3; C_g is the particle specific heat capacity, J/(kg $\cdot$ K); M is the moisture content at a certain location within the particle at a given time (d.b.); D is the moisture diffusion coefficient within the particle, m^2/s; t is the time variable, s; r, Z are cylindrical coordinate variables, m.

1.2.2 Dryer Scale

As shown in Figure 1b, let the vapor density at a certain pore node (i, j) in the pore network physical model at time $n\Delta t$ be $\rho_{v,ij}$. Applying mass and energy conservation laws and Darcy' s law yields the mass transfer, heat transfer, and momentum transfer control equations at the dryer scale:

Where: $\rho_{v,ij}$ is the vapor density at pore node (i, j) at a given time, kg/m^3; R_d is the node pore radius, m; u_h is the wind speed in the throat, m/s; r_h is the throat radius, m; A_g is the particle surface area, m^2; k_c is the convective mass transfer coefficient, m/s; ρ_{veq} is the vapor density at the particle surface, kg/m^3; Δt is the time step, s; T_{ij}^n is the gas phase temperature at pore node (i, j) at a given time, K; ρ is the gas phase density, kg/m^3; C is the gas phase specific heat capacity, J/(kg $\cdot$ K); h is the convective heat transfer coefficient, W/(m^2 $\cdot$ K); q_k is the gas phase volume flow rate in the throat, m^3/s; A_h is the throat cross-sectional area, m^2; k^* is the Darcy permeability, m^2; μ is the gas phase viscosity, Pa $\cdot$ s; l is the throat length, m; P is the pore node wind pressure, Pa; ρ_{vw} is the pure vapor density, kg/m^3; $A_g k_c(\rho_{veq} - \rho_{v,ij})$ is the steam release rate from the particle to a pore, kg/s.

1.2.3 Cross-scale Heat and Mass Exchange Control Equations

The heat and mass transfer information between the two scale equations is separate and unconnected. Therefore, additional cross-scale heat and mass exchange balance equations are required to link the information for solution.

On the surface of each skeleton particle in the pore network physical model, cross-scale heat and mass exchange occurs: the moisture reduction within the particle equals the amount of vaporized steam flowing into the surrounding pores; simultaneously, the enthalpy change within the particle equals the convective heat gained from the surrounding gas phase minus the heat consumed for moisture vaporization. Applying mass and energy conservation laws yields the cross-scale heat and mass exchange balance equations:

Where: ρ_g' is the absolutely dry particle density, kg/m^3; η_{fg} is the latent heat coefficient of vaporization, J/kg; ΔX is the moisture content difference of a particle over time t, kg/kg.

2 Validation Drying Experiments

Rice piles were used as a typical representative of grain packing porous media for hot-air drying experimental validation. First, rice grains were cleaned, washed, and conditioned to obtain uniform moisture content. The rice was then placed in a drying test chamber for hot-air drying, while the main structural characteristic parameters of the rice pile were measured. The drying chamber is a rectangular cavity with width 200 mm, height 200 mm, and thickness 100 mm. A right-angle isosceles triangular air inlet is located at the center of the chamber bottom; the top is open to ambient air. Measurement holes are opened on the front chamber wall.

At the start of the drying experiment, the hot-air temperature at the chamber inlet was 42.0°C, relative humidity 6.5%, and static pressure 56.0 Pa; ambient temperature was 20.1°C; initial rice grain temperature was 18.0°C, and initial moisture content was 31.2% (d.b.). During the drying experiment, rubber plugs at measurement holes were periodically removed to measure rice grain temperatures at various points using an infrared thermometer. Appropriate rice samples were extracted from measurement holes to determine moisture content using the oven method. Temperature and humidity of the pore gas phase within the rice pile were measured by sensors embedded at various measurement points.

3 Computer Simulation

Based on the above drying model, a simulation program was developed using combined VC++ and MATLAB programming. The dryer scale control equations and cross-scale heat and mass exchange balance equations are already in discrete difference form and can be solved directly using a finite difference segregated solution method. The particle scale equations are in partial differential form and require grid division before finite difference discretization for solution. Rice grains are ideal ellipsoids with symmetry, allowing computational efficiency by analyzing only one-quarter of the symmetric plane. During simulation, the initial and boundary conditions of the drying model match those of the validation experiments.

4.1 Average Moisture Content Change Curve in Drying Bin

As shown in Figure 2 [Figure 2: see original paper], the simulated and experimental curves for average moisture content of rice grains in the bin show good agreement, with a maximum relative error of approximately 7.6%. This demonstrates macroscopically that the established model is effective.

4.2.1 Hull Diffusion Coefficient

The hull diffusion coefficient was set to five different values while keeping other parameters constant for simulation of grain packing porous media drying. The resulting drying curves for different hull diffusion coefficients are shown in Figure 3 [Figure 3: see original paper]. The results indicate that the hull diffusion coefficient has a certain influence on the drying process. As the hull diffusion coefficient decreases, the drying rate gradually slows, requiring longer drying time to reach the same moisture content. This occurs primarily because a smaller hull diffusion coefficient makes moisture migration from within the particle to the hull surface more difficult, thus slowing drying.

4.2.2 Chaff Diffusion Coefficient

The chaff diffusion coefficient was set to five different values while keeping other parameters constant for simulation. The resulting drying curves for different chaff diffusion coefficients are shown in Figure 4 [Figure 4: see original paper]. The results show that the chaff diffusion coefficient has minimal influence on the drying process. Although the drying rate slows slightly with decreasing chaff diffusion coefficient, the magnitude of this effect is negligible. This is mainly because the physical thickness of the chaff tissue is much thinner compared to the hull and embryo, limiting the impact of its diffusion coefficient variation on internal moisture migration.

4.2.3 Embryo Diffusion Coefficient

The embryo diffusion coefficient was set to five different values while keeping other parameters constant for simulation. The resulting drying curves for different embryo diffusion coefficients are shown in Figure 5 [Figure 5: see original paper], with moisture content distributions (at t = 300 min) shown in Figure 6 [Figure 6: see original paper].

As shown in Figure 5, the embryo diffusion coefficient has a tremendous impact on the drying process. As the embryo diffusion coefficient decreases, the drying rate slows significantly, particularly in the middle and later stages of drying, substantially increasing the time required to reach the same moisture content. This is partly because the embryo occupies a large proportion of the particle tissue. Additionally, Figure 6 reveals that a smaller embryo diffusion coefficient makes moisture migration from within the embryo to the hull surface more difficult, effectively "trapping" moisture within the embryo. For instance, when the embryo diffusion coefficient is 2.98×10^{-11} m^2/s, the moisture content in the central region of the particle shows almost no reduction. Consequently, drying proceeds more slowly.

5 Conclusions

The multi-scale and multi-layer structural heat and mass transfer model established in this paper can effectively simulate the drying process of grain packing porous media. The simulated drying curves for rice in the bin reflect the actual drying process conditions. Different tissue physical characteristics within particles significantly influence grain packing porous media drying, with the embryo diffusion coefficient having the most pronounced effect, followed by the hull diffusion coefficient, while the chaff diffusion coefficient has minimal impact. During drying, decreasing the embryo diffusion coefficient noticeably slows the drying rate, particularly in the middle and later stages, substantially increasing the time required to reach the same moisture content. A smaller embryo diffusion coefficient can "trap" moisture within the embryo, making moisture migration from inside the particle to the hull surface more difficult.

References

[1] Liu Xiangdong, Yang Binbin. Review and Vista on Drying Theories of Porous Medium. Journal of China Agricultural University, 2005, 10(4): 81-92
[2] Naghavi Z, Moheb A, Ziaei-rad S. Numerical Simulation of Rough Rice Drying in a Deep-Bed Dryer Using Non-equilibrium Model. Energy Conversion and Management, 2010, 51(2): 258-264
[3] Wu Jianghang, Huang Shehua, James Glimm, et al. Multiscale Science: A Challenge for the Twenty-First Century. Advances in Mechanics, 1998, 28(4): 545-551
[4] Prat M. Recent advances in Pore-scale Models for Drying of Porous Media. Chemical Engineering Journal, 2002, 86(1-2): 153-164
[5] Yiotis A G, Tsimpanogiannis I N, Stubos A K, et al. Pore-network Study of Characteristic Periods in the Drying of Porous Media. Journal of Colloid and Interface Science, 2006, 297(2): 738-748
[6] Xiao Zhifeng, Yang Deyong, Yuan Yuejin, et al. Fractal Pore Network Simulation on the Drying of Porous Media. Drying Technology, 2008, 26(6): 651-665
[7] Shaeri M R, Beyhaghi S, Pillai K M. On Applying an External-Flow Driven Mass Transfer Boundary Condition to Simulate Drying from a Pore-network Model. International Journal of Heat and Mass Transfer, 2013, 57(1): 331-344

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.