

Numerical Simulation of Temperature-Moisture Field for Cylindrical Chinese Herbal Medicines During Preheating-balancing Stage of Hot-air Drying

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Abstract: Aiming at the preheating balancing process in hot air drying of cylindrical Chinese herbal medicines, a one-dimensional radial cylindrical heat mass transfer numerical model is established to reveal the evolution law of internal temperature and moisture content within short time scale. The conservative finite volume method is adopted for spatial discretization, and the Crank Nicolson implicit scheme combined with the Thomas algorithm is used to solve the equations. Simulations are carried out for the 0 1800 s preheating balancing stage. The results show that heat can effectively conduct into the medicine interior during preheating, while the moisture diffusion penetration depth is only about 0.11 0.28 cm. Water loss mainly occurs in the near surface thin layer and the moisture content at the core almost remains unchanged. The surface mass transfer coefficient imposes the most prominent influence on surface moisture content, whereas thermal conductivity and heat transfer coefficient have relatively limited effects on temperature field. Analytical solution verification and conservation checks prove the reliability of simulation results, which can provide theoretical reference for parameter configuration in the early stage hot air drying process of Chinese herbal medicines.

Keywords: Chinese Herbal Medicine Drying; Preheating Balance; Heat And Mass Transfer; Finite Volume Method; Temperature Moisture Field Simulation.

1. Introduction

Hot-air drying constitutes the primary primary-processing technique for Chinese herbal medicines with high moisture content after harvesting. As the initial phase of drying, the preheating-balancing stage governs the internal heat and moisture migration, which directly determines subsequent drying efficiency and product quality [1-3]. Improper control of preheating conditions may easily trigger surface hardening or internal thermal stress, further degrading the active-ingredient retention rate of medicinal materials. Cylindrical rhizome-type Chinese herbal medicines can be simplified as one-dimensional radial porous media. Revealing the temporal-spatial evolution of temperature-moisture field in preheating phase provides practical guidance for preliminary parameter configuration of drying processes[4-5]. Such basic research also helps avoid blind trial-and-error tests in actual drying production and cuts experimental costs.

Existing researches on hot-air drying of agricultural products and Chinese herbal medicines mostly focus on the complete drying cycle, investigating drying endpoints and overall kinetic characteristics via experimental tests and multi-physical-field simulations [6-7]. Laboratory drying experiments usually measure only surface or average moisture, and cannot capture fine internal gradient variations inside the material. Most numerical simulations directly proceed to the constant-temperature drying stage, while fine-scale modelling for the short-duration preheating-balancing phase is relatively insufficient. Some studies ignore the asynchronous migration of heat and moisture transport, and lack complete numerical verifications such as grid convergence check and analytical-solution comparison, so the thin-layer water-loss feature near material

surface cannot be accurately captured [8-10]. Without strict numerical validation, the simulation outputs may contain hidden numerical diffusion and bring deviation to process analysis.

To address the above gaps, this paper establishes a one-dimensional radial cylindrical heat-mass transfer numerical model for cylindrical Chinese herbal medicines. The conservative finite-volume method combined with Crank-Nicolson implicit scheme is adopted to solve the temperature-moisture field in the preheating-balancing stage. This work emphasizes the asynchronous migration characteristics of heat conduction and moisture diffusion during preheating, and carries out conservation verification and parameter sensitivity analysis. The obtained results can offer theoretical support for early-stage commissioning of hot-air drying for Chinese herbal medicines, and lay a benchmark foundation for subsequent full-cycle drying models. The established model framework can also be migrated to simulate preheating processes of other porous agricultural raw materials with similar geometric features.

2. Methodology

2.1. Model establishment

Under assumptions H1, H2, H3 and H5, the temperature and dry-basis moisture content inside the medicinal material satisfy the one-dimensional radial unsteady diffusion equations in cylindrical coordinates:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left(k r \frac{\partial T}{\partial r} \right), 0 < r < R, 0 < t \leq 1800s \quad (1)$$

$$\frac{\partial C}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left[D(C) r \frac{\partial C}{\partial r} \right], 0 < r < R, 0 < t \leq 1800s \quad (2)$$

$$D(C)=7 \times 10^{-9} \exp\left(-\frac{0.89}{C}\right) (\text{m}^2/\text{s}) \quad (3)$$

The initial and boundary conditions are:

$$T(r,0)=28.0\text{ }^{\circ}\text{C}, C(r,0)=2.5500\text{ kg/kg}, 0 \leq r \leq R \quad (4)$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=0}=0, \left.\frac{\partial C}{\partial r}\right|_{r=0}=0 \quad (5)$$

$$-k \left.\frac{\partial T}{\partial r}\right|_{r=R}=h[T_{\text{air}}(t)-T(R,t)], -D(C) \left.\frac{\partial C}{\partial r}\right|_{r=R}=h_m[C_{\text{air}}(t)-C(R,t)] \quad (6)$$

At $t = 1800\text{ s}$, $T_{\text{air}} = 41.5130\text{ }^{\circ}\text{C}$. The temperature equation is a linear equation with constant coefficients, while the moisture equation is a nonlinear equation with variable coefficients. Their distinct physical properties provide the basis for separate treatment in the subsequent numerical scheme. The dimensionless numbers characterizing the relative magnitude of each resistance are defined as:

$$\alpha = \frac{k}{\rho c_p}, Bi = \frac{hR}{k}, Bi_m = \frac{h_m R}{D}, Fo = \frac{\alpha t}{R^2} \quad (7)$$

2.2. Numerical solution method

The conservative finite volume method is adopted in space: the domain $[0, R]$ is divided into N control volumes with

$$-\frac{\Delta t}{2} B_i U_{i-1}^{n+1} + \left[1 + \frac{\Delta t}{2} (A_i + B_i)\right] U_i^{n+1} - \frac{\Delta t}{2} A_i U_{i+1}^{n+1} = U_i^n + \frac{\Delta t}{2} [B_i U_{i-1}^n - (A_i + B_i) U_i^n + A_i U_{i+1}^n] \quad (11)$$

The temperature field is a linear problem with constant tridiagonal coefficients, which can be assembled once outside the time loop, and only the right-hand side term is updated at each time step. Since D depends on C in the moisture equation, the Picard iteration is adopted at each time step: the concentration from the previous step is taken as the initial guess, and $D(C)$ and the linear system are updated alternately. The relaxation factor is 0.5, and the convergence criterion is that the infinite norm of concentration increment is less than 10^{-10} . Calculation settings: for the temperature field, $\Delta r = 0.005\text{ cm}$ (401 nodes), $\Delta t = 1\text{ s}$; for the moisture field, $\Delta r = 0.01\text{ cm}$ (201 nodes), $\Delta t = 0.25\text{ s}$. Output interpolation is performed at $r = 0 \sim 2.0\text{ cm}$ every 0.1 cm , and $t = 1 \sim 1800\text{ s}$ every 1 s .

3. Results

3.1. Result analysis

Table.1. Temperature ($^{\circ}\text{C}$) at Different Moments and Positions in Preheating-balancing Stage

Time/s	0.0	0.5	1.0	1.5	2.0
100	28.0001	28.0003	28.0040	28.0327	28.1801
300	28.0408	28.0635	28.1514	28.3681	28.8488
600	28.4533	28.5360	28.8039	29.3159	30.1652
900	29.3243	29.4583	29.8755	30.6161	31.7304
1200	30.5427	30.7098	31.2223	32.1126	33.4276
1500	31.9957	32.1867	32.7660	33.7463	35.1203
1800	33.5753	33.7720	34.3642	35.3621	36.7856

Table 1 presents the temperature at 7 time instants and 5 spatial positions. In the preheating-balancing stage, the temperature field rises monotonically over the whole domain. The radial temperature difference first increases and then tends to stabilize. At $t = 1800\text{ s}$, the central temperature $T(0,1800) = 33.5753\text{ }^{\circ}\text{C}$ and the surface temperature $T(R,1800) = 36.7856\text{ }^{\circ}\text{C}$, with a radial temperature

nodes r_i and interfaces $r_{i+1/2}$. Integrating over the control volume in cylindrical coordinates $\int r dr$, the conservative semi-discrete form is obtained:

$$\frac{dU_i}{dt} = A_i U_{i+1} + B_i U_{i-1} - (A_i + B_i) U_i, A_i = \frac{r_{i+1/2} D_{i+1/2}}{r_i \Delta r^2}, B_i = \frac{r_{i-1/2} D_{i-1/2}}{r_i \Delta r^2} \quad (8)$$

The harmonic average is used for physical properties at interfaces to guarantee continuous interface flux and discrete conservation:

$$D_{i+1/2} = \frac{2D_i D_{i+1}}{D_i + D_{i+1}} \quad (9)$$

For the central node $r = 0$, the mirror symmetry $u_{-i} = u_i$ is applied to convert it into the limit form:

$$(1+v)U_0^{n+1} - vU_1^{n+1} = (1-v)U_0^n + vU_1^n, v = \frac{2D_0 \Delta t}{\Delta r^2} \quad (10)$$

For the surface node $r = R$, the Robin boundary condition is treated as a source term of the surface control volume using the conservative finite volume form (including a factor of $1/2$). In the time domain, the second-order accurate Crank-Nicolson scheme is adopted. After assembling the equations, the tridiagonal linear system is solved by the Thomas algorithm with unconditional stability:

difference of about $3.21\text{ }^{\circ}\text{C}$. At this moment, the drying chamber temperature reaches $41.5130\text{ }^{\circ}\text{C}$, and the surface temperature is still significantly lower than the ambient temperature, indicating that the convective heat transfer resistance on the surface cannot be neglected.

Table 2 shows the moisture concentration at the corresponding moments and positions. During the whole preheating-balancing stage, the moisture content in the central region remains nearly unchanged ($C(0,1800) = 2.5500$, consistent with the initial value). Moisture variation only occurs within a thin layer of about 0.3 cm near the surface; the surface moisture content decreases from 2.55 to 1.5102 kg/kg . The moisture penetration depth $\sqrt{Dt}$ is only $0.11 \sim 0.28\text{ cm}$ at $t = 1800\text{ s}$, which is far smaller than the radius of the medicinal material, so moisture cannot penetrate into the interior.

Table.2. Moisture Concentration (kg/kg) at Different Moments and Positions in Preheating-balancing Stage

Time/s	0.0	0.5	1.0	1.5	2.0
100	2.5500	2.5500	2.5500	2.5500	2.2473
300	2.5500	2.5500	2.5500	2.5492	2.0510
600	2.5500	2.5500	2.5500	2.5353	1.8770
900	2.5500	2.5500	2.5497	2.5045	1.7548
1200	2.5500	2.5500	2.5482	2.4646	1.6586
1500	2.5500	2.5499	2.5445	2.4206	1.5787
1800	2.5500	2.5497	2.5383	2.3755	1.5102

Figure 1 and Figure 2 present the spatiotemporal distribution of temperature field and moisture concentration field, intuitively showing the overall rise of temperature field and the feature of moisture loss only in the surface layer. Figure 3 shows the radial profiles of the two fields at seven time instants. Figure 4 gives the time history of temperature and moisture content at the center and surface: the temperature difference between the center and surface increases with time, while the moisture curve at the center is

almost flat and the surface curve drops rapidly. Figure 5 shows the evolution of the $D(C)$ curve and the surface mass transfer Biot number $Bi_m = h_m R/D$. As the surface moisture

content decreases, D drops and Bi_m rises from about 3.2 to about 4.1. It indicates that the mass transfer resistance caused by surface crusting increases over time, which is the mechanism of "self-limitation of moisture variation".

Temperature field spatiotemporal distribution of the herb during the preheating-equilibrium stage

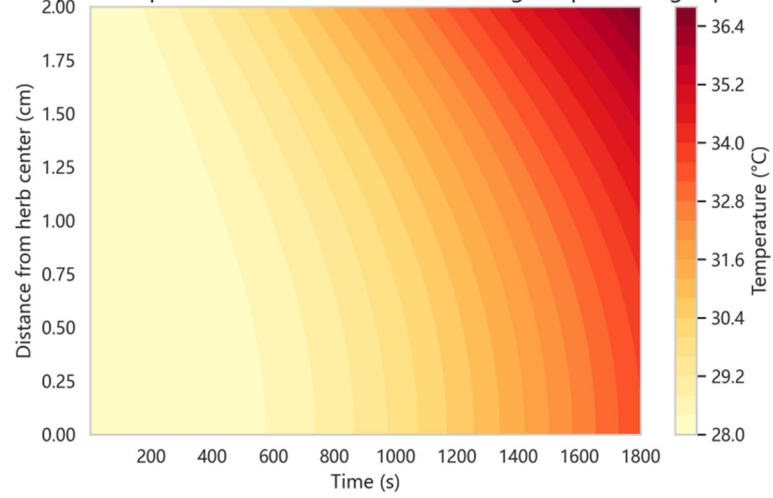


Figure 1. Spatiotemporal Distribution of Temperature Field of Medicinal Material in Preheating-balancing Stage

Moisture concentration field spatiotemporal distribution of the herb during the preheating-equilibrium stage

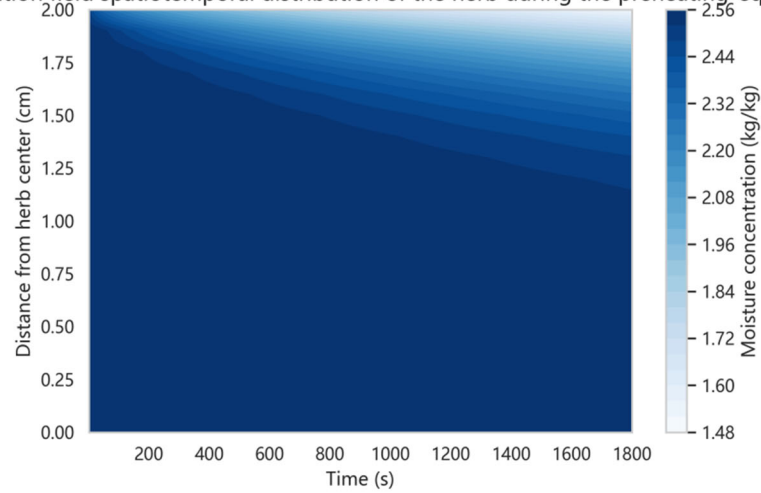


Figure 2. Spatiotemporal Distribution of Moisture Concentration Field of Medicinal Material in Preheating-balancing Stage

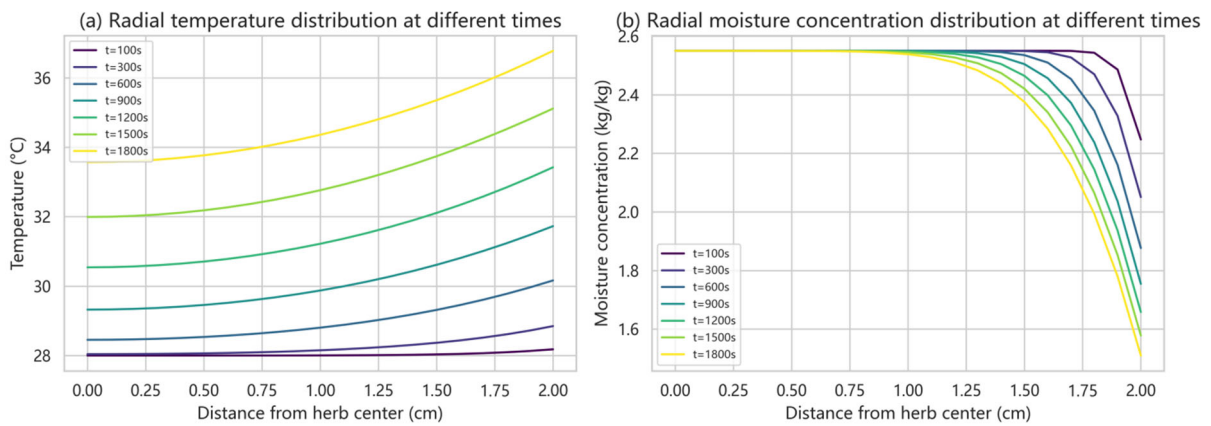


Figure 3. Radial Distribution of Temperature and Moisture Concentration

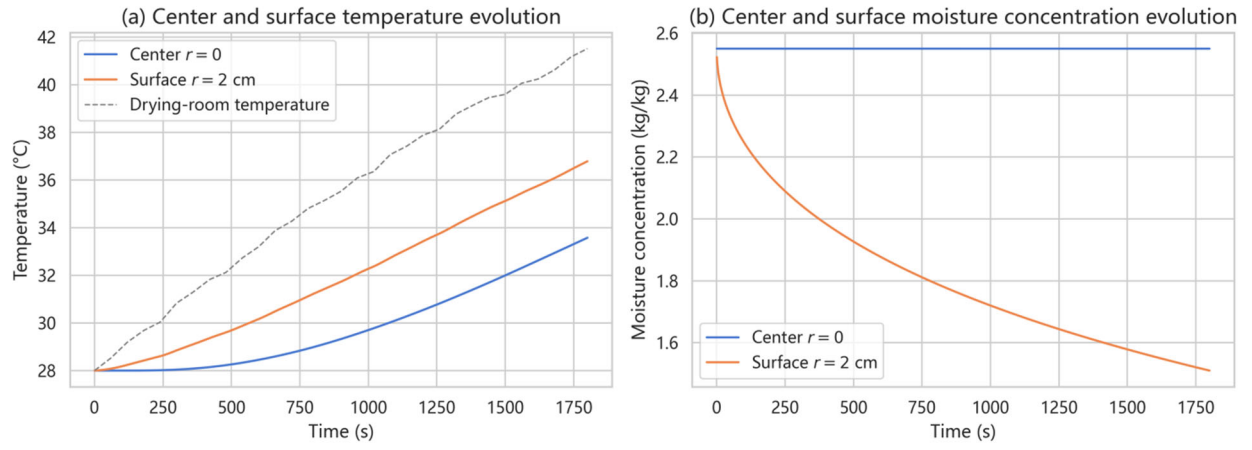


Figure 4. Time History of Central and Surface Quantities

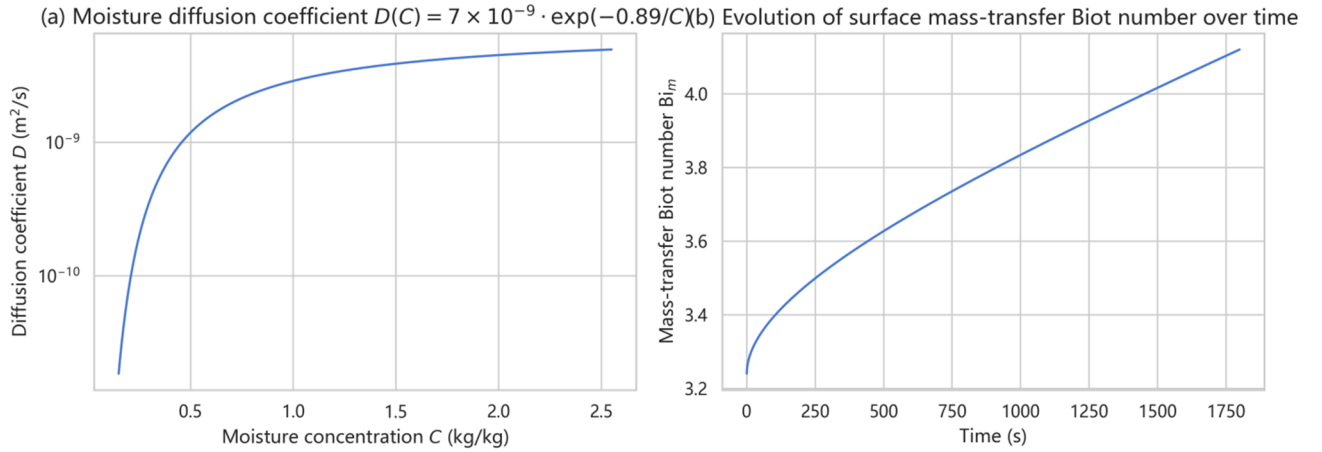


Figure 5. Moisture Diffusion Coefficient $D(C)$ and Mass Transfer Biot Number

3.2. Model validation

Table.3. Sensitivity of Key Outputs to Parameters (Relative Variation under ± 20 Perturbation)

Field	Parameter	Perturbation	Output	Baseline Value	Perturbed Value	Relative Change
Temperature	Convective heat transfer coefficient h	+20%	Central temperature $T(0,1800s)/^{\circ}C$	33.5753	34.0458	+1.40%
Temperature	Convective heat transfer coefficient h	-20%	Central temperature $T(0,1800s)/^{\circ}C$	33.5753	32.9846	-1.76%
Temperature	Thermal conductivity k	+20%	Central temperature $T(0,1800s)/^{\circ}C$	33.5753	33.9768	+1.20%
Temperature	Thermal conductivity k	-20%	Central temperature $T(0,1800s)/^{\circ}C$	33.5753	33.0174	-1.66%
Temperature	Thermal conductivity k	+20%	Surface temperature $T(R,1800s)/^{\circ}C$	36.7856	36.7080	-0.21%
Moisture	Convective mass transfer coefficient h_m	+20%	Surface moisture $C(R,1800s)/kg/kg$	1.5102	1.3759	-8.89%
Moisture	Convective mass transfer coefficient h_m	-20%	Surface moisture $C(R,1800s)/kg/kg$	1.5102	1.6637	+10.16%
Moisture	Diffusion coefficient magnitude D_0	+20%	Surface moisture $C(R,1800s)/kg/kg$	1.5102	1.5692	+3.90%
Moisture	Diffusion coefficient magnitude D_0	-20%	Surface moisture $C(R,1800s)/kg/kg$	1.5102	1.4352	-4.97%

The conservation and stability of the model are verified over the whole period $t = 0 \sim 1800s$: the temperature over the whole domain rises monotonically, the moisture content decreases monotonically, the temperature never exceeds the drying chamber temperature, and the moisture content never

exceeds the initial value. The conservation equations defined by the volume average are as follows:

$$\varepsilon_m = \frac{|\bar{C}(0) - \bar{C}(t)| - \frac{2}{R} \int_0^t h_m [C_{air}(\tau) - C(R, \tau)] d\tau}{|\bar{C}(0) - \bar{C}(t)|} \quad (12)$$

$$\varepsilon_E = \frac{|\rho c_p [\bar{T}(t) - \bar{T}(0)] - \frac{2}{R} \int_0^t h [T_{\text{air}}(\tau) - T(R, \tau)] d\tau|}{|\rho c_p [\bar{T}(t) - \bar{T}(0)]|} \quad (13)$$

The relative error of moisture conservation is 9.65×10^{-7} , and the relative error of energy conservation is 3.24×10^{-11} , both much less than 10^{-4} . After grid refinement by halving the spatial step of the moisture field, the surface deviation is 9.9×10^{-6} , and the deviation at $r = 1.5\text{cm}$ is 7.1×10^{-6} , showing good grid convergence. In addition, the temperature equation with constant physical properties has the Bessel series analytical solution:

$$\theta(\rho) = \sum_{n=1}^{\infty} \frac{2\text{Bi}}{\lambda_n(\lambda_n^2 + \text{Bi}^2)} J_0(\lambda_n \rho) e^{-\lambda_n^2 \text{Fo}} - \lambda_n J_1(\lambda_n) - \text{Bi} J_0(\lambda_n) = 0 \quad (14)$$

The upper bound of temperature is given by the comparison principle: surface 39.448°C , center 37.805°C . All numerical solutions are lower than this upper bound.

Each of the four key parameters is perturbed by ± 20 (the sensitivity is defined as the ratio of the relative change of output to the relative change of parameter), as shown in the following formula. The results are listed in Table 3 and Figure 6.

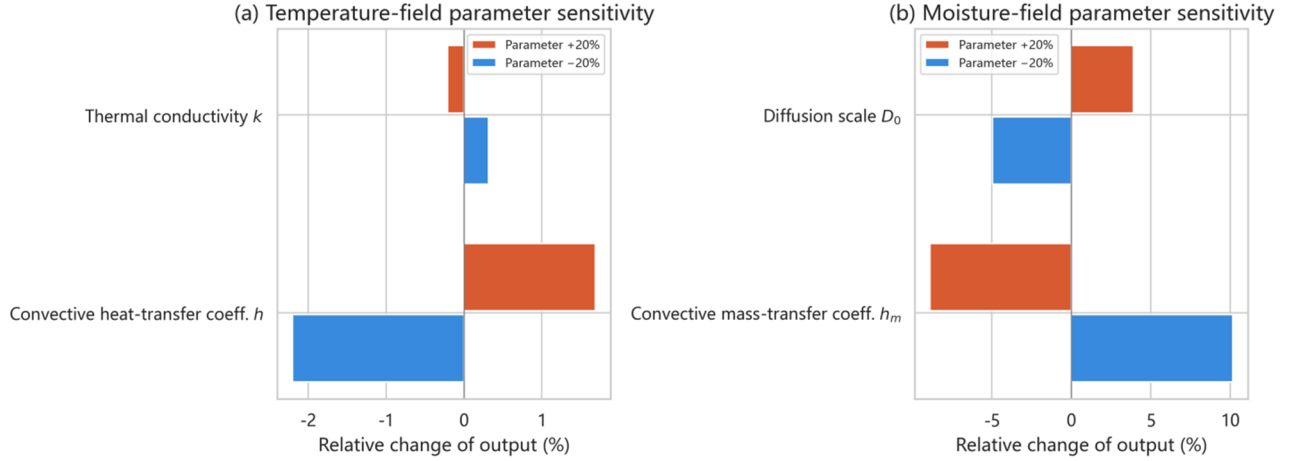


Figure 6. Parameter Sensitivity Analysis

Conclusions: (I) The temperature field is relatively stable to h and k (relative change < 2.2). The increase of k redistributes heat towards the interior; (II) The moisture field is highly sensitive to h_m (surface moisture content changes by about ± 9), and relatively insensitive to D_0 (± 4). It shows that water loss in the preheating-balancing stage is jointly controlled by surface convective mass transfer and internal diffusion ($\text{Bi}_m \approx 0(1)$); (III) The central moisture content is almost insensitive to all parameters (< 0.01), consistent with the conclusion that "moisture only varies in the surface layer", and the model conclusion is robust.

Table.4 Comparison of Interface Averaging Schemes (Surface Moisture Content $C(R, 1800\text{s})$)

Scheme	Surface Moisture (kg/kg)	Deviation from Baseline	Conservation
Harmonic average (adopted in this paper)	1.5102	0	Yes (continuous flux)
Arithmetic average (control case)	1.5103	4.0×10^{-6}	No (discontinuous interface flux)

Table.5. Comparison between Two-dimensional Axisymmetric Solution and One-dimensional Radial Solution ($t = 1800\text{s}$)

Test Item	One-dimensional Radial Solution	Two-dimensional Axisymmetric Solution	Deviation
Mid-plane $r = 0.00\text{cm}$	33.575307	33.575307	4.36×10^{-12}
Mid-plane $r = 0.40\text{cm}$	33.701137	33.701137	4.20×10^{-12}
Mid-plane $r = 0.80\text{cm}$	34.079408	34.079408	4.09×10^{-12}
Mid-plane $r = 1.20\text{cm}$	34.713616	34.713616	4.02×10^{-12}
Mid-plane $r = 1.60\text{cm}$	35.612076	35.612076	3.52×10^{-12}
Mid-plane $r = 2.00\text{cm}$	36.785492	36.785492	2.83×10^{-12}
Maximum deviation at mid-plane	36.7855 (surface)	36.7855 (surface)	4.36×10^{-12}
Thermal penetration depth $\sqrt{\alpha t}$	1.74 cm	12.5 cm (half length)	—
Maximum temperature difference between end face ($z = L$) and mid-plane ($z = 0$)	—	3.3131	—

The harmonic average gives a surface moisture content of 1.510245 kg/kg , and the arithmetic average gives 1.510250 kg/kg . The difference between the two is 4.1×10^{-6} ,

because the variation of D in the preheating-balancing stage is less than 2 times. The harmonic average is adopted in this paper, because it strictly guarantees continuous interface flux

and discrete conservation, and has obvious advantages in subsequent problems with larger variation of physical properties. Table 4 compares various surface averaging schemes.

To verify the one-dimensional radial assumption H1, a two-dimensional axisymmetric (r, z) model is built with the most unfavorable boundary of exposed end faces. The comparison of the two models at the mid-plane is shown in Appendix 3: the deviations at six radial points are all less than $4.4 \times 10^{-12} \text{ }^{\circ}\text{C}$. The thermal penetration depth $\sqrt{\alpha t} = 1.74\text{cm}$, which is much smaller than the half length $L/2 = 12.5\text{cm}$. The influence of end faces cannot reach the mid-plane within 1800 s. Table 5 compares the two-dimensional axisymmetric solution with the one-dimensional radial solution.

4. Conclusions

This paper establishes a one-dimensional radial heat-mass transfer numerical model for cylindrical Chinese herbal medicines to investigate heat and moisture migration during the preheating-balancing stage of hot-air drying. A conservative finite-volume method combined with the Crank-Nicolson implicit scheme and Thomas algorithm is adopted for numerical computation. Simulation results reveal that heat penetrates efficiently toward the interior of medicinal materials, whereas moisture migration is confined to a near-surface thin layer with a penetration depth of merely 0.11-0.28 cm, and the core moisture content almost remains unchanged. Parameter sensitivity analysis indicates that surface mass-transfer coefficient dominates the variation of surface moisture content. Multiple validation tests including energy-moisture conservation check, grid-convergence test and analytical-solution comparison verify the reliability of the established model. The present model can reproduce the heat-moisture asynchronous transport feature of porous cylindrical materials, and it is feasible to provide simulation support for the preliminary parameter debugging of hot-air drying process for rhizome-type Chinese herbal medicines.

Nevertheless, the current work only focuses on the short-time preheating-balancing phase under constant physical properties without considering property variation caused by temperature-moisture coupling. Besides, this study does not introduce material shrinkage effect and experimental measured data for model calibration. In future research, variable physical-property coupling terms will be incorporated to extend the simulation to the full drying cycle. Material shrinkage deformation will be further taken into account, and experimental drying data will be used to calibrate key model parameters, so as to improve the model's adaptability to real-world drying scenarios.

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