Validation and Optimization of Heat and Mass Transfer Model for Mushroom Convection Drying

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Abstract: In order to solve the problems of time consuming, energy consumption and low simulation accuracy in the hot air-drying system of food drying. Using computational fluid dynamics (CFD) to simulate the drying process of mushrooms can provide a reference for its technology research and development (R&D). The porous media approach was used to model the flow resistance offered by the mushroom. The resistance coefficient and porosity were determined through the experiments. Different air supply ways (wind speed, temperature, fresh air volume, reverse air supply period) were simulated and two optimize ways were suggested according the shortest possible drying time. The simulation results are in good agreement with the experimental results. The air supply way of periodic with reverse (SMPR), which means timed alternate the direction of air flow, or the way of mix in fresh air intermittently can effectively shorten the drying time. Considering comprehensively, the optimal air supply way was the mix in fresh air intermittently with fresh air accounts for 30% or SMPR with the period of 2h under the condition of the hot air temperature of 55°C and wind velocity of 0.6m/s.

1 Introduction

Drying is one of the most energy-consuming and complex devices. There are still many deficiencies in hot air-drying technology for food, such as long process time, large energy consumption, poor uniformity, etc. Modeling technology has great potential to develop drying technology. It can optimize the current drying equipment design and drying process. Moreover, the numerical model has cost advantages in industry, such as no additional lab space, maintenance and technical personnel operating equipment, reducing measurement and lab full-scale testing. Drying model plays an important role in drying technology R&D [1].

The accuracy of dry simulation based on CFD is limited, which is mainly due to the modeling method and technology [2-4]. The drying process is related to the knowledge of material properties, which are not well known. These have a great influence on the accuracy of the drying model results [5-7]. Increasing the reliability and confidence of numerical models can promote the development of drying technology. For specific drying materials, drying ways has to be guided by experience and validation studies.

2 Drying experiment

2.1 Properties experiment

The drying effect varies with the material properties. Mushroom material properties: heat capacity at constant pressure is 1800J/(kg·K); The diffusion coefficient takes an average of 10^{-9}m^2/s; Density is 860kg/m³; Thermal conductivity is 0.515W/(m·K)[8].

2.1.1 Materials and instruments

Fresh mushrooms samples were procured from local vegetable market and had a moisture content of about 80%. The air heated by an electric heater (PTC) was fed into drying box with a volume of 14×14×14cm³ by an axial flow fan (FD3-2). The inlet and outlet were both 14×14cm² with opposites. During the experimental process, a thermal anemometer (TSI-9565, USA) was used to measure the wind speed at the inlet of the drying box. A compensated micromanometer (YJB-1500) was used to measure the pressure difference between the inlet and outlet of the drying box, and a thermocouple temperature control box (1A1-K) was used to control the temperature of the supply air. The moisture loss of the sample was recorded at every 1h interval by a precision electronic balance weighing (BSM-220.4).

2.1.2 Experimental scheme

2.1.2.1 Resistance experiment

The porous media approach was used to model the flow resistance offered by the mushroom. The resistance is derived from experimental data of pressure drop at

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different velocity of air passing by. The relationship between pressure drops and wind speed was shown into Fig. 1. Fitting result and the goodness are also presented in it. The correlation coefficient of the fit R^2 is 0.9691.
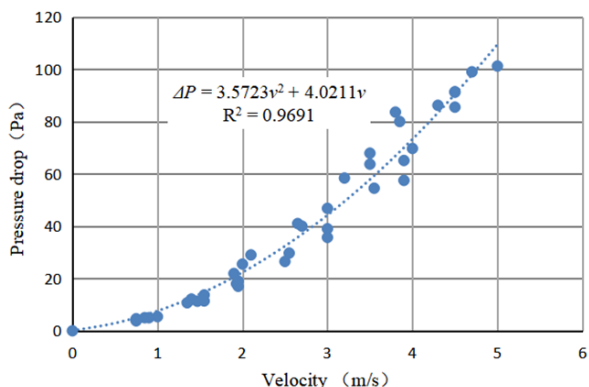
Figure 1. Air Supply Speed at the Inlet and Pressure Drop across the Drying Box

The influence of porous media is modelled by specifying a momentum source term in the standard fluid flow Equation (1) as:

$$S_i = -(\frac{\mu}{\alpha}v_i + \frac{1}{2}C_2\rho|v|v_i) \qquad (1)$$

Where, v is the velocity of air, m/s; μ is the viscosity, Pa·s; ρ is the density of air, kg/m³; ΔP is the pressure drop, Pa. where α is the permeability ($1/\alpha$=1604589m^{-2}) and C_2 is the inertial resistance factor. (C_2=41.6m^{-1}). The viscosity resistance drag coefficients and inertial drag coefficients are obtained by sorting out formula (1) and fitting results.

2.1.2.2 Porosity experiments

Since the whole box space were regarded as a porous medium in the following simulations. The procedure of porosity measurement was as follows: the initial apparent volume of the mushroom in its natural state was V which can be approximately considered as the volume of the box.

The actual volume of mushrooms was measured by drainage method: the mushrooms were reasonably laid in a thin plastic bag, and the air in the bag was discharged with the pressure of water, then the actual volume of mushrooms Vi was measured. The porosity of can be calculated by:

$$P = \frac{V - V_i}{V} \qquad (2)$$

The porosity P is divided into four stages according to the drying time, as shown in Table 1.

Table1. The porosity of mushrooms varies with time

Drying time / (h)	Total volume of the box / (m³)	Actual volume of mushroom / (m³)	porosity
0~1	2.74×10^{-3}	1.37×10^{-3}~1.26×10^{-3}	0.5
1~4	2.74×10^{-3}	1.23×10^{-3}~ 1.13×10^{-3}	0.55
4~6	2.74×10^{-3}	1.10×10^{-3}~9.01×10^{-4}	0.6
>6	2.74×10^{-3}	8.51×10^{-4}~8.11×10^{-4}	0.69

2.2 Drying test and model

2.2.1 Drying parameters

The experiment was carried out in winter, and the moisture content was not controlled due to the small difference in humidity in the air. Experimental conditions are shown in Table 2:

Table2. Mushroom drying experimental conditions

NO.	Dry-bulb temp./(°C)	Wet-bulb temp./(°C)	Relative humidity/(%)	Air supply velocity/(m/s)
1	45	20	7.36	1
2	55	23	4.6	1
3	65	26	3.31	1

Table 4. Modified formula of drying kinetics model at different temperatures

Temp. of supply air /(°C)	Formula of drying kinetics model	R^2
45	M_t=3.27exp(-(7.83E-07)×t$^{1.47}$)+1.59exp(-(9.2E-06)×t$^{1.47}$)	0.99995
55	M_t=3.71exp(-(3.71E-06)×t$^{1.26}$)+1.15exp(-(9.13E-05)×t$^{1.26}$)	0.99989
65	M_t=-39.39exp(-(2.18E-04)×t$^{0.91}$)+44.24exp(-(2.29E-04)×t$^{0.91}$)	0.99971

2.2.2 Selection and calculation of hot-air drying models

Calculation formula of dry base moisture content (M_t):

$$M_t = \frac{W_t - G}{G} \qquad (3)$$

Where, W_t is the material mass at any time point in the drying process, g; G is the mass of the material when it is completely dried (that is the dry base mass).

Match the experimental results with the commonly used drying model[9-17] (as shown in Table 3). Finally, it was found that Hii model was the most consistent with the law of mushroom drying. Fig. 2 and Table 4 show the model fitting results of M_t changes with time under different drying temperatures.

Table 3. Kinetic model of mushroom drying

NO.	The model name	Model formulation
1	Newton	$M_t = \exp(-k\,t)$
2	Henderson and Pabis	$M_t = a\exp(-k\,t)$
3	Page	$M_t = \exp(-k\,t^n)$
4	Logarithmic	$M_t = a\exp(-k\,t)+c$
5	Two term model	$M_t = a\exp(-k\,t) + b\exp(-g\,t)$
6	Verma et al.	$M_t = a\exp(-k\,t) + (1-a)\exp(-g\,t)$
7	Midili-kucuk	$M_t = a\exp(-k\,t^n) + b\,t$
8	Wang and smith	$M_t = 1+a\,t+b\,t^2$
9	Hii	$M_t = a\exp(-k\,t^n)+b\exp(-g\,t^n)$

Where, t is time, M_t is dry base moisture content, others are constants.
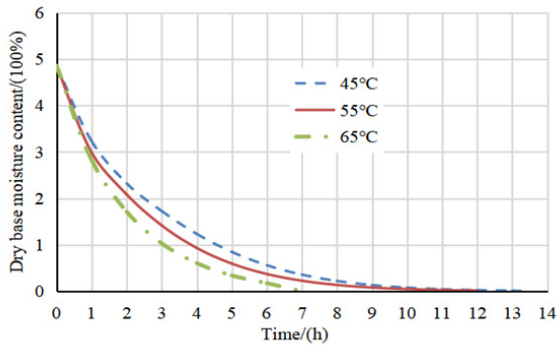
Figure 2. Relationship between Dry Base Moisture Content and Time at Different Temperatures

3 Model establishment

3.1 Numerical model

The turbulence model used in the air flow simulation is the k-ε model [18]. In the dynamic equilibrium state of water absorption and resolution of mushroom, the main factors that affect the amount of water released or absorbed by mushroom include temperature and the concentration of water vapor in the surrounding air. The concentration of water vapor in the air is equal to the sum of the concentration of water vapor in the air and the water vapor evaporated from the mushroom during the drying process. Vapor concentration equation is as follow:

$$\frac{\partial c}{\partial T} = D_A\left(\frac{\partial^2 c}{\partial x^2} + \frac{\partial^2 c}{\partial y^2} + \frac{\partial^2 c}{\partial z^2}\right) - \rho_s\frac{1-V_k}{V_k}\frac{\partial M}{\partial t} \tag{4}$$

The basis for establishing the temperature equation of dry-base matter is that the temperature change of mushrooms is composed of two parts: one is the heat exchange between mushrooms and hot air, the other is the heat consumed by the evaporation of water vapor in mushrooms. Its equation is as follow:

$$\frac{\partial T}{\partial t} = \frac{k}{\rho c}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{q}{\rho}\frac{\partial M}{\partial t} \tag{5}$$

The calculation formula of mass transfer rate is:

$$\frac{\partial M}{\partial t} \approx \frac{\Delta M}{\Delta t} \tag{6}$$

The mass of water vapor escaping is the product of the change in dry base moisture content and the dry base mass:

$$\Delta M = \Delta M_t \times G \tag{7}$$

In the simulated drying process, the parameters of each cell are different. Therefore, when calculating the dry basis moisture content of each cell, interpolation should be used to calculate the dry basis moisture content formula with the known temperatures:

$$M_t = M_{t_1} - \frac{M_{t_1} - M_{t_2}}{t_1 - t_2}(t_1 - t_0) \tag{8}$$

Where, D_A is the diffusion coefficient of water vapor in the air, m^2/s; V_k is the volume occupied by air in the porous medium, m^3; T is the temperature of the mushroom, K; c is water vapor concentration, kg/m^3; t is drying time, s; ρ_s is wet density of mushroom, kg/m^3; ρ is the apparent density of mushrooms, kg/m^3; k is thermal conductivity, W/(m·K); ΔM is the amount of water vapor escaped, kg; M_{t1}, M_{t2} are the moisture content of the dry basis when the temperature is t_1 and t_2, respectively, where t_1 and t_2 are the two temperature values closest to 45°C, 55°C and 65°C for t_0.

3.2 Physical model

The simulation target was a three-dimensional model of the drying box and transient simulations were carried out. The dimension of the box was 3m length, 2m width by 2m high (along x-axis, z-axis and y-axis, respectively). 0m~3m, z-axis: -1m~1m; y-axis: 0m~2m. The entrance was located in the yz plane with x=0m, and the exit was located in the yz plane with x=3m. Three sets of simulation experiments with the initial temperature of 17°C were performed.

The air supply parameters set in the simulations are consistent with those in the experiments. In order to reduce the drying time, energy consumption, and avoid excessive drying, the relative humidity at the end of the drying box needs to be reduced by PRAS or mix in fresh air. Three kinds of simulations have been performed in this paper.

• The first kind one was conducted under three set temperatures of 45°C, 55°C and 65°C and three wind velocities of 0.4m/s, 0.6m/s and 0.8m/s, in which temperature and velocity of hot drying air at the inlet were kept constant in the whole process of drying.

• The second kind was to add a way to mix in fresh air on the basis of the first kind , it was conducted under three fresh air ratio of 20%, 30%, 40%, in which the mixed fresh air temperature is 5°C, and moisture content is 4.1g/kg, and mixed air supply 10 minutes for every 1 hour.

• The third kind was conducted under three set temperatures of 45°C, 55°C and 65°C, three wind velocities of 0.4m/s, 0.6m/s and 0.8m/s, and three period of 2h, 3h and 4h, in which air supply direction changed every half period.

Reduce unnecessary workload through orthogonal experiment, 9 groups of simulation experiments were needed for each case.

4 Result and analysis

4.1 Accuracy analysis of simulation

As shown in Figure 3. When the temperature was 45 ℃, 55 ℃ and 65℃, the maximum relative errors between the experiment and simulation were 0.52%, 3.35% and 1.36%, respectively, in the drying process. The error tends to increase over drying time. The reasons may be caused by iterative convergence error and discrete error in the simulation process. In addition, the error increases as temperature increasing. This was because the increase of temperature in the actual drying process leads to a large amount of shrinkage of the mushroom, and the drying rule of the different moisture between surface and interior causes a large change in the diffusion rate of internal moisture to the surface. And the diffusion coefficient of this model was averaged. The simulated drying time at 45 ℃, 55 ℃ and 65℃ was 13.4h, 12h and 6.8h, respectively, which was similar to the experimental results.
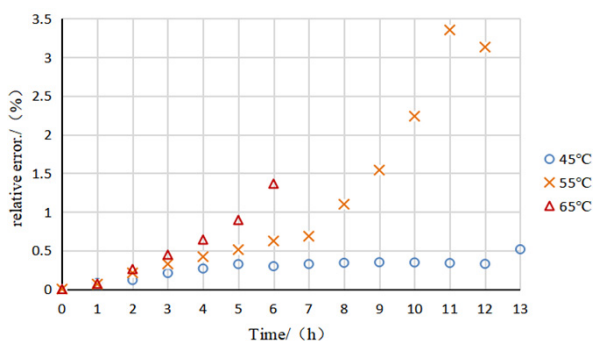

Figure 3. Relative Error between Experimental and Simulated Values of Dry Base Moisture Content of Mushrooms Per Hour at 45、55、65℃

4.2 Optimization of air supply scheme

The results of the two simulation methods are used as typical examples: one was conducted under temperature of 55℃, wind speed of 0.8m/s, fresh air ratio of 30%, and the other was under temperature of 45℃, wind speed of 0.4m/s, period of 2h (other similar figures were omitted due to space limitation). The drying box were divided into 9 parts along the direction of air supply. The dry basis moisture content of each part at different time is shown in Fig. 4 and Fig. 5. The initial decrease rate of dry basis moisture content is fast, but with the process of drying, the time needed gradually becomes longer when the dry basis moisture content decreases by 1. This is due to lower internal moisture content and a slower rate of water diffusion from interior region.
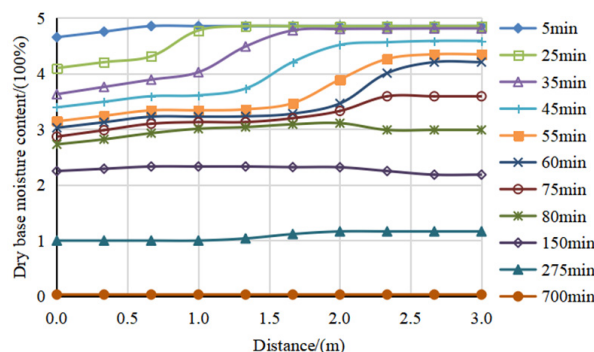
Figure 4. Dry Basis Moisture Content (Mt) at Different Time Points at method of periodic reverse the direction of air, in which was conducted under periodic of 2 hour, temperature of 45℃ and wind velocity of 0.4m/s
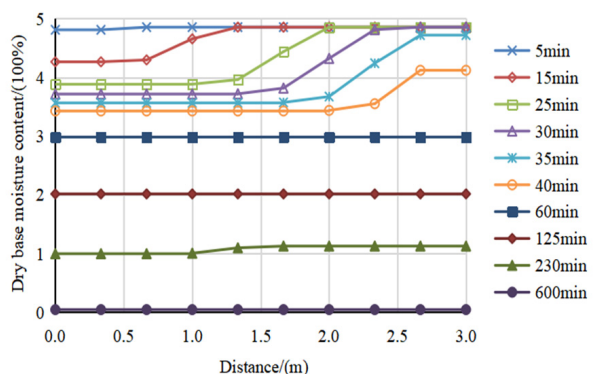
Figure 5. Dry Base Moisture Content (Mt) at Different Time Points at mix in Fresh Air, in which was conducted under Fresh Air Ratio of 30%, temperature of 45℃ and wind velocity of 0.4m/s

For the direct air supply, the closer to the outlet, the higher dry basis moisture content (significantly at the initial drying stage), because the relative humidity of air is one of the main factors affecting the drying rate. Simulated physical model according to the industrial production needs of the stacking volume of mushroom. Mushrooms near the entrance have the priority of convective heat and humidity exchange. In this process the increase of moisture content in the air decreases their drying ability. Therefore, the method of periodic reverse air supply and introduce the fresh air with low humidity in time can not only ensure the uniformity of drying, but also reduce drying time and energy consumption.

The total drying time under different working condition is shown in Table 5.

Table 5. Summary of drying time under various conditions

Air supply with constant		Mix in fresh air		SMPR	
Temp-wind speed /(°C-m/s)	Drying time /(min)	Temp-wind speed-fresh air ratio /(°C-m/s-%)	Drying time /(min)	Temp-wind speed-period /(°C-m/s-h)	Drying time /(min)
45-0.4	730	45-0.4-20	695	45-0.4-2	700
45-0.6	720	45-0.6-30	720	45-0.6-4	700
45-0.8	700	45-0.8-40	700	45-0.8-3	690
55-0.4	690	55-0.4-20	650	55-0.4-3	640

55-0.6	670	55-0.6-30	600	55-0.6-2	600
55-0.8	670	55-0.8-40	600	55-0.8-4	600
65-0.4	375	65-0.4-20	370	65-0.4-4	365
65-0.6	370	65-0.6-30	370	65-0.6-3	365
65-0.8	365	65-0.8-40	365	65-0.8-2	365

The method of periodic reverse the direction of air can solve the situation that the relative humidity of the air in the exit section is higher than that in the entrance section, as shown in Fig. 4 after 80mins later, which will lead to low drying speed at the exit section and excessive drying at the entrance section. The method of introducing fresh air can reduce the relative humidity of air from the source, increase the concentration difference and water vapor partial pressure difference, promote the overflow of water, and reduce the drying time.

Temperature plays a more important role on drying rate than wind speed does. At the same temperature, the higher wind speed, the shorter drying time, but it is not obvious. At the same wind speed, the higher the temperature, the faster the drying rate is, and it is more significant. The main reason is that the temperature and enthalpy of mushrooms increase during the drying process, which can promote the evaporation of water. However, temperature will affect the shrinkage degree of the material, and the higher temperature, the greater shrinkage, as shown in Figure 6. The shrinkage of 65°C is obvious, and the difference between 45°C and 55°C is small. Therefore, the optimal working condition is temperature of 55°C, wind speed of 0.6m/s, fresh air ratio of 30% and reverse air supply with a period of 2 hours, both of which are shortened by 70min.
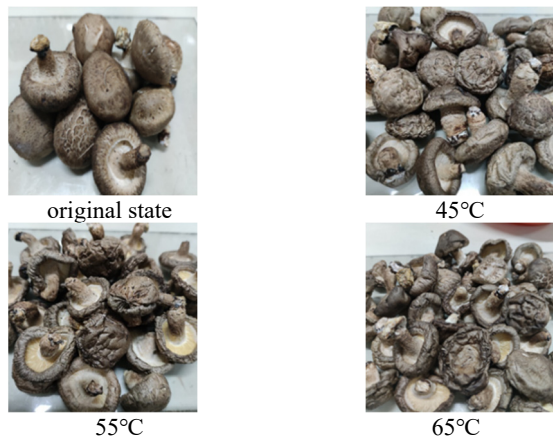
Figure 6. The Original State of Mushrooms and the State at Each Temperature When Drying Completely

5 Conclusions

Based on the mechanism of heat and moisture transfer and drying characteristics of mushrooms, a drying model of mushrooms with high accuracy was established. The simulation results can guide mushroom production practice. This simulation method provides a new idea for other food drying industry production and has a reference significance. The contents are as follows:

• Measure and calculate mushroom physical parameters: resistance coefficient, porosity.

• Drying kinetics model: according to the experimental results and the commonly used drying kinetics model, the Hii model has the highest fitting degree, $R^2 > 0.999$.

• A new mathematical calculation model was proposed, and the UDF program was coupled to the CFD. The maximum relative error between the experimental and simulation results was 3.35%.

• Three air supply ways are simulated: air supply with constant, mix in fresh air and SMPR. Drying time, uniformity, appearance shrinkage, energy saving and other factors should be considered. Analytically there are two optimal dry conditions. One is mix in fresh air, in which is conducted under temperature of 55°C, wind speed of 0.6m/s and fresh air ratio of 30%. The other is SMPR. It is conducted under temperature of 55°C, wind speed of 0.6m/s and period of 2 hours. Both of them can shorten the drying time by 70 minutes.

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