Research on Mathematical Model of Hot Air Drying of Onion

Han Wang[1, a], Lin Dong[2, b], Wenlong Tang[3, c]

[1]School of Mechanical Engineering, Xihua University, Chengdu 610039, China

[2]Institute of Modern Agricultural Equipment, Xihua University, Chengdu 610039, China

[3]Chongqing Chuanyi Automation Co., LTD. Suda Instrument & Meter Branch, Chongqing 400700, China

[a]970744383@qq.com, [b]donglin11723@163.com, [c]tangwenlong1998@126.com

Authors contributed equally: Han Wang, Lin Dong, Wen-Long Tang

Abstract

Onions' pronounced perishability stems from their elevated moisture content. While hot air drying prevails as a common dehydration method, empirical determination of process parameters frequently compromises operational efficiency and product quality. This investigation employed single-factor experimentation to establish optimal drying conditions, revealing an inverse correlation between drying duration and thermal parameters (temperature: 60-80°C; airflow velocity: 1.5-2.5 m/s), contrasted by direct proportionality to accumulation thickness (15-25 mm). Quantitative analysis identified the effective moisture diffusion coefficient (Deff: 2.17×10^{-10} to 6.43×10^{-10} m^2/s) and activation energy (Ea: 32.18 kJ/mol) within characteristic ranges, with the modified Page model demonstrating optimal suitability (R^2=0.9973, χ^2=0.0008) for process characterization. These findings provide a scientific foundation for enhancing dehydration kinetics and preserving organoleptic properties in onion processing, offering crucial guidance for industrial dryer optimization.

Keywords

Onion; hot air drying; drying mathematical model; drying process parameters; numerical modeling.

1. INTRODUCTION

As consumers increasingly pursue healthy lifestyle [1], the demand for fresh fruits and vegetables, which are rich in vitamins, dietary fiber and minerals, continues to grow. However, the high water content in these products makes them prone to post-harvest deterioration, causing significant economic losses. Therefore, developing efficient and reliable drying technologies is essential to extend shelf life and enhance added value of agricultural produce.

As a globally consumed food staple [2], onions are valued not only for their distinctive flavor but also as an important functional food due to their rich nutritional profile. While traditional sun-drying produces visually appealing products, it remains weather-dependent, prone to contamination, and inefficient for mass production. In contrast, hot air drying has gained widespread industrial adoption due to its cost-effectiveness, scalability, and compatibility with automation systems.

Nevertheless, conventional hot air drying presents challenges including uneven moisture distribution, excessive energy consumption, and prolonged processing times - all of which compromise product quality and market competitiveness. To address these limitations, this

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study conducts mechanistic analysis of drying processes combined with experimental verification to identify optimal parameters : temperature, airflow velocity, and material bed thickness, ultimately establishing an optimized protocol for onion dehydration.

This research aims to develop practical and easy-to-implement hot air drying solutions for the food industry, facilitating industrial-scale processing of onions and other produce while meeting market demands, reducing operational costs, and improving economic returns

2. DRYING METHOD AND CALCULATION OF PHYSICAL PROPERTY PARAMETERS OF ONION

2.1. Test materials and methods

2.1.1 Test material

The purple onion used in this experiment was procured locally in Chengdu. To ensure experimental consistency, we selected specimens with uniform size (approximately 200g weight), maximum diameter of ~8 cm, vivid purple coloration, and no visible mildew. The onion's moisture content was determined as 91.8% using the drying-weight method according to GB/T 5009.3-2016 national standard, with samples dried to constant weight at (80±2)°C. Prior to testing, all onions were stored in sealed bags within a refrigerated chamber maintained at (4±1)°C.

Figure 1. The onion used in the test

2.1.2 Test method

To ensure the accuracy of the onion drying experiment, the electric thermostatic bellows must be preheated for 30 minutes prior to testing. The experimental procedure involves peeling fresh onions, conducting root treatment, and slicing them into 1cm-wide strips. These strips are then evenly distributed in 115mm-wide metal baskets according to predetermined stacking thickness specifications. During the drying process, the basket is removed every 30 minutes for weight measurement. Drying completion is determined when consecutive weight variations remain below 0.1g over any 30-minute interval. Finally, the dehydrated onions undergo cooling before being hermetically sealed in moisture-proof packaging with desiccants for subsequent quality evaluation.

Figure 2. A control diagram was prepared before and after the test material

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2.2. Measurement and calculation of onion physical property parameters

2.2.1 Density test

To determine the packing density of onions for drying applications, the static weighing method was implemented as follows:

Materials and equipment: Purple onion samples underwent standardized pretreatment including outer layer removal. Experimental apparatus comprised: high-precision electronic scale (LQ-T3; capacity 10kg, accuracy ±0.01g), 50mL graduated cylinder, 1.8L polypropylene container, 500mL borosilicate beaker, and 50mL precision syringe.

Procedure: Samples were extracted from the cryogenic storage chamber, peeled, and subjected to static weighing measurements. Mass and volumetric parameters under natural stacking conditions were recorded using calibrated equipment, enabling calculation of packing density (ρ = m/V).

During the onion drying process, the continuous volume shrinkage causes dynamic changes in packing density. Through five replicate measurements using the aforementioned protocol, the mean actual density was determined as 882.96±1.2 kg/m^{3}with packing density measuring 258.56±1.4 kg/m^3. These quantified parameters are systematically presented in Table 1

Table 1. Actual density and packing density of onion

Measurement serial number	Actual density ρ_p(kg/m^3)	Packing density ρ_s(kg/m^3)
1	900	257.94
2	870.73	263.55
3	850	260
4	862.65	256.43
5	931.43	254.88
Mean value	882.96	258.56

2.2.2 Porosity calculation

Industrial onion dehydration protocols employ strip-cutting techniques to facilitate bulk drying configurations. The resultant stratified architecture exhibits multiscale porosity: continuous microscopic voids within parenchyma tissue and macroscopic inter-strip channels. Given this anisotropic porosity distribution across spatial dimensions (axial/lateral ratio: 1.38±0.15) and hierarchical pore structure (micro: 10-50μm, macro: 2-5mm), we implement a homogenized continuum assumption for computational modeling. The effective porosity (ε_eff) is mathematically expressed as:

$$\varepsilon/\% = \frac{V_1 - V_0}{V_1} \times 100 = (1 - \frac{\rho_S}{\rho_P}) \times 100 \quad (1)$$

In the formula:

ε—Onion porosity, %;

V_1—Onion bulk, m^3:

V_0—Actual onion volume, m^3;

By substituting the data listed in Table 1, the porosity of onion is 70.71%.

2.2.3 Permeability calculation

Permeability quantifies the volumetric flux through porous media per unit cross-sectional area under hydraulic gradient, serving as a critical dimensionless parameter for mass transfer characterization. This transport property inversely correlates with hydraulic resistance while

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being functionally dependent on porosity and effective particle diameter. The governing relationship is mathematically expressed by:

$$k_d = cd_e^2 \tag{2}$$

In the formula:

k_d—Penetration rates can be obtained by bringing in the above data, $2.747 \times 10^{-6} m^2$:

c—Proportional coefficient:

d_e—Effective particle size, m.

2.2.4 Calculation of thermal conductivity

Permeability refers to the flow density through unit width and thickness of porous media per unit time, which serves as a crucial indicator of mass transfer performance. The permeability magnitude reflects flow resistance intensity, while being influenced by porous media's porosity and particles' effective size. The permeability calculation formula is as follows:

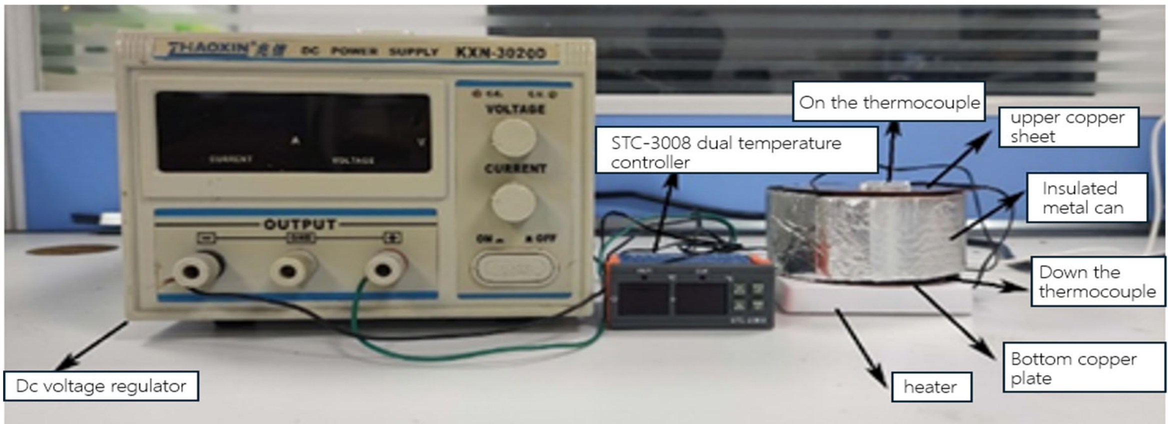

Figure 3. Thermal conductivity simple measuring

To accurately capture the heat conduction characteristics of onions during drying, a simplified thermal conductivity measurement device was constructed based on Fourier's heat conduction theory. The apparatus consists of a DC regulated power supply, STC-3008 dual-channel thermostat, two K-type thermocouples (diameter φ1 mm), a 3mm-thick copper plate with 50mm radius, and a cylindrical insulated metal container (50mm radius and height) filled with onion strips. The thermal conductivity of the onion porous medium was measured by monitoring temperature variations during heating, thereby determining its heat conduction properties. The device configuration is shown belo

Add onion into the metal insulated tank, the cross-sectional area is A, the thickness is h, turn on the heater, and after the temperature of the upper and lower copper plates is stable, the upper copper plate temperature T_0 and the lower copper plate temperature T_1 are measured respectively. The thermal conductivity of onion porous medium is as follows:

$$\lambda = cm \frac{\Delta T}{\Delta t} |T = T_1 \frac{h}{\Delta t} \frac{r+2d}{2r+2d} \frac{1}{A} \tag{3}$$

In the formula:

λ—Thermal conductivity of onion porous medium, W/(m · K);

c—Specific heat capacity of copper, 385 J/(kg · K);

m—The weight of the copper sheet, 33.5 g;

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T_1—Steady state temperature of upper copper sheet, °C;

h—Upper and lower copper sheet thickness, mm;

r—Upper and lower copper plate and onion porous medium radius, mm;

A—Upper and lower copper plate and onion porous media cross-sectional area, m^2.

The onion porous medium to be measured with an initial temperature of 22°C and an initial moisture content of 91.8% was measured three times under this device to obtain its average value, as shown in Table 2:

Table 2. The average measured thermal conductivity of onion

sample	Thermal conductivity $w/(m \cdot k)$	T_0	T_1
Onion	0.568	55.6	28.5

2.3. Common drying mathematical models and evaluation indexes

To prevent energy waste and quality degradation during dehydration processes, drying mathematical models are employed to characterize moisture transport kinetics in agricultural products [4]. These models provide critical data support for dryer R&D and enable operators to implement real-time process optimization. This study validated model accuracy through regression analysis of onion moisture ratio data from Chapter 2's single-factor experiments, utilizing three statistical metrics: coefficient of determination (R^2), residual sum of squares (RSS), and reduced chi-square (χ^2) [5]. Eight established drying models were evaluated as follows:

Table 3. Drying mathematical model

Model number	Model name	Model equation
1	Geometric	$MR = at^{-n}$
2	Newton	$MR = exp(-kt)$
3	Page	$MR = exp(-kt^n)$
4	Page modified	$MR = exp[-(kt)^n]$
5	Henderson and pabis	$MR = a\,\exp(-kt)$
6	Logarithmic	$MR = a\,\exp(-kt) + b$
7	Two term exponential	$MR = aexp(-kt) + (1-a)\exp\,(-kat)$
8	Wang and singh	$MR = a + bt + ct^2$

Note: In the table, a,b,c,n,k,k_1,k_2 are parameter variables, and t is drying time

3. STUDY ON HOT AIR DRYING CHARACTERISTICS AND DRYING MATHEMATICAL MODEL OF ONION

3.1. Experimental design

Single-factor experimental design for onion hot-air drying

The test protocol was formulated [6-8] through comprehensive analysis of onion dehydration parameters and horizontal experimental requirements. Specific test parameters are detailed in Table 2.1:

Tests 1-4: Maintained constant air velocity (1 m/s) and bed thickness (80 mm) while varying temperature (50-80°C)

Tests 5-8: Fixed temperature (60°C) and air velocity (1 m/s) with varying bed thickness (60-100 mm)

Tests 9-11: Controlled temperature (60°C) and bed thickness (80 mm) while adjusting air velocity (0.5-2.0 m/s)

Table 4. Drying test design and parameters

series	Temperature/°C	Wind speed m/s	bulking thickness mm
1	50	1	80
2	60	1	80
3	70	1	80
4	80	1	80
5	60	1	40
6	60	1	60
7	60	1	80
8	60	1	100
9	60	0.5	80
10	60	1	80
11	60	2	80

3.2. Results and analysis

3.2.1 Effect of hot air temperature on drying characteristics of onion

When the wind speed of hot air is controlled to 1m/s, the thickness of onion accumulation is 80mm, and the temperature of hot air is changed to 50°C, 60°C, 70°C, 80°C, the curve of hot air drying moisture ratio and drying rate of onion are as follows:

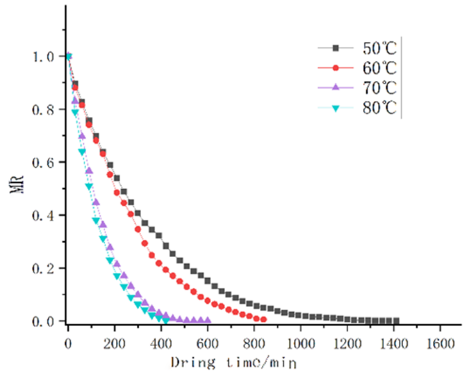

Figure 4. Curve of dry moisture ratio of onion at different hot air temperatures

Elevated hot air temperatures accelerate moisture equilibrium attainment in onions. At 80°C, the minimum drying duration was recorded at 420 minutes. Under identical conditions, equilibrium times at 50°C, 60°C, and 70°C measured 1410, 840, and 600 minutes respectively - representing 235.7%, 100%, and 42.9% prolongations compared to 80°C. The moisture ratio curves exhibited steeper initial slopes followed by gradual stabilization. Distinct curve progression patterns emerged between 60°C and 70°C trials, with thermal intensification correlating to increased slope gradients and reduced dehydration periods. This thermal response likely stems from initial-stage dominance of free water removal [9], where surpassing critical temperature thresholds enhances evaporation kinetics. Late-stage hardening of epidermal layers impeded internal moisture diffusion, decelerating dehydration rates. The analogous moisture ratio profiles at 70°C and 80°C suggest temperature-driven evaporation mechanisms superseding material-specific characteristics at elevated thermal conditions.

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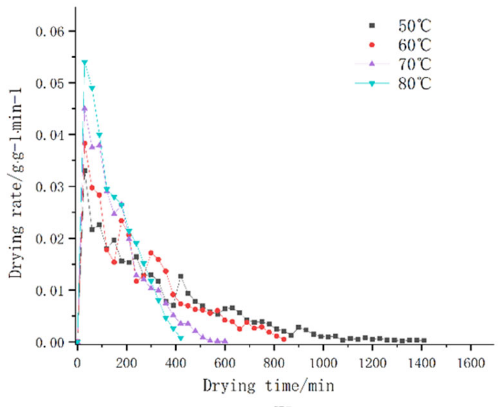

Figure 5. Graph of drying rate of onion at different hot air temperatures

As can be seen from Figure 6, the higher the hot air drying temperature, the higher the maximum drying rate, and the drying time is shortened accordingly. At 80 ° C and 70 ° C, the highest drying rate is reached in the early drying period (30 minutes), and then the rate decreases rapidly, and the rate is lower than 50 ° C, 60 ° C and 70 ° C in the late drying period. The reason for this is that Onions contain a lot of free water, which evaporates quickly at high temperatures. When the hot air temperature is 60℃, the drying rate increases greatly at 150 minutes and 240 minutes. At 50℃, the drying rate increased significantly at 390 minutes. The overall drying rate of onion showed a downward trend, but there was a sudden growth rate at some time points, which may be due to the hardening and folding of onion skin with the drying process, hindering the evaporation of internal water, which led to the increase of partial pressure difference of water inside and outside onion and the increase of the driving force of internal water diffusion to the skin. When the partial pressure difference broke the critical point, the drying rate rose suddenly.

In summary, in the drying process of onion, the free water can be quickly evaporated at a higher temperature in the early stage, and the combined water can be slowly evaporated at a lower temperature in the middle and late stage, so as to achieve energy-saving and efficient drying effect.

3.2.2 Influence of accumulation thickness on drying characteristics of onion

When the wind speed of the hot air is controlled to 1m/s, the temperature of the hot air is 60℃, and the accumulation thickness of the onion is changed to 40mm, 60mm, 80mm, 100mm, the curve of the hot air drying moisture ratio and drying rate of the onion are as follows:

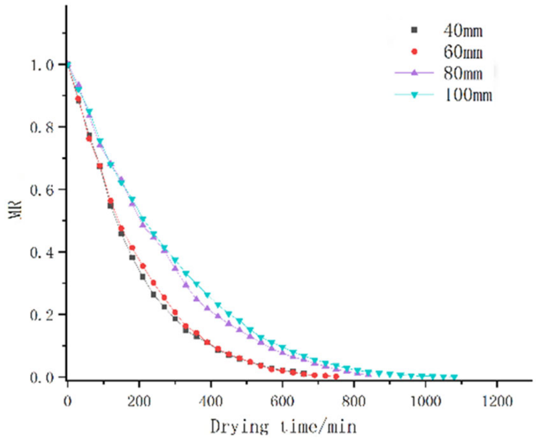

Figure 6. Curve of dry moisture ratio of onion under different packing thickness

As the thickness of the onion pile increases, so does the time it takes to achieve water balance. At 40mm, the drying time is the shortest, 660 minutes. Under the same conditions, the drying time of 60mm, 80mm and 100mm is 750 minutes, 840 minutes and 1080 minutes, respectively, which increases the drying time by 25%, 27% and 63.6% compared with 40mm. The trend of water ratio curve is different under different deposit thickness, and the trend of curve change at 60mm and 80mm is special. This may be due to the fact that as the accumulation thickness decreases, the hot air can penetrate the onion surface better and the resulting water vapor can be carried away more quickly, thus speeding up the drying process.

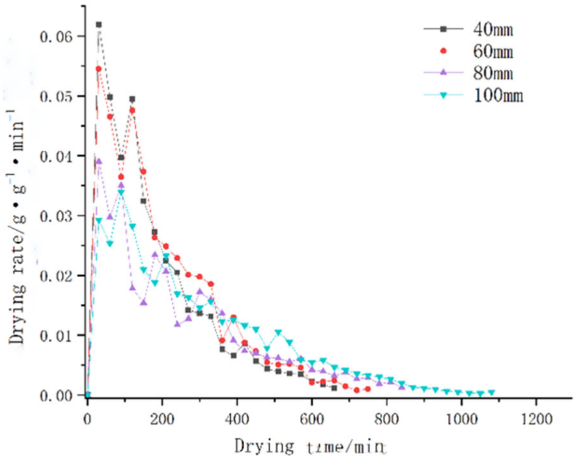

Figure 7. Graph of drying rate of onion at different stacking thickens

As can be seen from FIG. 8, the accumulation thickness of onion was negatively correlated with the pre-drying rate, and the overall drying rate showed a step-type fluctuation and decline. The drying rate was the highest at the accumulation thickness of 40mm, but there was a sharp decline at 180 minutes, and then the drying rate was lower than other thickens. In the late drying period, deposit thickness had a positive correlation with drying rate. The reason for this phenomenon may be that at the early stage of drying, the larger accumulation thickness makes it difficult for the center of the onion pile to fully contact the hot air, and the water vapor is difficult to disperse, thereby reducing the drying rate. At the later stage of drying, the central temperature of the onion pile rose, and the internal water began to evaporate, and the drying rate increased, and then gradually decreased.

In the early drying period, a small onion packing thickness should be used to ensure uniform heat and quickly carry away a large amount of water vapor. The accumulation thickness can be appropriately increased in the late drying period, and the large available space after the drying volume shrinks at this time can be used to improve the drying efficiency and achieve energy saving.

3.2.3 Influence of hot air speed on drying characteristics of onion

When the temperature of hot air is controlled to 60°C, the thickness of onion accumulation is 80mm, and the wind speed of hot air is changed to 0.5m/s, 1m/s, 2m/s, the curve of hot air drying moisture ratio and drying rate of onion are as follows:

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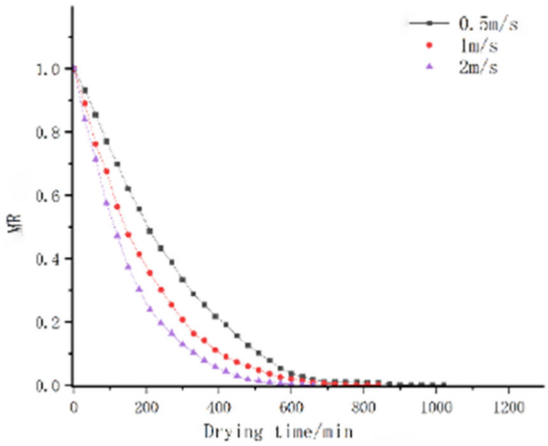

Figure 8. Curve of dry moisture ratio of onion under different hot air speed

When the hot air speed increases, the time required for the onion to reach equilibrium moisture content decreases. At 2m/s, the drying time is the shortest, only 660 minutes. Under the same conditions, at 0.5m/s and 1m/s, the time for the onion to reach the equilibrium moisture content is 1020 minutes and 840 minutes, respectively.

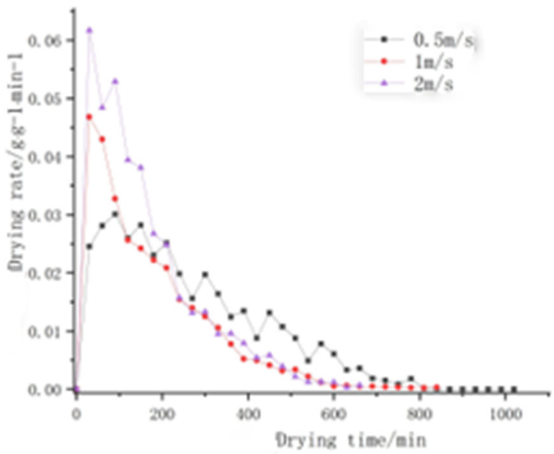

Figure 9. Curve of drying rate of onion under different hot air speed

As can be seen from Figure 10, the drying rate reached the maximum value in the initial drying period, and then showed a trend of fluctuation and decline. This is because the onion has high water content, the initial water evaporation is large, the greater the wind speed, the stronger the ability to take away water vapor, the greater the humidity gradient formed, so as to achieve the maximum drying rate. The higher the wind speed of hot air, the faster the drying rate in the early stage, but the more obvious the downward trend. After 240 minutes, the smaller the wind speed, the greater the drying rate, 0.5m/s drying rate is the highest, then 1m/s and 2m/s drying rate is similar. This may be due to the high wind speed that enhances the heat exchange capacity of the onion surface and the ability to carry away water vapor, but it also causes the onion surface to harden prematurely and form folds, which prevents the internal water from spreading outward, resulting in a rapid decline in the rate of post-drying.

Overall, higher wind speed is used in the early drying stage to quickly evaporate free water and take away water vapor, and lower wind speed is used in the late drying stage to improve efficiency and save energy.

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3.3. Drying mathematical model

3.3.1 Mathematical model fitting of onion drying at different hot air temperatures

Hot air temperature is an important factor affecting the drying process of onion. In order to reflect the fitting results of the drying mathematical models at different hot air temperatures, the moisture ratio data measured at the accumulation thickness of 80mm, the wind speed of 1m/s, and the hot air temperature of 50-80 ℃ were modeled. As shown in Figure 10---17, Geometric, Two term exponential, Wang and singh models showed poor fitting results, while other drying mathematical models showed better fitting results.

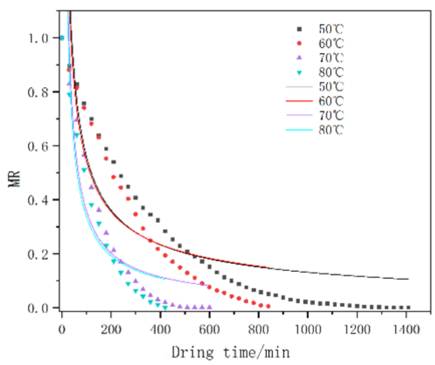

Figure 10(a) Geometric model

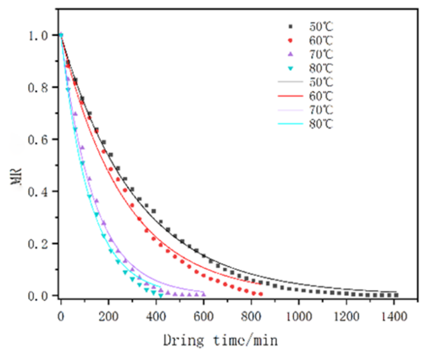

Figure 11(b) Newton model

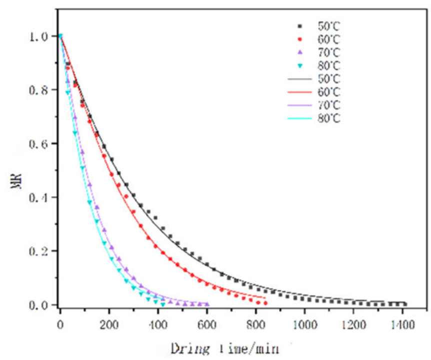

Figure 12(c) Page model

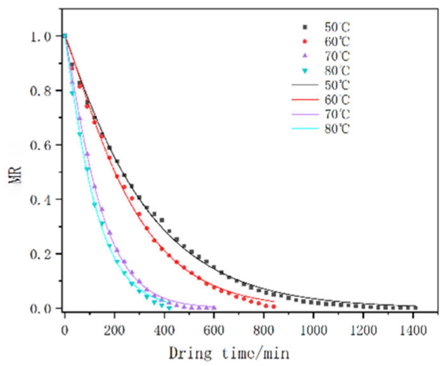

Figure 13(d) Page modified model

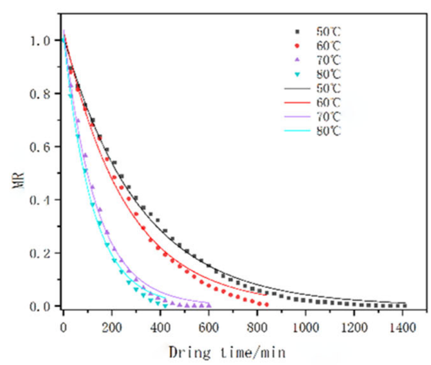

Figure 14(e) Henderson and pabis model

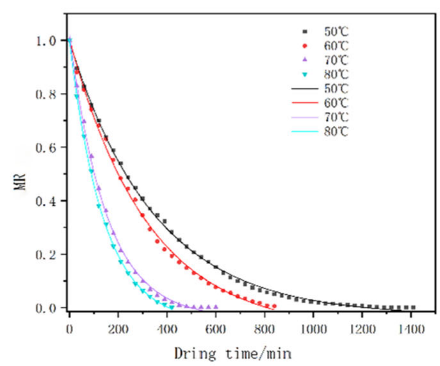

Figure 15(f) Logarithmic model

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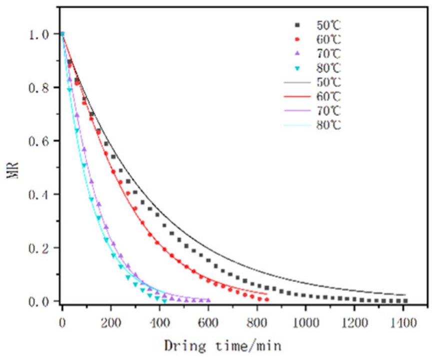

Figure 16(g) Two term exponential model

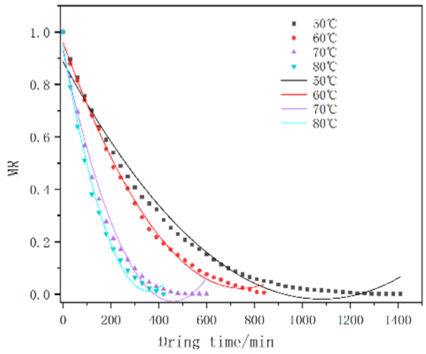

Figure 17(h) Wang and singh model

In order to further determine the optimal drying mathematical model, the fitting determination coefficient (R^2), residual sum of squares (RSS) and chi-square (χ^2) are analyzed. Logarithmic model R^2 is closest to 1, and the minimum RSS is 0.00058~0.005. The smallest values of χ2 ranged from 4.7479E-5 to 1.7533E-4, indicating that this model could well predict the change of hot-air drying moisture ratio of onion under different drying temperatures.

3.3.2 Drying mathematical model fitting of onion with different accumulation thickness

In order to reflect the fitting results of drying mathematical models with different stacking thickths, model fitting was carried out on moisture ratio data measured at hot air temperature of 60℃, wind speed of 1m/s and stacking thickness of 40~80mm, as shown in FIG. 18---25. Geometric, Wang and singh models showed poor fitting results. The other drying mathematical models fit well.

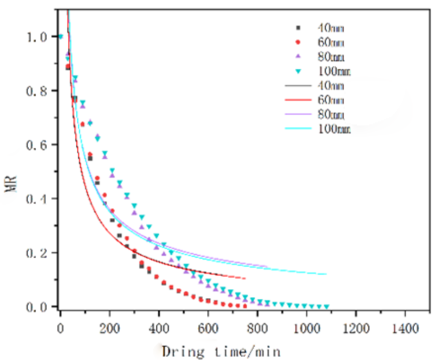

Figure 18(a) Geometric model

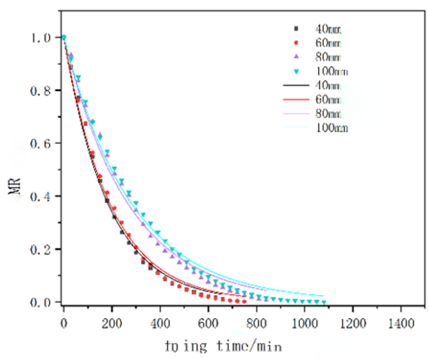

Figure 19(b) Newton model

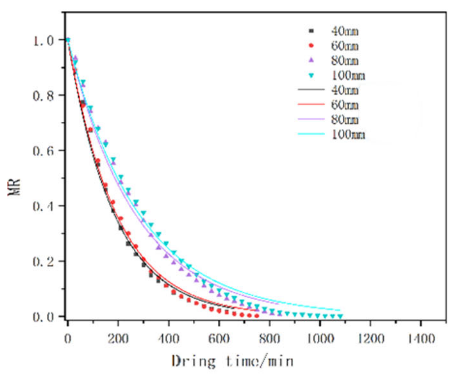

Figure 20(c) page model

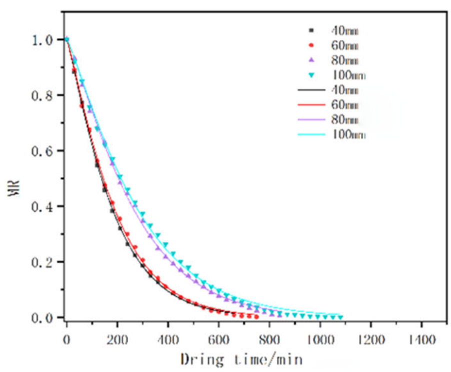

Figure 21(d) page modified model

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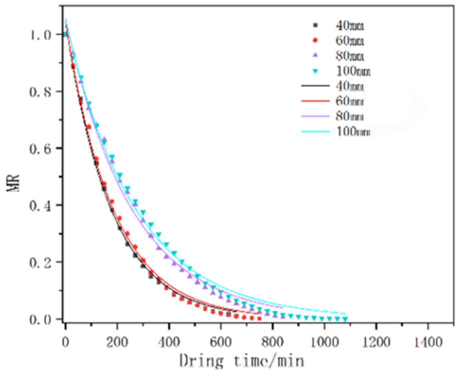

Figure 22(e) Henderson and pabis model

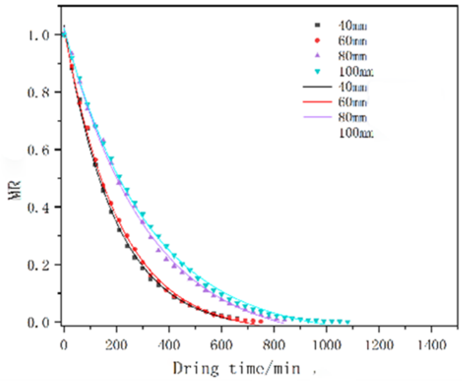

Figure 23(f) Logarithmic model

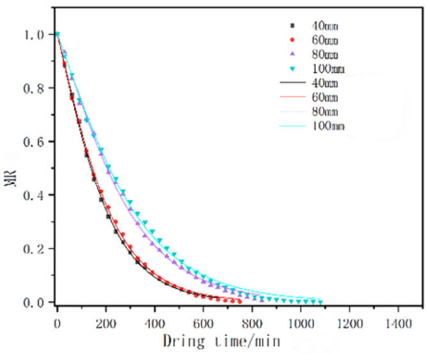

Figure 24(g) Two term exponential model

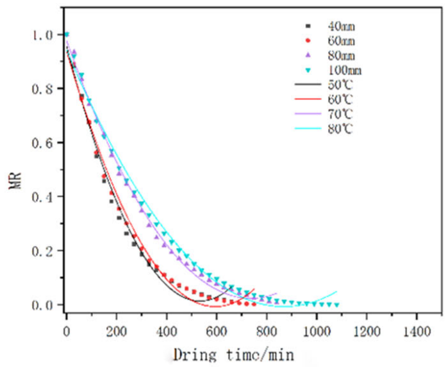

Figure 25(h) Wang and singh model

After analyzing the fitted data, it was found that the page modified model R^2 was closest to 1 ranging from 0.9981 to 0.9996, the RSS value was the smallest 0.00087 to 0.0017, and the χ2 value was the smallest 4.14E-05 to 1.66E-04. The above data indicate that the page modified model can more accurately predict the change of moisture ratio in the whole drying process of onion under different accumulation thickens.

3.3.3 Mathematical model fitting of onion drying with different hot air velocity

FIG. 26---33 shows the fitting results of different drying models with hot air temperature of 60℃, accumulation thickness of 80mm, and wind speed of 0.5~2m/s. It can be seen from the figure that Geometric, Newton, Henderson and pabis, Wang and singh models have poor fitting results, while other models have better fitting results.

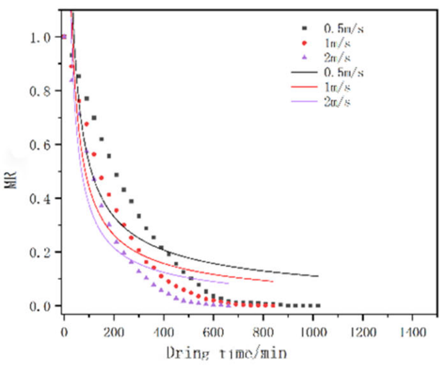

Figure 26 (a) Geometric model

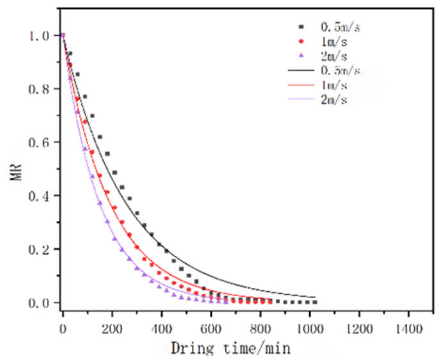

Figure 27 (b) Newton model

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202506_11(6).0008

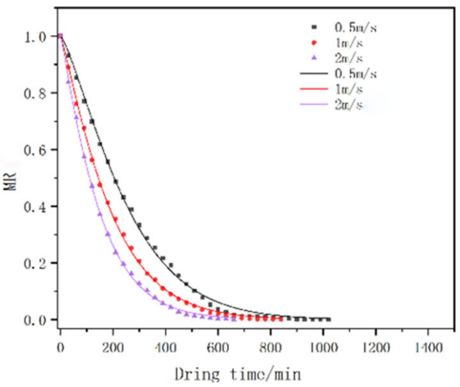

Figure 28(c) Page model

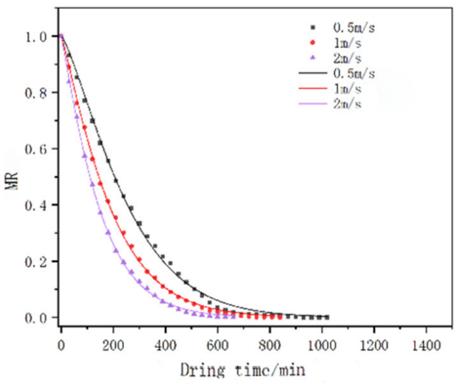

Figure 29(d) Page modified model

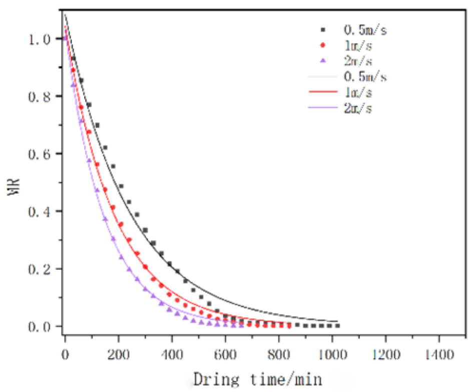

Figure 30(e) Henderson and pabis model

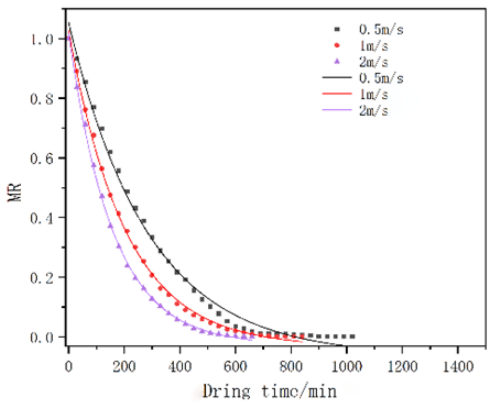

Figure 31 (f) Logarithmic model

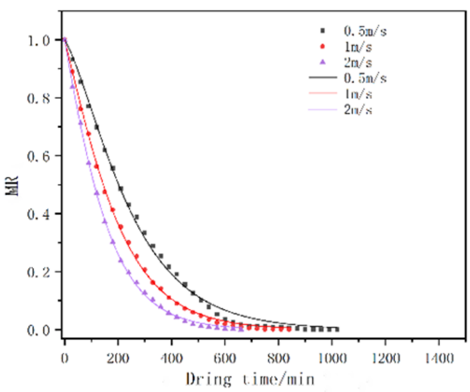

Figure 32(g) Two term exponential model

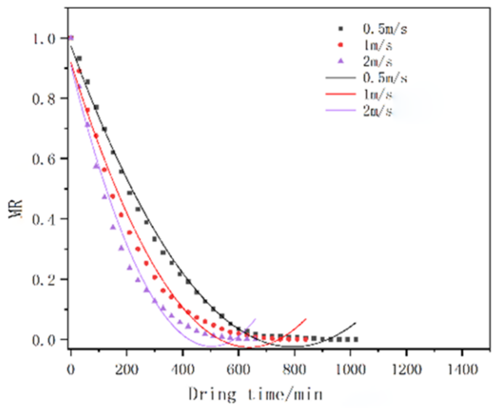

Figure 33 (h) Wang and singh model

After analyzing the fitted data, it was found that the page modified model R^2 was closest to 1 ranging from 0.998 to 0.9995, the RSS value was smallest from 0.0011 to 0.0063, and the χ2 value was smallest from 4.98E-05 to 1.92E-04. The above data indicate that the page modified model can accurately predict the moisture ratio of onion in the whole drying process under different wind speeds.

3.3.4 Selection of mathematical model of onion drying

The accuracy of the Page modified model R^2 fitted with different hot air temperatures of onion ranges from 0.997 to 0.9991, the RSS values from 0.0017 to 0.0074, and the χ2 values from 9.18E-05 to 2.72E-04 are second only to that of Logarithmic model. The Page modified drying mathematical model can accurately predict the change process of onion dry moisture ratio with different stacking thickness and wind speed. In order to facilitate researchers to

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accurately predict the whole process of hot air drying of onion and widely apply to different drying parameters, the Page modified drying mathematical model was selected[10~ 15].

3.3.5 Verification of drying mathematical model

In order to better verify the accuracy of the Page modified drying mathematical model, drying parameters were randomly selected as: hot air temperature 70℃, pile thickness 60mm, hot air speed 1m/s for verification tests. The model was used to fit the measured moisture ratio in the test. It can be seen from the fitting diagram that the test value closely surrounded the predicted curve of the model, and the statistical index R^2 was 0.9954, RSS value was 0.0073, and χ2 value was 4.5334E-04. The above results show that the Page modified drying mathematical model can accurately predict the change of the overall moisture ratio during hot air drying of onion[16~ 18].

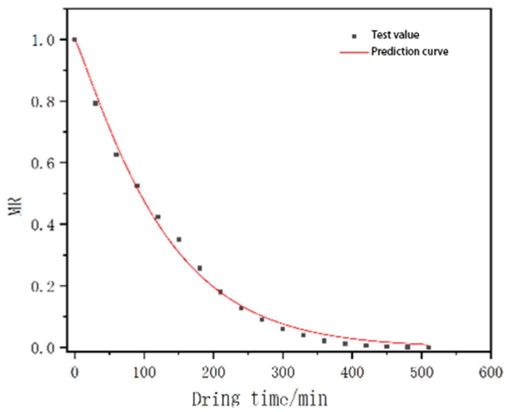

Figure 34. Page modified model validation diagram

3.4. Model verification conclusion

It was found that the initial water activity of onion was high (mean 0.971±0.05), which made it easy to rot. After drying, its water activity is reduced to 0.368±0.03, which meets the standard suitable for long-term storage. The hot air drying process of onion belongs to the type of reduced rate drying.

The hot air temperature and wind speed were positively correlated with the drying rate, while the accumulation thickness of onion was negatively correlated with it. In the early stage of drying, these parameters had a great effect on the drying rate, but the effect was weakened in the middle and late stage. Through data analysis and theoretical derivation, it was determined that the effective water diffusion coefficient of onion during hot air drying ranged from 5.039×10^(-7) to 1.364×10^(-6) m^2/s, and the activation energy was 34.473 kJ/mol.

After comparing various drying mathematical models, it was found that the modified Page model was the most accurate to describe and predict the hot air drying characteristics of onion. The coefficient of determination R^2 of this model was greater than 0.997, the residual square and RSS were between 0.0017 and 0.0074, and the mean square error χ2 was between 9.18E-05 and 2.72E-04. In addition, multiple linear regression analysis was carried out by SPSS software to further optimize the model.

4. CONCLUSION

Aiming at the key problems in the hot air drying process of onion, such as processing difficulty, product quality and energy consumption, this paper explored the optimal drying process parameters and determined the optimal drying mathematical model through systematic experiment and theoretical analysis. Through the drying test of different factor levels, we

ISSN: 2472-3703 DOI: 10.6911/WSRJ.202506_11(6).0008

determined the key parameters that affect the drying efficiency of hot air of onion, including hot air temperature, wind speed and accumulation thickness of onion. The experimental results show that higher hot air temperature can significantly shorten the drying time, and suitable wind speed and thin accumulation layer also help to improve the drying efficiency. By calculating the permeability and thermal conductivity of onion, the physical properties of onion as a porous medium in the drying process are more deeply understood, which is of great significance for optimizing the drying process. We evaluated a variety of drying mathematical models and found that the modified Page model was most suitable for describing the hot air drying characteristics of onion. The model not only has high fitting accuracy, but also can effectively predict the moisture change in the drying process.

The optimization scheme and mathematical model proposed in this paper have important practical guiding significance for improving the efficiency and quality of hot air drying of onion. Reasonable setting of drying parameters can effectively reduce energy consumption, improve the taste, color and other sensory quality of dried onion, and reduce the loss of nutrients, and ultimately improve the market competitiveness of the product. Future research directions could further explore how these optimization measures can be achieved on an industrial scale and how they can be combined with other drying technologies (e.g., infrared, microwave, etc.) to further improve drying efficiency and product quality. In addition, the development of more accurate mathematical models can be considered to better simulate the water-heat transfer process under complex dry conditions.

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