Agricultural Science; Vol. 3, No. 3; 2021
ISSN 2690-5396 E-ISSN 2690-4799
https://doi.org/10.30560/as.v3n3p1

The Solar-Heat Pump Combined Drying Characteristics and Dynamic Model of Kelp Knots

Yang Li[1], Zicheng Hu[1], Yongguang Hu[2], Fenghua Ge[1] & Hongzhi Cai[1]

[1] School of Energy and Power Engineering, Jiangsu University, Zhenjiang, China

[2] School of Agricultural Engineering, Jiangsu University, Zhenjiang, Jiangsu, China

Correspondence: Yang Li, School of Energy and Power Engineering, Jiangsu University, Zhenjiang, 212013, China. E-mail: 2578196264@qq.com

Received: August 9, 2021 Accepted: August 15, 2021 Online Published: August 29, 2021

The research is financed by National Natural Science Foundation of China (51806088) and Jiangsu University Scientific Research Foundation for the Senior Scholars (14JDG186).

Abstract

For controlling the entire drying process of a material, it is crucial to understand the moisture ratio of the material in the drying process. In order to ascertain the moisture change rules of kelp knots in the solar-heat pump combined drying process, an analysis was made on the impacts of different drying temperatures, wind speeds and loading capacities on the drying rate in this research; meanwhile, three common drying dynamic models were selected and compared to know their applicability to the solar-heat pump combined drying of kelp knots. Further, the model coefficient was determined and the optimal model was obtained. The results reveal as follows: drying temperature, wind speed and loading capacity have significant impact on and significant correlation ($P<0.05$) with the drying rate of kelp knots; under different drying conditions, the drying rate is always high in the early stage, lowered and gradually moderate in the later stage. After fitting the drying dynamic model, it is found that among the experimental data, regression coefficient (R^2) is the largest in the Verma model, and the sum of squares for error (*SSE*) and root mean square error (*RMSE*) are low. This indicates that the Verma model can be used to accurately express and predict the change rules of moisture in kelp knots during the solar-heat pump combined drying. According to Fick's second diffusion law, the effective diffusion coefficient *Deff* increases with the increase in drying temperature and wind speed, and decreases with the increase in loading capacity.

Keywords: kelp knots, solar-heat pump combined drying, drying characteristics, drying dynamic model

1. Introduction

The kelp production in China accounts for about 50% of the total kelp production in the world. Fresh kelp is an important marine resource due to its high moisture ratio, seawater growth environment, wide distribution, rich nutrients and low cost (Wang, et al., 2008), but usually needs to be dried and dehydrated because of its high moisture ratio and perishability. Due to the huge demand for kelp in Chinese market, it is necessary to apply industrial equipment and technology, such as drying equipment and technology, to the preservation and transportation of kelp (Song, et al., 2014).

Drying process is widely used in various fields (2000), and drying is also a technological operation with high energy consumption. According to statistics, in developed countries such as Britain, the United States, and France, the energy consumption of drying process accounts for about 12% of the total energy consumption (Bhesh, et al., 2015). Therefore, it is of important practical significance to research the energy saving and consumption reduction in the drying process, and research new drying process.

Usually, fresh kelp knots are dried in the open air without any cost. However, this drying method is of low efficiency, easy to get the material mouldy under environmental influence, and has a narrow range of application, leading to insufficient drying of the material and loss of nutritional value. In contrast, solar drier as a new energy-saving drying machine can convert light energy into heat energy (Ban, et al., 2011) to improve the drying efficiency of material greatly. However, it is not applicable to continuous operation for reason that it is susceptible to weather, day and night (Kapsalis, et al., 2016). Heat pump has high drying stability, low operating cost and short drying cycle. In actual application, solar collector is combined with heat pump to form a solar-heat pump combined drier to overcome the unfavorable factors (Xu, et al., 2004). Currently, solar-heat pump combined drying technology has been applied to drying of lentinula edodes (Zhu, et al., 2020), tobacco (Li, et al., 2021) and Chinese chestnut (Liu, et al., 2020), etc. and obtained remarkable effects.

Moisture ratio is an important indicator affecting the drying quality of a material, but difficult to be determined in the drying process. In order to better control the drying process, it is necessary to establish a mathematical model and analyze the drying process by mathematical means. Both in China and foreign countries, there have already been a large number of researches on the dehydration of fruits, medical materials and other materials. Reference (Zhang, et al., 2021) studied the characteristics and dynamic model of the hot-air drying of yellow peach fruits and found that temperature played a key role in the drying of yellow peach fruits; with the increase in drying temperature, the drying time was shortened and the drying rate was significantly improved. Reference (Liu, et al., 2020) studied the characteristics and dynamic model of the hot-air drying of Chinese chestnuts and discovered that page model conformed to the drying characteristics of Chinese chestnuts. Reference (Wu, et al., 2020) researched the characteristics and dynamic model of the drying of seahorse in different drying methods and proved that page model and Midilli model were more suitable for characterizing the hot-air drying process of seahorse, while page model and weibull model can describe the vacuum drying model of seahorse accurately. However, there are few researches on the characteristics and dynamic model of the drying of kelp knots (Hu, et al., 2019), making it important to research the solar-heat pump combined drying of kelp knots.

Taking fresh kelp knots as the research object, solar-heat pump combined drying technology is used in this paper to research the rules in which different drying temperatures, wind speeds and loadings affect the drying characteristics of kelp knots, and determine the drying dynamic model suitable for characterizing the change in moisture ratio of kelp knots in the drying process. The result can provide a technical support and theoretical basis for the application of solar-heat pump combined drying technology in the drying of kelp knots in the future.

2. Materials and Methodology

2.1 Materials and Instruments

The experimental materials are fresh kelp knots purchased from the local market of Zhenjiang, China, with uniform size and without mechanical damage.

A set of solar-heat pump combined drying equipment was designed and installed in order to research the drying characteristics of kelp knots. The flow chart of the equipment is as shown in Figure 1.

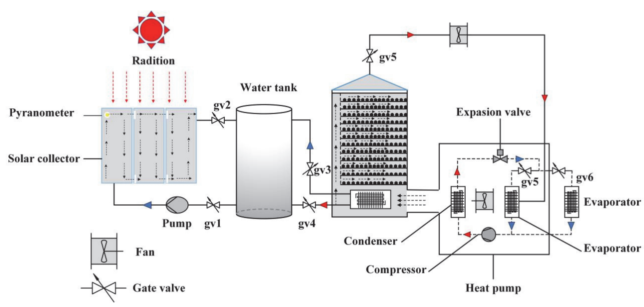

Figure 1. Flow chart of the drying equipment

Working principle: Water in the water tank is heated up by the solar radiation energy absorbed by the solar collector, then passes through the radiator below the drying box under the traction of the water pump, and exchanges heat with the air filled in the radiator by the fan; after that, the heated air passes through the pallet loaded with dried materials and flows through the wet materials at constant speed to finish the heat and mass transfer. In this equipment, the temperature and wind speed can be adjusted as required.

The heat pump is used for auxiliary heating. When the temperature in the water tank is lower than the set temperature, the heat pump will start to compensate for the heat till reaching the set temperature. The intelligent control system is used to control (temperature and wind speed) and digitalize the drying process.

Figure 2. Picture of the real solar-heat pump combined drying equipment

Other instruments and devices: FA1604N analytical balance (Jiangsu Jiangdong Precision Instrument Co., Ltd.); FLUKE-923 hot-wire anemometer (Changsha Tesai Measurement and Control Technology Co., Ltd.).

2.2 Experimental Method

In order to explore the impacts of different drying conditions on the drying characteristics of kelp knots, the experiments were respectively conducted at different drying temperatures (35, 40, 45 and 50℃, with an error of ±1℃) but constant loading capacity (3.6 kg±6 g) and wind speed (1.5±0.1 m/s), at different wind speeds (0.5, 1.0, 1.5 and 2.0 m/s, with an error of ±0.1 m/s) but constant loading capacity (3.6 kg±6 g) and drying temperature (45±1℃), and at different loading capacities (1.2, 3.6, 6.0 and 8.0 kg, with an error of ±6 g) but constant drying temperature (45±1℃) and wind speed (1.5±0.1 m/s). The initial mass of the kelp knots was measured, and then the mass of the kelp knots was measured at an interval of 10 min during the drying till the moisture ratio of the kelp knots dropped to 0.2 and the drying is stopped. Each group was conducted three parallel experiments.

2.3 Method for Calculation of Drying Parameters

2.3.1 Moisture Ratio of Dry Basis

The moisture ratio of dry basis can be calculated as per the following equation:

$$M_t = (m_t - m_d) / m_d \tag{1}$$

In the equation, M_t is the moisture ratio of dry basis of the material at time t, in g/g; m_t is the mass of the material at time t, in g; m_d is the mass of the absolutely dried material, in g;

2.3.2 Drying Rate

The equation of drying rate can be expressed as:

$$D_R = \frac{M_1 - M_2}{t_1 - t_2} \tag{2}$$

In the equation, D_R is the drying rate, in g/(g·min); M_1 is the moisture ratio of the dry basis when the material is dried to t_1, in g/g; M_2 is the moisture ratio of the dry basis when the material is dried to t_2, in g/g;

2.3.3 Moisture Ratio

The equation of moisture ratio can be expressed as:

$$M_R = \frac{M_t - M_e}{M_0 - M_e} \tag{3}$$

In the equation, M_R is the moisture ratio; M_e is the moisture ratio of dry basis of the material at drying equilibrium, in g/g; M_0 is the initial moisture ratio of dry basis of the material, in g/g.

2.4 Drying Dynamic Model and Evaluation Parameters

The drying of kelp knots can be classified as a dehydration process of wet porous media, which is a typical heat-mass coupling process. Through a large amount of experimental and data analysis, scholars both in China and foreign countries (Shi, et al., 2010; Yang, et al., 2013; Li, et al., 2016;) have summarized multiple theories on the rules in which moisture ratio changes with time in the drying process and established semi-empirical and empirical models. As found by reading relevant documents, the most common drying dynamic models for drying agricultural products are as illustrated in Table 1 (Shi, et al., 2013). Hence, the dynamic model used in this experiment is as shown in Table 1.

Table 1. Drying Dynamic Mathematical Models Selected

Model name	Model equation
Logarithmic	$M_R = a\,exp(-kt) + c$
Page	$M_R = exp(-kt^n)$
Verma	$M_R = a\,exp(-kt) + (1-a)\,exp(-gt)$

By analyzing the R^2, *SSE* and *RMSE* between the experimental data and the predicted data, it is concluded that the higher the R^2 is, the lower the *SSE* and *RMSE* are and the better the fitting effect is.

2.5 Effective Moisture Diffusion Coefficient

Effective moisture diffusion coefficient represents the ability to remove moisture by diffusion and transfer. Since the width of kelp knot is much larger than its thickness, it is assumed that the mass transfer only occurs in axial one-way manner. Hence, Fick's second law can be used to characterize the moisture diffusion in the drying process of kelp knots well. The volume shrinkage of kelp knot is ignored in the drying process (Simal, et al., 1997). Assuming that the samples have the same initial moisture distribution, the effective moisture diffusion coefficient can be calculated as per the following equation:

$$lnM_R = ln(\frac{8}{\pi^2}) - \frac{\pi^2 Deff}{L^2}t \tag{4}$$

In the equation, M_R is the moisture ratio; t is the drying time (h); L is the thickness of the sample (m); *Deff* is the effective moisture diffusion coefficient (m^2/h), which is estimated in slope method; the average *Deff* at different temperatures can be obtained as per the logarithmic drying curve. Letting the slope of equation (4) be k_0, the effective moisture diffusion coefficient can be expressed as:

$$Deff = -\frac{k_0 L^2}{\pi^2} \tag{5}$$

2.6 Data Processing

The software Origin2018 was used for drawing, and Matlab2020a was applied to linear/non-linear regression fitting of the experimental data; based on this, the degree of fitting was analyzed.

3. Results and Analysis

3.1 The Impact of Drying Temperature on the Drying Characteristics of Kelp Knots

Figure 3a shows the drying characteristic curves of kelp knots at different drying temperatures. As shown in Figure 3a, when the set drying temperature is within the range of 35 ~ 50℃, the moisture ratio of dried kelp knots shows a decreasing trend with time (fast in early stage but gradually gentle in the later stage). Within this drying temperature range, the higher the drying temperature is, the faster the drying is, which greatly reduces the drying time. This is because in this drying method, low-humidity hot air is used as the drying medium, the heat-humidity exchange with material is conducted in form of convection; when the air temperature rises, the moisture on the surface of the kelp knot will get more heat, leading to moisture diffusion inside the kelp knot, acceleration of water evaporation and shortening of the drying time. When the drying temperatures are 35℃ and 40℃, the drying times are 380 min and 280 min, respectively. However, long drying time is not conducive to saving cost. When the drying temperatures are 45℃ and 50℃, the drying times are 150 min and 200 min respectively and the drying trends are almost the same. Comprehensive analysis reveals that about 45℃ is the suitable temperature for solar-heat pump combined drying of kelp knots.

The impacts of different drying temperatures on the drying rate of kelp knots are presented in Figure 3b. As can be seen, the drying rate of the material depends on temperature. Drying temperature is directly proportional to the highest drying rate (Baher, et al., 2018). The drying rate is high initially till reaching the peak, then maintains low for a long time. The reason may be as follows: in the early stage of drying, there is much moisture on the surface and much free moisture inside the material; the internal temperature is also rising increasingly while moisture on the surface is evaporated fast under the action of hot air, so that the free moisture inside the material transfers quickly outward and the drying rate is increased. As the drying time goes, the moisture of the material reduces, and the drying rate begins to reduce. This may be for reason that kelp knot is a porous media so that the internal moisture is evaporated out through the holes and cracks; with the shrinking and hardening of the kelp surface, the heat and mass transfer encounters enhanced resistance in the process of conveying the internal moisture to the surface of the material, resulting in lowered decrease in drying rate. From the 120th min of drying to the time finishing the final drying goal, there is no large difference in the drying rate at different drying temperature. This reveals that after the 120th min of drying, temperature almost has no effect on the drying rate.

Provided that the drying efficiency is improved and the energy consumption is reduced, about 45℃ is the most suitable temperature for solar-heat pump combined drying of kelp knots.

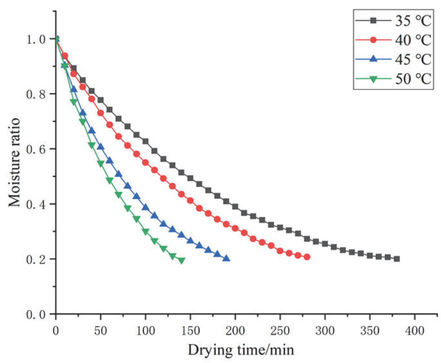

Figure 3a.

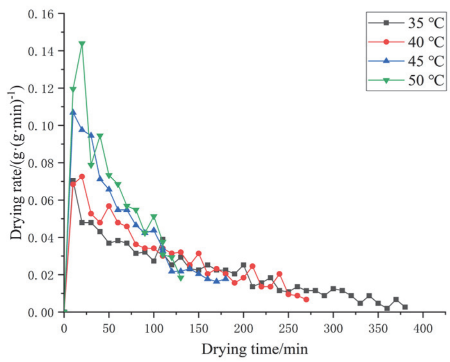

Figure 3b.

3.2 The Impact of Wind Speed on the Drying Characteristics of Kelp Knots

Figure 4a presents the drying characteristic curves of kelp knots at different wind speeds. As shown in Figure 4a, wind speed has a certain impact on the drying characteristics of kelp knots. When the wind speed is at 0.5 m/s, 1.0 m/s, 1.5 m/s and 2.0 m/s, it takes 280 min, 260 min, 190 min and 150 min respectively to have the kelp knots dried to the target moisture ratio. This reveals that the time taken to have the material dried to the target moisture ratio is shortened significantly with the increase in wind speed. The reason is that with the increasing of wind speed, the coefficient of convective heat transfer between hot air and kelp knot is increased, leading to acceleration of the moisture evaporation on the surface of the kelp knot and improvement in the drying efficiency. The increase in wind speed can help take away the water vapor on the surface of the kelp knot as soon as possible, increase the partial pressure difference of water vapor between the surface of the kelp knot and the air. In the early stage of drying, the pressure difference measured by air promotes less diffusion of moisture inside the kelp knot. In the middle and late stages of the drying, increasing heat transfer resistance is faced between air and the material. The results demonstrate that in the drying process by heat pump, internal diffusion is the physical mechanism most possible to control the internal moisture of kelp knots. By comprehensive analysis of experimental results, it is determined that the suitable wind speed for drying of kelp knot is 1.5 m/s approximately.

Figure 4b shows the impact of wind speed on the drying rate of kelp knots. As displayed, there is no stage of constant speed in the solar-heat pump combined drying process of kelp knots, but the stages of adjustment and deceleration, which is similar to the drying characteristics of Clausena lansium (Yang, et al., 2021). When the moisture ratio is fixed, the drying rate increases with the increase in wind speed. In the initial stage of drying, the kelp knot has a relatively high moisture ratio and contains much bound water on the surface, and the moisture evaporation speed is accelerated with the increase in wind speed; after the drying rate reaches the peak, the drying rate will maintain at low level for a long time. When the wind speed is 1.5 m/s, the drying rate is little different from that at wind speed of 2.0 m/s in terms of the downtrend.

On the premise of improving efficiency, as well as energy saving and emission reduction, the optimal wind speed for solar-heat pump combined drying of kelp knots is 1.5 m/s.

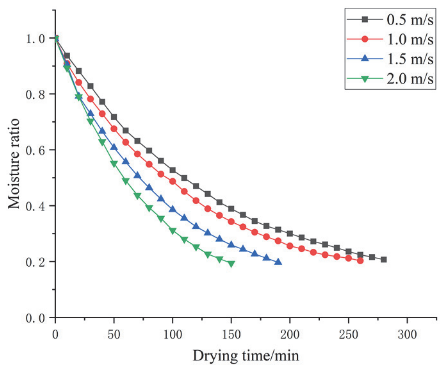

Figure 4a.

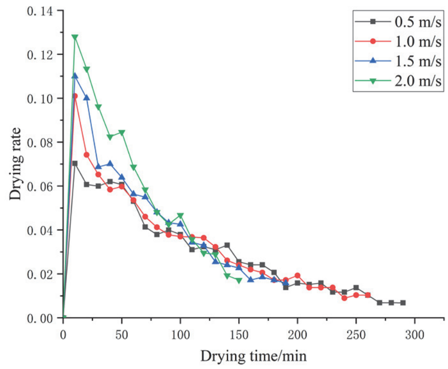

Figure 4b.

3.3 The Impact of Loading Capacity on the Drying Characteristics of Kelp Knots

Figure 5a illustrates the drying characteristic curves of kelp knots with different loading capacities. As observed, loading capacity has certain impact on the drying of kelp knots, and the lower the loading capacity is, the larger the downtrend of the moisture ratio is, and the shorter the time is taken to reach the required drying goal. When the loading capacity is 1.2 kg, 160 min is needed for drying; when the loading capacity is 8.0 kg, the time for drying is 320 min. This indicates that the loading capacity is directly proportional to the drying time required. As can be seen from the figure, with the increasing of loading capacity, the spreading density of kelp knots on a single pallet is increased, the relative surface area of heat and mass transfer with the air is decreased, and the resistance to heat and mass transfer is increased. The greater the loading capacity is, the higher the total moisture ratio of kelp knots is, the more the moisture is to be evaporated to reach the same moisture ratio, the longer the drying time is. As discovered in Figure 5a, when the loading capacities are 1.2 kg and 3.6 kg, the drying times and curves tend to be consistent basically. Based on an analysis of the economic effects and experimental results, it is known that the suitable loading capacity for drying kelp knots is about 3.6 kg.

The impact of loading capacity on the drying rate of kelp knots is demonstrated in Figure 5b. To be specific, the drying rate varies with the change in loading capacity. Given the same moisture ratio, the lower the loading capacity is, the shorter the drying time is and the higher the drying rate is. The increase in loading capacity contributes to the increase in drying time and decrease in drying rate. This may be for the following reasons: namely, the contact between materials becomes closer with the increase in loading capacity, resulting in decreased contact between air and the material; meanwhile, the increase in the material may also cause increase in the required moisture evaporation capacity; however, at certain drying temperature and wind speed, the heat is fixed. Hence, the increase in the material may lead to reduction in the heat provided to unit mass of the material in the unit time.

On the premise of improving efficiency, the optimal loading capacity for solar-heat pump combined drying of kelp knots is 3.6 kg.

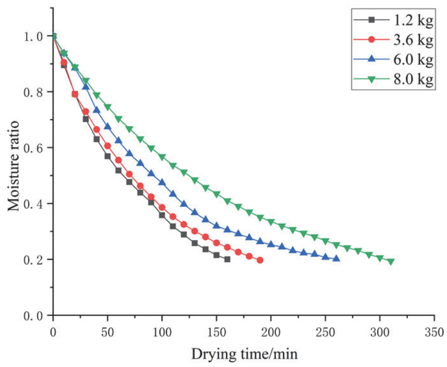

Figure 5a.

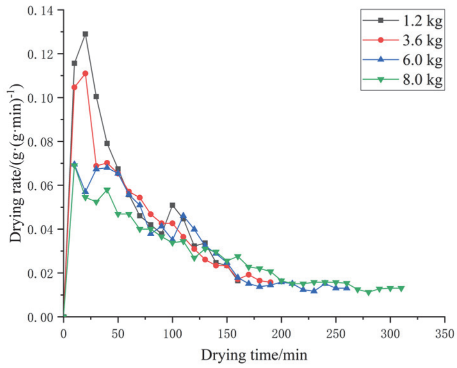

Figure 5b.

3.4 Establishment of Dynamic Model

3.4.1 Fitting Results of the Drying Dynamic Model of Kelp Knots

The statistical results obtained by experimental data based nonlinear fitting of three common drying dynamic models are shown in Table 1. In detail, the R^2 of Logarithmic, Page, and Verma models are the highest, all above 0.994; the *RMSE* varies within the range of 0.0029 ~ 0.0059, 0.0035 ~ 0.0192, and 0.0029 ~ 0.0079, respectively; and the *SSE* is within the range of 0.0001 ~ 0.0014, 0.0001 ~ 0.0092, and 0.0001 ~ 0.0011, respectively. This demonstrates that the three models can be used to characterize the change rules of moisture ratio in the solar-heat pump combined drying process of kelp knots. Among them, the Verma model has the highest R^2 (0.9996) and the lowest *SSE* (0.0004) and *RMSE* (0.0042), indicating that the Verma model has the highest fitting degree. Thereby, it can be confirmed that the Verma model is the dynamic model most suitable for characterizing the moisture ratio of kelp knots in the process of solar-heat pump combined drying.

Table 1. Statistical Result of Drying Mathematical Models for Dried Kelp Knots

Model	*SSE*	R^2	*RMSE*
Logarithmic	0.0006	0.9994	0.0053
Page	0.0017	0.9988	0.0071
Verma	0.0004	0.9996	0.0042

3.4.2 Solving of the Verma Model

Table 2 lists the statistical results of the parameters of the three models. On the basis of the parameters (*a*, *k* and *g*) of the Verma model, software matlab2020a was used to fit the experimental data and finally obtain the parameter values, taking drying temperature, wind speed and loading capacity as variables. The equations of the optimal results are expressed as follows:

$$a = 3.124 - 0.044T - 0.6871V + 0.060M \quad (R^2=0.91)$$
$$k = -1.457 + 0.035T + 0.0786V - 0.0221M \quad (R^2=0.93)$$
$$g = -0.457 + 0.0053T + 0.0589V + 0.0589M \quad (R^2=0.90)$$

In the equations, *T* is the drying temperature, in°C; *V* is the wind speed, in m/s; *M* is the loading capacity, in kg.

Table 2. Parameters Statistical Results of Three Models for Drying Process of Kelp Knots

Model	Parameters	35℃ 1.5m/s 3.6kg	40℃ 1.5m/s 3.6kg	45℃ 1.5m/s 3.6kg	50℃ 1.5m/s 3.6kg	45℃ 0.5m/s 3.6kg	45℃ 1.0m/s 3.6kg	45℃ 2.0m/s 3.6kg	45℃ 1.5m/s 1.2kg	45℃ 1.5m/s 6.0kg	45℃ 1.5m/s 8.0kg
Logarithmic	*a*	0.9301	0.9301	0.8949	0.9849	0.9098	0.8798	0.9580	0.9319	0.9007	0.9335
	k	0.0052	0.0052	0.0114	0.0123	0.0074	0.0086	0.0127	0.0117	0.0097	0.0061
	c	0.0598	0.0598	0.1014	0.0169	0.0937	0.1017	0.0459	0.0591	0.1224	0.0613
Page	*k*	0.0067	0.1631	0.0148	0.0125	0.0091	0.0124	0.0131	0.0147	0.0109	0.0075
	n	0.9320	0.0284	0.8993	0.9904	0.9215	0.8854	0.9721	0.9256	0.9163	0.9392
Verma	*a*	0.0059	0.0037	0.6816	0.0006	0.9535	0.8356	0.0007	0.0782	0.9799	0.2683
	k	-	0.03810.0057	0.0136	0.7847	0.0070	0.0095	-0.0237	0.0508	0.0070	0.0104
	g	0.0053		0.0039	0.0119	-	0.0009	0.0118	0.0096	0.9075	0.0044
		0.0049				0.0017					

3.4.3 Verification of the Verma Model

In order to verify the accuracy of the model, an experiment was made on the kelp knots under different drying conditions such as drying temperature of 45℃, wind speed of 1.5 m/s, and loading capacity of 3.6 kg respectively. The fitting verification result of the drying dynamic model for kelp knots is as shown in Figure 6. To be specific, the fitting degrees of the experimental result and the result predicted by the model are basically consistent and significantly correlated ($P<0.05$). This implies that the Verma model can well characterize the moisture ratio of kelp knots in the process of solar-heat pump combined drying.

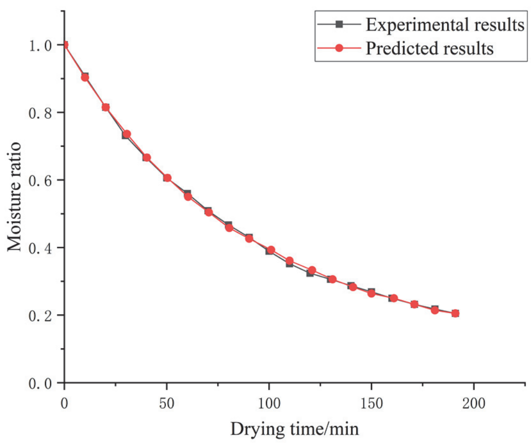

Figure 6. Verification of the Verma Model

3.5 Effective Moisture Diffusion Coefficient in the Drying Process of Kelp Knots

Drying is a process of mass, momentum and energy transfer. When the heat absorbed by the material is transferred from the outside to the inside, the moisture in the material will absorb the heat and be evaporated to the outside. Till reaching the critical moisture ratio, the drying process is finished. In order to simplify the calculation results, liquid diffusion theory was used in the drying process of the material regardless of the driving force of diffusion; the influence of all dynamics was counted in the diffusion coefficient; the effective diffusion coefficient *Deff* was used to characterize the average speed of moisture transfer in the drying process (He, et al., 2016); then nonlinear fitting was conducted on the ln*MR* and drying time *t* of kelp knots in different drying manners.

Table 3 shows the moisture diffusion coefficient in the drying process of kelp knots under different conditions. As revealed in Table 3, provided that the drying temperature is 35 ~ 50℃ and other drying conditions are fixed, the effective moisture diffusion coefficient *Deff* is $3.9251\times10^{-9} \sim 1.0012\times10^{-8}$ m^2/s; provided that the wind speed is 0.5 ~ 2.0 m/s and other drying conditions are fixed, the *Deff* is $5.1118\times10^{-9} \sim 1.0028\times10^{-9}$ m^2/s; when the loading capacity of the material is 1.2 ~ 8.0 kg and other drying conditions are fixed, the *Deff* is $2.1908\times10^{-9} \sim 9.1282\times10^{-9}$ m^2/s. The analysis demonstrates that the effective moisture diffusion coefficient in the drying process of kelp knots is directly proportional to the drying temperature and wind speed, and inversely proportional to the loading capacity. Moreover, the coefficient of determination R^2 varies within the range of 0.9421 ~ 0.9994, indicating a good linear regression result. According to Pearson correlation analysis, drying temperature, wind speed, and loading capacity are of extremely significant correlation with *Deff* ($P<0.01$), which is consistent with the results of researches on potato (Yin, et al., 2016), Daqu (Xia, et al., 2018), tomato slices (Salih, et al., 2017) and seahorse (Wu, et al., 2020).

Table 3. Effective Moisture Diffusion Coefficient of Kelp Knots under Different Drying Conditions

Experimental number	Drying temperature/°C	Wind speed/($m\cdot s^{-1}$)	Loading capacity/kg	k_0	R^2	*Deff*/($m^2\cdot s^{-1}$)
1	35	1.5	3.6	-0.0043	0.9425	3.9251×10^{-9}
2	40	1.5	3.6	-0.0057	0.9862	5.2031×10^{-9}
3	45	1.5	3.6	-0.0084	0.9991	7.6677×10^{-9}
4	50	1.5	3.6	-0.0118	0.9994	1.0012×10^{-8}
5	45	0.5	1.5	-0.0056	0.9951	5.1118×10^{-9}
6	45	1.0	1.5	-0.0062	0.9915	5.6595×10^{-9}
7	45	2.0	1.5	-0.0112	0.9981	1.0028×10^{-8}
8	45	1.5	1.2	-0.0100	0.9984	9.1282×10^{-9}
9	45	1.5	6.0	-0.0064	0.9807	5.8420×10^{-9}
10	45	1.5	8.0	-0.0024	0.9421	2.1908×10^{-9}

4. **Conclusion**

In this paper, a discussion is made on the impact of solar-heat pump combined drying equipment on the drying characteristics and dynamics of kelp knots at different drying temperatures, wind speeds and loading capacities, obtaining the following conclusions:

First, as revealed in the analysis on the drying characteristics of kelp knots under three different drying conditions, the drying curves of the material under different drying conditions tend to be the same basically; there is a short period of adjustment in the initial stage of drying, but decelerated drying predominates in the whole drying process; with the increase in drying time, the moisture ratio of the material shows an exponential downtrend.

Second, three common drying dynamic models was used to fit the experimental curves of different drying processes. By comparing R^2, *RMSE* and other relevant evaluation parameters, it is found that the Verma model is the fittest model for characterizing the moisture ratio change in the solar-heat pump combined drying process of kelp knots. The equation of this model was obtained by linear regression analysis on the experimental data. As discovered by verification of the equation, the experimental value fits the value predicted by the model well. This further verifies that the Verma model is most suitable for characterizing the solar-heat pump combined drying process of kelp knots.

Third, as calculated as per Fick's second diffusion law, the effective moisture diffusion coefficient *Deff* under different drying condition is within the range of $2.1908\times10^{-9} \sim 1.0012\times10^{-9}$ m^2/s; it is directly proportional to the drying temperature and wind speed, and inversely proportional to the loading capacity. By comparing the impacts of the three drying conditions on the *Deff*, it is discovered that drying temperature has extremely significant impact on the *Deff*.

Acknowledgments

The authors are grateful for financial support from the National Natural Science Foundation of China (51806088) and Jiangsu University Scientific Research Foundation for the Senior Scholars (14JDG186).

References

Tsotsas, E., & Mujumdar, A. S. (2000). Modern Drying Technology. *Chemical Industry and Engineering Progress,* (01), 52.

Baher, M. A. A., Klaus, G., & Hossain, M. A. (2018). Integrated hybrid solar drying system and its drying kinetics of chamomile. Renewable Energy. https://doi.org/10.1016/j.renene.2018.01.055

Ban, T., Zhu, M., & Wang, H. (2011). Design and Structural Optimization of Flat-Plate Solar Air Collector. *Transactions of the Chinese Society of Agricultural Engineering,* (S1), 277-281.

Bhesh, B. (2015). *Handbook of Industrial Drying.* In A. S. Mujumdar (Ed.), *Drying Technology,* (1), https://doi.org/10.1080/07373937.2014.983704

He, J. (2016). *Numerical simulation of drying oil shale and Drying Kinetic Analysis. Master's thesis. Dalian University of Technology.* Retrieved from https://kns.cnki.net/KCMS/detail/detail.aspx?dbname=CMFD201701&filename=1016219544.nh

Hu, Z. C., Qin, H., Bao, Q., Ge, F. H., & Gao, X. H. (2019). Drying characteristics and mathematical model of kelp junction heat pump. *Journal of Jiangsu University (Natural Science Edition),* (06), 649-654. https://doi.org/10.3969/j.issn.1671-7775.2019.06.005

Kapsalis, V., & Karamanis, D. (2016). Solar thermal energy storage and heat pumps with phase change materials. Applied Thermal Engineering. https://doi.org/10.1016/j.applthermaleng.2016.01.071

Li, D. Q., Yang L. W., Chen, J. X., Zhang, C., & Wei, J. (2021). Tobacco Drying System Combining Solar Energy with Heat Pump. *Journal of Engineering Thermophysics,* (01), 25-32.

Li, X. Q., & Chen, H. R. (2016). Hot-air Drying Characteristics and Mathematical Model of Blueberry. *Farm Products Processing,* (13), 9-13+17.

Liu, Y. N., Bian, Y. B., Guo, X. X., L, Y., & Wang, H. (2020). Drying Characteristics and Mathematical Model of Air-Dried Chestnut by Combined Solar Energy and Heat Pump. *Transactions of the Chinese Society for Agricultural Machinery*, (S1), 509-516. https://doi.org/10.6041/j.issn.1000-1298.2020.S1.060

Salih, C., İbrahim, D., Cüneyt, T., & Seçil, E. (2017). Investigation of drying kinetics of tomato slices dried by using a closed loop heat pump dryer. *Heat and Mass Transfer,* (6). https://doi.org/10.1007/s00231-016-1946-7

Shi, Q. L., Zhao, Y., Li, Z. J., & Xue, C. H. (2010). Characteristics of Moisture Migration during Drying of Horse Mackerel by Heat Pump Dehumidifier. *Transactions of the Chinese Society for Agricultural Machinery,* (02). 122-126. https://doi.org/10.3969/j.issn.1000-1298.2010.02.025

Shi, Q. L., Zheng, Y. Q., & Zhao, Y. (2013). Mathematical modeling on thin-layer heat pump drying of yacon (Smallanthus sonchifolius) slices. *Energy Conversion and Management.* https://doi.org/10.1016/j.enconman.2013.03.032

Simal, S., Deyá, E., Frau, M., & Rosselló, C. (1997). Simple modelling of air drying curves of fresh and osmotically pre-dehydrated apple cubes. *Journal of Food Engineering,* (1). https://doi.org/10.1016/S0260-8774(97)00049-6

Song, X. Y., Zhong, Y., & Deng, Y. (2014). Status and Development Trend of Heat Pump Drying Technique. *Journal of Shanghai Jiaotong University (Agricultural Science Edition),* (04), 60-66+70. https://doi.org/10.3969/J.ISSN.1671-9964.2014.04.011

Wang, W. l., Wang, S. j., Song, K., & Deng, P. (2008). *Research on the Function and Exploitation of the Laminaria Japonica Resource,* (04), 40-41. https://doi.org/10.3969/j.issn.1673-5404.2008.04.012

Wu, J. N., Chen, X. T., Pan, N., Liao, D. Y., Zhang, J. H., & Liu, Z. Y. (2020). The Drying Characteristic and Mathematical Modeling of Various Drying Method of Seahorse. *Modern Food Science and Technology,* (12), 133-142. https://doi.org/10.13982/j.mfst .1673-9078.2020.12.0583

Xia, Y., Luo, H. B., Zhou, P., Huang, D., Deng, B., Shen, C. P., & Zhang Man (2018). Study on Hot-air Drying Characteristics and Dynamic Model of Daqu. *Modern Food Science and Technology,* (04), 206-214. https://doi.org/10.13982/j.mfst.1673-9078.2018.04.031

Xu, C. X., Zhang, B. G., Chang, J. M., Gao, J. M., Y, S. l., & Zhang S. B. (2004). Current State of Studies on the Technology of Combined Drying for Solar Energy and Heat Pump. *Wood Processing Machinery,* (05), 36-39. https://doi.org/10.3969/j.issn.1001-036X.2004.05.011

Yang, W. J., Tang, D. B., Xu, Y. J., Wu, J. J., & Xiao, G. S. (2013). Drying Characteristics and Mathematical Modeling for Heat Pump Drying of Litchi. *Food Science,* (11), 104-108. https://doi.org/10.7506/spkx1002-6630-201311023

Yang, W. R., Peng, J., Zhang, X. M., Yu, Y. S., Bu, Z. B., Xu, Y. J., & Chen, S. P. (2021). Research on the drying characteristics and quality of Clausena lansium at different hot-air drying temperatures. Food and Fermentation Industries. https://doi.org/10.13995/j.cnki .11-1802/ts.027121

Yin, H. M., Nie, Y. Y., Shen, J., Wu, W. F., Dou, J. P., Cheng, R. M., & Chen, J. Y. (2016). Drying characteristics of diced potato with thin-layer by hot-wind based on Weibull distribution function. *Transactions of the Chinese Society of Agricultural Engineering,* (17), 252-258. https://doi.org/10.11975/j.issn.1002-6819.2016.17.033

Zhang, Q., Shu, N., Huang, Y. N., & Li, Q. L. (2021). Effects of Drying Methods on Quality Properties and Microstructure of Yellow Peach (Amygdalus persica). *Hunan Agricultural Sciences,* (04), 86-89+95.

Zhu, C. H., Li, B.G., Yang, H. F., Luo, Q. Q., & Li, Y. L. (2020). Design of Solar-Heat Pump Combined Device and Experiment on Drying of Shiitake Mushroom. *Acta Energiae Solaris Sinica,* (11), 149-155.

Copyrights