Zhanyong Guo*, Fachuang Li, Guang Su, Demei Zhai and Chenhui Liu

Microwave drying of nickel-containing residue: dielectric properties, kinetics, and energy aspects

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Abstract: Nickel-containing residue (NCR) is a hazardous solid waste from battery production lines. Recently, the interest in recovering valuable metals from NCR has increased because sustainable utilization of resources is more and more valued. Drying is a key part of the recovery process. In this study, we measured the dielectric properties of the NCR for different moisture contents and temperatures using the cavity perturbation method at 2.45 GHz. The microwave absorption characteristics of NCR had a positive correlation with the moisture content, while it was less efficient in the 20–180°C temperature range. Then found that the microwave drying data at different microwave powers (400–700 W) and for different sample weights (60–120 g) have a better fit with the Midilli-Kucuk model. The activation energy (E_a) was received as 9.76 W/g using an exponential expression based on the Arrhenius equation. Finally, the energy consumption reduce 110 W·h/kg than that of drying with a single microwave power by optimizing the microwave drying process.

Keywords: nickel-containing residue; microwave drying; dielectric properties

1 Introduction

In the battery production process, some components like the battery case and chip must be nickel plated [1,2]. Therefore, a large number of electroplating wastewater is produced and is usually treated by chemical precipitation to meet the discharge standards [3,4]. This then creates nickel-containing residue, a cheap secondary resource [5,6].

If not handled properly, secondary pollution will occur and have a negative impact on the environment and on human health. Currently, common treatment methods include separation and recovery of the heavy metals [7,8], solidification treatment [9,10], and high-temperature incineration [11]. However, because of the high water content and the stickiness, it becomes crucial to efficiently yet economically dry the NCR before recycling, solidification, or incineration.

Compared to the conventional low-efficiency, time-consuming, and energy-consuming drying technologies [12], such as fluidized bed drying [13], rotary kiln drying [14] as well as other conventional drying methods [15,16], the efficiency of microwave drying is more than twice that of conventional drying methods [17,18]. The water molecules in the material make most of the sample have an excellent absorbency for the electromagnetic wave. During microwave heating, heat and water vapor travel in the same direction which causes a high drying efficiency [19–22].

As a sticky material the NCR tends to absorb and retain a large amount of water, which makes a great obstacle for the press filtration process, and there is still a high moisture content in the material after dehydration. Furthermore, in the conventional drying process, the viscosity of the material maintains a high internal cohesion, thus delaying the evaporation of water molecules. From our earlier results drying a CuCl residue, need more than 90 min to reduce the moisture content of the residue from 36% to about 4% [23]. By contrast, under a microwave power of 550 W, the same effect can be achieved in just about 10 min [24].

In this study, the dielectric properties is measured by cavity perturbation method, microwave drying kinetics is collected using eight thin layer drying models, and energy consumption during microwave drying process is optimized using response surface methodology (RSM).

2 Materials and methods

2.1 Raw materials

The nickel-containing residue (NCR) was supplied by a battery manufacturer in Henan Province, China. The

* Corresponding author: Zhanyong Guo, School of Materials Science and Engineering, Henan Institute of Technology, Xinxiang, Henan, China, e-mail: guozhanyong123@126.com, Tel: +86-0373-3691137

Fachuang Li, Guang Su, Demei Zhai, School of Materials Science and Engineering, Henan Institute of Technology, Xinxiang, Henan, China
Chenhui Liu, Key Laboratory of Unconventional Metallurgy, Ministry of Education, Kunming, Yunnan, China

received samples contained 45.8% water and were very sticky.

After drying, the sample was analyzed chemically and by X-ray powder diffraction (XRD). The results of the chemical composition and the XRD pattern are shown in Table 1 and Figure 1.

As shown in Table 1, there is a variety of metallic elements in the NCR and nickel content is found to be above 8%. It is practically important to effectively separate the impurities and recovery of nickel.

From Figure 1, the material composition is relatively complex, with a main phase of CaCO_3 . Mg mainly exists in the MgSiO_3 form while Ni mainly exists in the NiO form. Low amounts of NiCO_3 and $\text{Ni(OH)}_2 \cdot 2(\text{H}_2\text{O})$ are also present whereas Fe mainly exists in the FeSiO_3 form.

2.2 Experimental devices

2.2.1 Permittivity measurement system

A permittivity measurement system based on microwave cavity perturbation method was used to measure the dielectric parameters of the NCR. The testing equipment has been widely used for the measurement of dielectric properties of materials [25-27]. A schematic of the system is shown in Figure 2.

The device consists of a vector network analyser, a waveguide-coax transition, a directional coupler, an

Table 1: Chemical composition of the NCR residue.

Composition	O	Ca	Mg	C	Ni	Fe	Si	Cd
Content (%)	53.42	14.09	8.67	8.30	8.02	4.64	1.57	0.71

Figure 1: XRD pattern of the raw material.

electromagnetic induction heater, a water re-circulator, a gas lift, and a cavity resonator. The test control unit is connected to a computer via a USB data cable and software calculates the dielectric parameters. The system accuracy has been demonstrated in our preliminary work which was estimated to be 3% in the dielectric constant and 10% in the loss factor during the tests [27].

During the experiments, the test sample was placed into the heater of the permittivity measurement system with a small quartz tube. When the NCR was heated to a pre-set temperature and subsequently lifted into the cavity resonator via the gas lift, the computer rapidly calculated the dielectric parameters using the test-cavity perturbation theory. After the test, the quartz tube was lowered into the heater and heated to a higher pre-set temperature to measure the permittivity at different temperatures.

2.2.2 Microwave oven for the drying experiments

A microwave reactor with a power of 3 kW and a frequency of 2.450 GHz was used for the drying experiments. Its schematic is presented in Figure 3. The microwave drying system consists of a weightlessness measurement system, a temperature control unit with a thermo-element, two magnetrons, a multimode cavity, a quartz glass container, and a data acquisition computer. A thermocouple pyrometer was inserted into the centre of the sample to measure the heating temperature.

During the microwave drying experiments, a certain amount (120 g, 100 g, 80 g, or 60 g) of sample with a moisture content of 45.8% (d.b.) and shaped into a 10 mm thin layer was loaded into a quartz glass

Figure 2: Schematics of the permittivity measurement system.

Figure 3: Schematics of microwave drying system.

container, placed inside the microwave oven, and heated at a given microwave power (700 W, 600 W, 500 W, or 400 W).

2.3 Data analysis and mathematical modeling

The microwave drying date was calculated using the following equations:

$$M_t = \frac{m_t - m_g}{m} \times 100\% \quad (1)$$

where M_t is the moisture content at a specific time t , kg/kg (d.b.), m_t is the mass at a specific time t and m_g is the mass after completely drying.

$$M_R = \frac{M_t - M_e}{M_0 - M_e} \quad (2)$$

where M_R is the moisture ratio, M_0 is the initial moisture content, kg/kg (d.b.) and M_e is the equilibrium moisture content, kg/kg (d.b.). The equilibrium moisture content for this material is assumed to be zero and:

$$v_d = \frac{M_{t+dt} - M_t}{dt} \quad (3)$$

where v_d is the drying rate, M_t and M_{t+dt} are the moisture contents at t and $t+dt$ time, respectively, kg/kg d.b.

The loss tangent ($\tan\delta$) describes how well the material dissipates stored energy into heat at a given

Table 2: Mathematical thin-layer drying models used for the approximation.

Models	Equations
Newton	$M_R = \exp(-kt)$
Henderson and Pabis	$M_R = a \exp(-kt)$
Page	$M_R = \exp(-kt^n)$
Modified Page	$M_R = \exp(-ktn)$
Midilli-Kucuk	$M_R = a \exp(-kt^n) + bt$
Logarithmic	$M_R = a \exp(-kt) + c$
Diffusion approach	$M_R = a \exp(-kt) + (1-a) \exp(-kbt)$
Wang and Singh	$M_R = 1 + at + bt^2$

frequency and temperature. The loss tangent ($\tan\delta$) can be expressed as:

$$\tan\delta = \frac{\epsilon''}{\epsilon'} \quad (4)$$

where ϵ' is the dielectric constant, which reflects the ability of the material to store electromagnetic energy within its structure, ϵ'' is the dielectric loss factor that characterizes the ability of the material to convert the stored electromagnetic energy into thermal energy.

The penetration depth (D_p) is defined as the depth at which the power of an applied microwave field is reduced to $1/e$ of its surface value and is expressed with the following equation:

$$D_p = \frac{\lambda_0}{2\sqrt{2\pi\epsilon' \left[1 + \left(\frac{\epsilon''}{\epsilon'} \right)^2 - 1 \right]}} \quad (5)$$

where λ_0 is the wavelength ($\lambda_0 = 12.24$ cm at 2.45 GHz) and π is a constant.

The material drying is a complex heat and mass transfer process. The choice of drying model is an important part of the research work to predict the process parameters. The basic equations commonly used to describe a thin layer drying process are shown in Table 2 [28-30].

3 Results and discussion

3.1 Dielectric properties of the NCR

The dielectric constant (ϵ') and loss factor (ϵ'') of NCR were measured at various of temperature (20-180°C) for different of moisture contents and the results are shown in Figure 4a. The dielectric loss angle tangent ($\tan\delta$)

was calculated according to: $\tan \delta = \epsilon''/\epsilon'$ and is shown in Figure 4b. From Figures 4a and 4b, both ϵ' and ϵ'' increased remarkably from 2.7541 to 14.5374 and 0.0374 to 2.991, respectively, when the moisture content increased to 14%. In the meantime, $\tan \delta$ gradually increased from 0.0141 to 0.2057. The increase of ϵ' and ϵ'' with the moisture content also occurs in certain waste residues. For example, the moisture content of CuCl residue is 10-15% and its dielectric constant at room temperature is higher than 14 [24]. In general, with the increase of moisture content the absorbency of materials has been significantly improved, which means that the microwave drying efficiency will be higher.

As shown in Figures 4c and 4d, the ϵ' and ϵ'' of the dried sample do not change much with the increasing temperature in the 20-180°C range. This phenomenon also occurs in certain metallurgical residues, such as spent adsorbent with zinc sulfate [25] and molybdenite concentrate [26]. By comparison with the dielectric constant of water at room temperature of 78 and a loss factor of 16.2, Figures 4a, 4c and 4d show that the dielectric properties of the material is strongly associated with the moisture content. Therefore, the microwave energy is mainly absorbed by the water molecules that evaporate during the drying process and the material consumes less energy. Therefore, the efficiency of the microwave heating for water evaporation is higher.

The values of penetration depth (D_p) for different moisture content and temperature were calculated using Eq. 5 and shown in Figures 4e and 4f. The moisture content has obvious effect on the D_p , within the measurement range, the D_p decreases rapidly from 82.6 cm to 2.4 cm with the increase of moisture content, while temperature has little effect on the D_p , and the values are above 84 cm. In this drying experiment the sample was shaped into a 10 mm thin layer, the penetration depth of microwave has little influence on the drying process, but in the follow-up industrialization experiment must pay attention to the sample thickness.

3.2 Energy balance analysis in a micro-section of the NCR

The heat balance of the drying process mainly considers energy introduction and dissipation. The thermal and mass equilibrium between the water, the gas, and the matrix were proposed by Suwannapum [31] and Prat [32]. In consideration of their study, we performed an energy balance analysis on the microsection of porous NCR, as

shown in Figure 5. The thermal equilibrium analysis was performed with the thin-layer micro-section of $\partial x \partial z$.

The heat input of the system consists of two parts. The first one is the heat transfer in other micro-sections of the system. The second one is the conversion of the microwave energy into internal energy during the heating process. They can be expressed by the following formula:

$$Q = 2\pi f E_y^2 \epsilon_0 \epsilon'' \quad (6)$$

$$q = \frac{\partial}{\partial x} \left[\lambda_{\text{eff}} \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial z} \left[\lambda_{\text{eff}} \frac{\partial T}{\partial z} \right] \quad (7)$$

where Q is the heat generated by the absorption of the microwaves, f is the frequency of the microwave (Hz), E_y is the electric field intensity in the y direction (V/m), ϵ_0 is permittivity of free space: 8.854 (pF/m), q is the heat transfer in the other micro-sections, λ_{eff} is the effective thermal conductivity (W/m·K), and T is the temperature (K).

The heat loss includes the following three parts:

1. Heating of the material mixture

$$q_1 = \frac{\partial}{\partial t} \left[(\rho C_p)_T T \right] \quad (8)$$

where $(\rho C_p)_T$ is the effective heat capacitance of the water-gas matrix mixture:

$$(\rho C_p)_T = \rho_l C_{pl} \phi s + \rho_g C_{pg} \phi (1-s) + \rho_p C_{pp} (1-\phi) \quad (9)$$

where t is the time (s), ρ is density and C_p is specific heat capacity. ρ_l , ρ_a , ρ_p are the density of liquid water, air and residue particle, respectively (kg/m³). C_{pl} , C_{pa} , C_{pp} are the specific heat capacity of liquid water, air and residue particle, respectively (J/kg·K). ϕ is the porosity and s is the water saturation.

2. Heat loss caused by air, water, and vapor escape

$$q_2 = \frac{\partial}{\partial x} \left\{ \left[\rho_l C_{pl} u_l + (\rho_a C_{pa} + \rho_v C_{pv}) u_g \right] T \right\} + \frac{\partial}{\partial z} \left\{ \left[\rho_l C_{pl} w_l + (\rho_a C_{pa} + \rho_v C_{pv}) w_g \right] T \right\} \quad (10)$$

where ρ_v is the density of water vapor (kg/m³), C_{pv} is the specific heat capacity of water vapor (J/kg·K). u_l and u_g are the velocity of liquid water and the gas phase in the x direction (m/s), respectively. w_l and w_g are the velocity of liquid water and the gas phase in the z direction (m/s), respectively.

Figure 4: Dielectric properties of the NCR for different moisture content and temperature. (a) Dielectric constant (ϵ') and loss factor (ϵ'') for different moisture content. (b) Dielectric loss angle tangent ($\tan\delta$) for different moisture content. (c,d) Dielectric constant (ϵ') and loss factor (ϵ'') for the dried sample at different temperature. (e,f) Penetration depth (D_p) for different moisture content and temperature.

3. Latent heat of vaporization

$$q_3 = H_v \cdot \dot{m} \quad (11)$$

where H_v is the latent heat of evaporation (J/kg) and $\dot{m}$ is the phase change term (kg/m³·s) expressed as [24]:

$$\dot{m} = \frac{\partial}{\partial t} \left[\rho_v \phi (1-s) \right] + \frac{\partial}{\partial x} \left[-D_m \frac{\partial \rho_v}{\partial x} \right] + \frac{\partial}{\partial z} \left[\rho_v \frac{KK_{rg}}{\mu_g} \rho_g g_z - D_m \frac{\partial \rho_v}{\partial x} \right] \quad (12)$$

Figure 5: Energy balance analysis in a micro-section of NCR.

where, D_m is the effective molecular mass diffusion (m²/s), K is the permeability (m²), K_{rg} is the relative gas permeability (m²), μ_g is the gas dynamic viscosity (Pa·s), and g_z is the gas of direction z .

Therefore, the total heat balance of the micro-section can be described as:

$$\begin{aligned} & \frac{\partial}{\partial t} \left[(\rho C_p)_T T \right] + H_v \cdot \dot{m} + \\ & \frac{\partial}{\partial x} \left\{ \left[\rho_l C_{pl} u_l + (\rho_a C_{pa} + \rho_v C_{pv}) u_g \right] T \right\} + \\ & \frac{\partial}{\partial z} \left\{ \left[\rho_l C_{pl} w_l + (\rho_a C_{pa} + \rho_v C_{pv}) w_g \right] T \right\} \\ & = 2\pi f E_y^2 \epsilon_0'' \epsilon'' + \frac{\partial}{\partial x} \left[\lambda_{eff} \frac{\partial T}{\partial x} \right] + \frac{\partial}{\partial z} \left[\lambda_{eff} \frac{\partial T}{\partial z} \right] \end{aligned} \quad (13)$$

3.3 Microwave drying kinetics of the NCR

Figures 6a and 6c show that the moisture content of NCR significantly decreases with the decrease of sample mass and the increase of microwave power. A similar rule was mentioned by several researchers for different materials

Figure 6: Microwave drying curves of NCR. (a) Drying curves of 100 g sample at different microwave powers, (b) drying rate curves of 100 g sample at different microwave powers, (c) drying curves with a different sample mass at 500 W and (d) drying rate curves with a different sample mass at 500 W.

dried using microwave energy [33,34]. According to various microwave power and material mass, it will take 14 to 28 min to remove the water of the NCR from 45.8% to 0.3% kg/kg (d.b.). Figures 6b and 6d illustrate the significant impact of the microwave power and material mass on the drying rate. At a power of 400 W and 500 W or a mass of 100 g and 120 g, the drying rate

is close unlike at other conditions. After a short period of heating, the values of drying rate of the process changed from rapid increase to a constant. The constant rate stage occurred from nearly 3.8% to about 4.3% kg/kg (d.b.) per min and was followed by a stage of decreasing drying rate period where the internal diffusion of water molecules becomes the limiting link in drying [35].

Table 3: Statistical analysis of each model at various microwave powers.

Model	Power (W)	R ²	SSR	Mass (g)	R ²	SSR
Newton	400	0.9618	0.0918	120	0.9622	0.0972
	500	0.9573	0.0891	100	0.9573	0.0891
	600	0.9609	0.0697	80	0.9583	0.0647
	700	0.9683	0.0480	60	0.9600	0.0517
Henderson and Pabis	400	0.9786	0.0493	120	0.9785	0.0533
	500	0.9756	0.0481	100	0.9756	0.0481
	600	0.9773	0.0379	80	0.9750	0.0360
	700	0.9801	0.0279	60	0.9726	0.0322
Page	400	0.9851	0.0338	120	0.9825	0.0433
	500	0.9964	0.0071	100	0.9964	0.0071
	600	0.9941	0.0098	80	0.9954	0.0068
	700	0.9926	0.0093	60	0.9916	0.0099
Modified Page	400	0.9601	0.0918	120	0.9607	0.0972
	500	0.9549	0.0891	100	0.9549	0.0891
	600	0.9584	0.0697	80	0.9551	0.0647
	700	0.9658	0.0480	60	0.9560	0.0517
Logarithmic	400	0.9788	0.0468	120	0.9778	0.0528
	500	0.9838	0.0303	100	0.9838	0.0303
	600	0.9835	0.0257	80	0.9857	0.0190
	700	0.9828	0.0223	60	0.9786	0.0226
Diffusion approach	400	0.9671	0.0725	120	0.9649	0.0834
	500	0.9747	0.0471	100	0.9747	0.0471
	600	0.9747	0.0396	80	0.9778	0.0296
	700	0.9756	0.0317	60	0.9706	0.0310
Wang and Singh	400	0.9768	0.0535	120	0.9762	0.0589
	500	0.9836	0.0323	100	0.9836	0.0323
	600	0.9834	0.0278	80	0.9833	0.0241
	700	0.9845	0.0218	60	0.9795	0.0241
Midilli-Kucuk	400 W	a=1.0213;k=0.0318;n=1.5706;b=0.0042			0.9958	0.0095
	500 W	a=1.0097;k=0.0411;n=1.5915;b=0.0029			0.9993	0.0011
	600 W	a=1.0252;k=0.0660;n=1.4864;b=0.0031			0.9968	0.0046
	700 W	a=1.0162;k=0.0803;n=1.5057;b=0.0053			0.9959	0.0023
	120 g	a=1.0185;k=0.0332;n=1.5679;b=0.0043			0.9953	0.0098
	100 g	a=1.0097;k=0.0411;n=1.5915;b=0.0029			0.9993	0.0011
	80 g	a=1.0241;k=0.0693;n=1.4706;b=0.0027			0.9967	0.0040
	60 g	a=1.0261;k=0.1067;n=1.5070;b=0.0054			0.9961	0.0051

The moisture content of NCR reduced from 15% to 0.3% kg/kg (d.b.) at power of 600 W and 700 W or mass of 60 g and 80 g in the decreasing stage. The reason is that a higher temperature of the NCR will be received at higher power densities, leading to quick drying. These results were in agreement with the study on parsley leaf drying by Soysal et al. [36].

As shown in Table 3 and Figure 7, eight thin-layer drying models as mentioned above were used to analyze the drying kinetics. After date fitting, it is found that Midilli-Kucuk model is the most suitable for experimental data with a determination coefficient (R^2) of over 0.9958 and a sum of squared residuals (SSR) lower than 0.0095. The value of the drying constant k increases with the increase of power density (microwave power/material mass). This implies that the drying curve becomes steeper with increasing microwave power. The a , n , and b parameters of the Midilli-Kucuk model were almost the same for all drying conditions. This means that the parameters a , n and b can be assumed constant and equal to 1.0188, 1.5363, and 0.0038, respectively.

Figure 7: Comparison of the experimental data with the predicted Midilli-Kucuk equation.

3.4 Estimation of the activation energy

An exponential expression based on the Arrhenius equation was used to calculate the activation energy for the drying process

$$k = k_0 \exp \left(\frac{-E_a \cdot m}{P} \right) \tag{14}$$

where k and k_0 is corresponding to the drying rate constant and pre-exponential factor (min^{-1}). E_a is the activation energy ($\text{W} \cdot \text{g}^{-1}$). m and P are corresponding to microwave power (W) and sample mass (g), respectively. The linear fitting according to Eq. 12 between $\ln(k)$ and m/P is shown in Figure 8 with SSR and R^2 values of 0.0239 and 0.9794, respectively. Afterwards, k_0 and E_a were determined at 0.3321 min^{-1} and $9.7604 \text{ W} \cdot \text{g}^{-1}$, respectively. k can be calculated using these estimated values for the desired power and mass. By this, the moisture ratio of NCR can be estimated at any given time during microwave drying or vice versa using the values of k calculated with the Midilli-Kucuk model and the constant values of the a , n , and b discussed earlier.

Figure 8: Evolution of the $\ln(k)$ with the mass/power ratio (m/P).

Table 4: Microwave drying stage division.

Step (moisture content)	Dielectric properties as Figure 4	Drying stage as Figure 6
1. Above 15%	Strongly associated with the moisture content	Accelerating drying stage + Constant drying stage
2. 6-15%	Strongly associated with the moisture content	Decelerating drying stage
3. Below 6%	Relatively weak absorption capacity	Difficult drying stage

3.5 Energy consumption statistics and optimization

According to the dielectric properties of NCR and dynamic simulation, the microwave drying processes of NCR can be divided into three stages, which is shown in Table 4.

During the optimization experiment, 100 g material is dried in 10 mm thin layer, and finally dried to 3.3%. The response surface methodology (RSM) is used to optimize the microwave power input in three stages for the drying processing of NCR with low energy consumption. The energy consumption (y) is chosen as the dependent

variable, while microwave input power at each stage (χ_1 , χ_2 , χ_3) is chosen as three independent variables and the exact experimental conditions are shown in Table 5.

Table 6 shows the analysis of statistical data of the significant quadratic predictive model. The R^2 is 0.9895, indicating that only 2.05% of the variations is outside the model. And a high value of adjusted determination coefficient (adjusted $R^2 = 0.9760$) also indicating the model is significant. In addition, the model F-value of 73.3 and P-value less than 0.0001 show that model is significant. The coefficient of variation is low ($CV = 1.25\%$), indicating that the experimental value has a high accuracy.

As Table 7 and Figure 9 show, the optimum microwave power in each stage is identified to be 700 W, 550 W and 400 W. We repeated the experiment at the optimized conditions obtained an average energy consumption of 158.3 W·h and found that the deviations between the experimental value and the predicted value is small.

Stage 1, preheating and steaming stage: Large amounts of water in the sample need more microwave energy to evaporate.

Stage 2, decelerating drying stage: Water content decreased, but the diffusion process is smooth. In this stage, only the latent heat of vaporization which is supplied by microwave power is needed.

Stage 3, internal diffusion stage: With the decrease of free water, only capillary water is left in the material and

Table 5: Experimental design matrix and result.

Run	Step1 (W)	Step1 (W)	Step1 (W)	Step1 (W·h)
1	400	700	550	181.6
2	700	400	550	193.3
3	550	550	550	176.3
4	550	700	400	172.2
5	550	400	400	187.5
6	400	550	400	151.6
7	400	550	700	153.3
8	700	550	700	150.2
9	400	400	550	196.6
10	550	550	550	176.7
11	550	550	550	177.1
12	550	550	550	175.8
13	550	400	700	189.6
14	550	550	550	174.1
15	700	550	400	157.9
16	700	700	550	178.6
17	550	700	700	175.6

Table 7: Energy consumption statistics under the optimized conditions.

Step 1 (W)	Step 2 (W)	Step 3 (W)	Energy consumption (W·h)	
			Predicted	Experimental
700.000	550.000	400.000	155.2	158.3

Table 6: Variance (ANOVA) analysis for quadratic model.

Source	Coefficient	Standard error	Sum of squares	df	Mean square	F-value	p-value Prob > F
Model	176.00	0.98	3135.77	9	348.42	73.30	< 0.0001
χ_1	-0.39	0.77	1.20	1	1.20	0.25	0.6306
χ_2	-7.38	0.77	435.13	1	435.13	91.54	< 0.0001
χ_3	-0.063	0.77	0.031	1	0.031	0.00657	0.9376
$\chi_1\chi_2$	0.075	1.09	0.023	1	0.023	0.00473	0.9471
$\chi_1\chi_3$	-2.35	1.09	22.09	1	22.09	4.65	0.0680
$\chi_2\chi_3$	0.33	1.09	0.42	1	0.42	0.089	0.7743
χ_1^2	-8.22	1.06	284.84	1	284.84	59.93	0.0001
χ_2^2	19.75	1.06	1642.37	1	1642.37	345.53	< 0.0001
χ_3^2	-14.53	1.06	888.32	1	888.32	186.89	< 0.0001

$R^2 = 0.9895$; adj. $R^2 = 0.9760$; $CV = 1.25\%$.

Figure 9: Optimized microwave drying process.

a dense crust will form on the surface of the material in the last stage stage. While the water content of the NCR is not sufficient to absorb the microwave energy, therefore a burning period is possible to appear with the microwave distribution inside the material becomes more and more uneven. So a lower microwave power and longer drying time is needed.

Changing the microwave power in the drying process can effectively reduce energy consumption. According to the optimized process, the energy consumption above of 110 W·h/kg can be reduced than that of drying with a single microwave power. It can provide effective basic data for industrialization experiment.

4 Conclusion

1. The dielectric properties of a NCR with various moisture contents were measured at low temperatures. And found that the dielectric properties of the material are strongly related to the moisture content. During the drying process, the microwave energy is mainly absorbed by the water molecules.
2. The drying characteristics of the NCR were studied at different microwave powers and various sample masses. The variations in moisture content, drying rate, and moisture ratio were significantly affected by the power density.
3. The Midilli-Kucuk model was used to describe the drying characteristics of the NCR with a high value of R^2 and low value of SSR. The values of k_0 and E_a were received as 0.3321 min^{-1} and $9.7604 \text{ W} \cdot \text{g}^{-1}$ using the Arrhenius equation. They correctly described the

dependence of the drying rate constant on the powers/mass ratio P/m . In actual production, it can be used to predict and control the drying rate and moisture content at any time for a given power and sample mass.

4. By adjusting the microwave power in the drying process, the energy consumption above of 110 W·h/kg can be reduced.

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