Research Article

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Dynamic absorption efficiency of paracetamol powder in microwave drying

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Abstract: In microwave drying technology, research into the dynamic absorbing properties of the powder is indispensable. In this study, the reflection loss coefficient of paracetamol powder under different temperature, water content, and thickness was calculated based on the principle of electromagnetic wave transmission. The results show that the absorption performance of powder fluctuates dynamically with a series of absorption peaks, and the position of the absorption peak shifts toward the smaller thickness direction as the water content increases or the temperature rises. Because of the influence of the powder thickness on absorbing efficiency, the powder thickness should be adjusted in real time to increase drying efficiency. This study provides the thickness range for which the absorption performance of paracetamol powder under different conditions is over 99%. This study is of great significance for understanding the drying mechanism and optimizing process parameters for microwave drying of pharmaceutical powder.

Keywords: paracetamol, pharmaceutical powder, microwave drying, absorption efficiency, reflection loss

1 Introduction

Drying is a common processing technique that is currently used in the manufacture of biotherapeutic products [1]. Moisture removal offers many benefits, including ease of processing and storage, low shipping costs and high product stability. Freeze-drying is a common drying method, and is used in food manufacture, pharmaceutical processing, and bioengineering [2]. However, freeze-drying also has many disadvantages, such as long processing times, low energy efficiency, and high costs of purchasing and maintaining equipment. In addition, freeze-drying is suited to mass production, which makes it potentially difficult for use in continuous production processes. Such restrictions have motivated studies into the next generation of drying technologies that can be applied to the manufacture of biotherapeutic products. Microwave drying technology has been widely used in many applications in the pharmaceutical industry such as drying, synthesis, extraction, and sterilization because of its high efficiency, low environmental impact, and energy efficiency [3, 4].

Paracetamol is currently the most commonly used non-anti-inflammatory antipyretic analgesic and is one of the most widely applied drugs in the world [5, 6], and the drying process is an indispensable part of paracetamol production. Compared with traditional drying methods, microwave drying can be better applied to continuous and automated mass production of drugs because of its fast drying speed, high finished product quality, and high energy efficiency. In the microwave drying process, the complex permittivity of the heated medium changes dynamically with the decrease of moisture content [7], which results in changes in absorption efficiency. Given that the microwave absorption property plays a decisive role in microwave heating, any change in the microwave absorption property eventually leads to continuously changing microwave heating efficiency, which would reduce the heating efficiency in most cases [8]. Therefore, the study of the dynamic absorption efficiency of the heated media is particularly important to increase the utilization of microwave energy.

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At present, studies of Microwave heating have been applied in the field of metallurgy [9, 10]. Pan ShunKang *et al.* [11] calculated and analyzed the absorbing properties of $\text{Mn}_{55}\text{Al}_{45}$ alloy for different high-energy ball-milling times and tempering temperatures. They found that when the temperature was lower than 400°C , the absorption peaks shifted toward lower frequency with increased grinding time; however, when the temperature was higher than 400°C , the absorption peaks shifted toward higher frequency with increased grinding time. They also calculated the minimum reflectance values at 200, 400, and 600°C .

Studies on the dynamic absorption efficiency of pharmaceutical powders are still relatively rare. Magee *et al.* [12] measured the dielectric properties of commonly used pharmaceutical powders, such as paracetamol, and modeled the data. They found that the magnitudes of the dielectric constant (ϵ'), the loss factor (ϵ''), and the microwave penetration depth (D_p) are affected by frequency, moisture content, temperature, and powder type. Notably, the dielectric properties of pharmaceutical powder containing water increase linearly with moisture content, but the relationship between temperature and dielectric properties is a quadratic form. Currently, studies of drug powders remain focused on the measurement of parameters, and the microwave absorption efficiencies of the relevant drug powders are yet to be calculated. Microwave heating efficiency is not only related to the complex permittivity of the material in the microwave drying process [13], but also to the size and shape of the heated medium, the location, the design of the microwave heating equipment, and other factors [14, 15]. As a result, some adjustments to the size of the heated medium can make it a strong absorber [16, 17]. However, the influence of the thickness of the absorbing material is usually ignored by researchers. Although high moisture content can make the heated medium a strong absorber in the initial stages of microwave drying, the wrong thickness may soon convert the material into a weak absorber of microwaves. Conversely, a suitable thickness can make a low-moisture medium in the later stages of microwave drying become a strong absorber. Therefore, studies on microwave absorption properties under different conditions (moisture content, temperature, powder thickness) are meaningful. Despite this need, there is a scarcity of reports on theoretical calculations of the absorption efficiency of paracetamol powder in microwave drying.

This study calculated the reflection loss coefficient of paracetamol powder based on the principle of electromagnetic wave transmission, with a frequency of 2450 MHz, and using the variables of temperature ($20\text{--}70^{\circ}\text{C}$), moisture content ($0.2\text{--}1.0\text{ kg kg}^{-1}$), and powder thickness ($0\text{--}0.060\text{ m}$). The study analyzed the relationships between

the absorption efficiency and the temperature, moisture content, and powder thickness, which may provide a reference for the selection of the best thickness interval in microwave drying.

2 Reflection Loss Theory

Microwave heating is a process in which a material absorbs incident electromagnetic wave energy and converts it into thermal energy. Two main factors should be considered in the specific evaluation of the microwave absorption property of materials. One is the impedance match of the material [18]. The electromagnetic waves must penetrate the inside of the material as much as possible for the high-efficiency absorption of electromagnetic waves. Therefore, the input impedance of the material must match the wave impedances of the free space to offset the interference by the two columns of reflected electromagnetic waves (two columns of waves reflected back into the air medium at the former and latter interfaces of the absorbing layer), as displayed in Figure 1. The second factor is the electromagnetic wave attenuation properties of the material [19, 20]. The attenuation properties refer to the ability of the material to absorb electromagnetic waves (the electromagnetic loss property of the material). The main parameters affecting these two properties are the electromagnetic parameters of the material, which are affected by the moisture content and temperature. For non-magnetic materials (paracetamol is regarded as non-magnetic), the main parameter affecting microwave heating is the relative complex permittivity of the material. Table 1 presents the relative complex permittivity of paracetamol powder at a frequency of 2450 MHz (the frequency used in this study), with the tem-

Figure 1: Schematic of a single absorber under microwave irradiation.

Table 1: The relative complex permittivity of paracetamol at various moisture contents and temperatures (2450 MHz).

relative complex permittivity		Moisture content (X/kg kg ⁻¹)				
		0.2	0.4	0.6	0.8	1.0
Temperature (°C)	20°	8.87-0.54j	16.91-1.55j	22.47-1.98j	24.86-2.24j	26.58-2.83j
	30°	12.22-1.01j	22.91-2.66j	25.02-2.99j	26.91-3.27j	27.77-3.36j
	40°	13.42-1.14j	25.12-2.79j	26.21-3.17j	29.09-3.54j	32.70-4.09j
	50°	19.28-2.18j	26.48-3.61j	32.26-3.96j	34.73-4.33j	36.34-4.52j
	60°	24.01-3.23j	30.74-3.86j	33.54-4.03j	39.40-4.82j	44.73-5.61j
	70°	27.08-3.38j	34.45-4.29j	39.13-4.80j	44.73-5.54j	48.31-5.94j

perature of 20–70°C, and the moisture content of 0.2–1.0 kg kg⁻¹ [12].

Figure 1 is a schematic view showing the transmission of electromagnetic waves through an absorber with a metal plate having strong reflection characteristics as the substrate. According to transmission line theory [21], when a fixed-frequency uniform-plane electromagnetic wave is perpendicularly incident on the surface of a single-layer absorbing material, the power reflection of the material on the electromagnetic wave can be calculated with the reflection loss coefficient RL (dB) [22, 23]:

$$RL = 20 \lg \left| \frac{Z_{in} - 1}{Z_{in} + 1} \right| \quad (1)$$

$$Z_{in} = \sqrt{\mu_r/\epsilon_r} \cdot \tanh [j(2\pi fd/c)\sqrt{\mu_r \cdot \epsilon_r}] \quad (2)$$

where Z_{in} is the input impedance of the absorber; μ_r is the relative complex permeability of the material ($\mu_r = \mu' - j\mu''$; $\mu' = 1$ and $\mu'' = 0$ for non-magnetic material); ϵ_r is the relative complex permittivity of the material ($\epsilon_r = \epsilon' - j\epsilon''$); c is the velocity of light; f is the frequency of the electromagnetic wave; and d is the thickness of the absorbing material. Based on Eqs. (1) and (2), the absorption efficiency is mainly subject to the frequency of the electromagnetic wave, the thickness of the absorption layer, and the relative complex permittivity of the material under the corresponding conditions. Therefore, an expression for the reflection loss coefficient that changes with the thickness of the absorbing material can be calculated with data from Table 1. When the particle size of the powder is much smaller than the wavelength of the electromagnetic wave, the interaction between the particles is negligible [24]. The particle size of the pharmaceutical powder used in this study was much smaller than the wavelength of the electromagnetic wave, so it was considered to be a single uniform medium.

Different from the traditional heating method, the microwave heating process requires electromagnetic waves to penetrate into the material to be lost and converted into

Figure 2: Microwave penetration depth in paracetamol at temperatures between 20 and 70°C and in the moisture contents range of 0.2–1 kg kg⁻¹ (2450 MHz).

heat energy, thereby achieving the purpose of heating. Because of the electromagnetic wave attenuation properties of the material, microwave heating also has the problem of uniformity. In most cases, D_p is the microwave penetration depth, which measures the uniformity of microwave heating. The penetration depth equation for microwaves in non-magnetic materials is [25]:

$$D_p = \frac{\lambda_0}{2\pi(2\epsilon_r')^{1/2}} \left\{ \left[1 + \left(\frac{\epsilon_r''}{\epsilon_r'} \right)^2 \right]^{1/2} - 1 \right\}^{-1/2} \quad (3)$$

where D_p is the penetration depth of the microwave in the medium, which is defined as the distance at which the dissipated power is attenuated to $1/e$ ($e \approx 2.718$, $1/e \approx 36.8\%$); and λ_0 is the microwave wavelength in free space ($\lambda_0 = c/f$). The microwave penetration depth of paracetamol powder can be calculated at 2450 MHz, under different temperature and moisture conditions, with the parameters in Table 1. As shown in Figure 2 and Table 2, except for the case where the penetration depth of the paracetamol powder with a moisture content of 0.2 kg kg⁻¹ is in the range

Table 2: The microwave penetration depth in paracetamol at temperatures between 20 and 70°C and in the moisture contents range of 0.2–1 kg kg⁻¹ (2450 MHz).

D_p/m		Moisture content (X/kg kg ⁻¹)				
		0.2	0.4	0.6	0.8	1.0
Temperature (°C)	20°	0.1075	0.0518	0.0467	0.0434	0.0356
	30°	0.0675	0.0351	0.0327	0.0310	0.0306
	40°	0.0627	0.0351	0.0315	0.0297	0.0273
	50°	0.0393	0.0278	0.0280	0.0266	0.0260
	60°	0.0296	0.0280	0.0281	0.0254	0.0233
	70°	0.0301	0.0267	0.0254	0.0236	0.0228

Table 3: The microwave length in paracetamol at temperatures between 20 and 70°C and in the moisture contents range of 0.2–1 kg kg⁻¹ (2450 MHz).

λ_d/m		Moisture content (X/kg kg ⁻¹)				
		0.2	0.4	0.6	0.8	1.0
Temperature (°C)	20°	0.0411	0.0297	0.0258	0.0245	0.0237
	30°	0.0350	0.0255	0.0244	0.0236	0.0232
	40°	0.0334	0.0244	0.0239	0.0227	0.0214
	50°	0.0278	0.0237	0.0215	0.0207	0.0203
	60°	0.0249	0.022	0.0211	0.0195	0.0183
	70°	0.0235	0.0208	0.0195	0.0183	0.0176

of 0–0.10 m, the penetration depths under the other conditions were below 0.06 m in this study. From these data, the thickness range of paracetamol powder under uniform heating conditions can be calculated, which then allows further studies on the microwave absorption property of the material with different thicknesses.

3 Results and discussion

3.1 Impact of temperature on absorption efficiency of paracetamol powder

Figure 3 presents the patterns of the reflection loss coefficient of the paracetamol powder, which changes with thickness at different temperatures (20, 30, 40, 50, 60, 70°C) with a certain fixed moisture content (0.2, 0.4, 0.6, 0.8, 1.0 kg kg⁻¹). Figure 3 shows that the reflection loss of the paracetamol powder fluctuates at different temperatures and there are several troughs (absorption peak) in the RL curves. (Although RL is a negative value, the larger the absolute value of RL, the smaller the energy of the electromagnetic wave reflected by the material surface, indicating more energy taken by the material and better absorption efficiency of the material.) The fluctuation can be explained by the 1/4 wavelength theory [26, 27]: the match-

ing thickness of the corresponding material is very close to 1/4 of the wavelength of the microwave in the material and multiplied by an odd number, at which an interference phenomenon occurs, thereby forming an absorption peak.

When the moisture content is fixed, the number of absorption peaks of the paracetamol powder at different temperatures in the same thickness range is different. For example, when the water content is 0.2 kg kg⁻¹ and the thickness range is 0–0.10 m, there are five absorption peaks at 20°C, but when the temperature rises to 70°C, there are eight absorption peaks. This is because the increase in temperature results in an increase in the dielectric constant of paracetamol powder, which makes the microwave wavelength in the powder shorter. The wavelength variation law and the wavelength values under various conditions are shown in Figure 4 and Table 3. The wavelength in the medium is given by [28]:

$$\lambda_d = \sqrt{2} \lambda \left\{ \varepsilon' \mu' - \varepsilon'' \mu'' + \left[(\varepsilon' \mu')^2 + (\varepsilon'' \mu'')^2 + (\varepsilon' \mu'')^2 + (\varepsilon'' \mu')^2 \right]^{1/2} \right\}^{-1/2} \quad (4)$$

where λ_d is the propagation wavelength of the electromagnetic wave in the medium. According to the 1/4 wavelength theory, the wavelength in the drug powder medium becomes shorter, which leads to an increase in the number

Figure 3: Temperature dependence ($20, 30, 40, 50, 60, 70^\circ\text{C}$) of reflection loss of paracetamol as thickness varies from 0 to 0.1 m for moisture contents: (a) 0.2 kg kg^{-1} , (b) 0.4 kg kg^{-1} , (c) 0.6 kg kg^{-1} , (d) 0.8 kg kg^{-1} , (e) 1.0 kg kg^{-1} .

Figure 4: Microwave length in paracetamol at temperatures between 20 and 70 °C and in the moisture contents range of 0.2–1 kg kg⁻¹ (2450 MHz).

of absorption peaks in the same thickness interval, and the positions of the absorption peaks also shift toward the smaller thickness direction. The shorter wavelength makes the microwave phase constant increase, because the dielectric constant varies widely, so the values of the position shift of the absorption peaks are larger as the temperature increases. As the thickness increases, the subsequent position shift accumulates an extra wavelength deviation. Thus, more absorption peaks appear later, which is the more obvious sign of this shift phenomenon. For example, when the moisture content was fixed at 0.2 kg kg⁻¹, the first absorption peak at 20 °C was located at a thickness of 0.01078 m, while at 70 °C, the first absorption peak was at 0.00596 m; the fifth absorption peak at 20 °C was located at a thickness of 0.09257 m, and at 70 °C it was at 0.05288 m. Table 4 lists the distribution of absorption peaks of paracetamol powders at different temperatures and moisture contents (values at which RLs tend to be flat are not listed).

There is a thickness for the maximum absorption efficiency in each reflection loss curve of paracetamol powder under different conditions. For example, when the moisture content was 0.2 kg kg⁻¹ and the temperature was 70 °C, the absorption peak amplitude first increased with the powder thickness, and the maximum value (RL = -32.39 dB) was obtained when the powder thickness was 0.01765 m. Above this thickness, the absorption peak amplitude began to decrease, and at higher temperatures, this reduction was more pronounced. This is because the penetration depth of the microwave in the pharmaceutical powder decreases with the increase in temperature (the pattern of D_p is shown in Figure 2). For example, the penetration depth of the microwave was 0.1075 m when the moisture content of the paracetamol powder was 0.2 kg kg⁻¹ and the

temperature was 70 °C, but it was only 0.0301 m when the temperature increased to 70 °C. Therefore, there is still an absorption peak (RL = 47.11 dB) at 20 °C when the powder thickness is 0.09257 m, but the RL values around the peaks are slightly over -10 dB when the temperature rises to 70 °C.

According to the variation law of the absorption peaks in Figure 3, it can be found that under the premise of ensuring uniform heating (the powder thickness is smaller than the microwave penetration depth), the thickness values for the second absorption peak should be selected as the preferred thickness. This is because the position shifts of the absorption peaks around the second absorption peaks are smaller, and with higher absorption efficiency, and it applies under various temperature conditions. The complex dielectric constants of the pharmaceutical powders change dynamically under different temperature conditions. Therefore, under the condition of fixing the thickness of the powder layer, it is difficult to ensure the best heating efficiency for microwave drying under different temperature conditions. The best powder thickness should be based on the absorption peak positions and RL values that create the best absorbing efficiency under conditions that match the powder thickness. Table 5 lists the thickness ranges corresponding to the reflection loss coefficients of paracetamol powder less than -20 dB. The reflection loss coefficient that is less than -20 dB (99% of the microwave energy can be absorbed) is usually taken as an indicator of absorption efficiency [29, 30]. Therefore, in microwave drying of paracetamol powder, the thickness of the powder should be preferentially selected in the thickness range listed in Table 5.

3.2 Impact of moisture content on absorption efficiency of paracetamol powder

Figure 5 shows the variation of the reflection loss coefficients of paracetamol powder with different moisture contents and increasing thickness under fixed temperature conditions. Figure 5 shows that the impact on the reflection loss of the paracetamol powder caused by moisture content is similar to that caused by temperature: the curve of the reflection loss coefficients with powder thickness also fluctuates with different moisture contents and at the same temperature. This is because the impact on the electromagnetic parameters of the pharmaceutical powder caused by moisture content is similar to that caused by temperature. As the moisture content increases, the real and imaginary parts of the relative complex permittivity of the paracetamol powder increase. Thus, the fluctuation

Table 5: Thickness ranges of paracetamol with RL values less than -20dB at 2450 MHz.

Thickness (m)		Temperature (°C)						
		20°C		30°C	40°C	50°C	60°C	70°C
Moisture content (X/kg kg ⁻¹)	0.2	1	0.05120-0.05297	0.02545-0.02736	0.02424-0.02614	0.02009-0.02188	0.00609-0.00662	0.00575-0.00619
		2	0.07015-0.07402	0.04243-0.04534	0.04052-0.04321	0.03411-0.03563	0.01806-0.01949	0.01705-0.01831
		3	0.09044-0.09482	0.05983-0.06291	0.05720-0.05989			
		4		0.07754-0.08019				
		5		0.09598-0.09668				
0.4	1	0.02153-0.02331	0.01847-0.02000	0.01767-0.01906	0.00575-0.00634	0.00535-0.00584	0.00504-0.00553	
	2	0.03620-0.03834	0.03157-0.03237	0.03019-0.03088	0.01725-0.01849	0.01605-0.01711	0.01521-0.01611	
	3	0.05132-0.05292						
0.6	1	0.01873-0.02014	0.00610-0.00634	0.00590-0.00624	0.00523-0.00569	0.00513-0.00557	0.00471-0.00519	
	2	0.03156-0.03307	0.01770-0.01909	0.01731-0.01863	0.01568-0.01669	0.01539-0.01636	0.01432-0.01506	
	3	0.04499-0.04541						
0.8	1	0.01181-0.01913	0.00580-0.00618	0.00555-0.00597	0.00502-0.00550	0.00470-0.00517	0.00439-0.00486	
	2	0.03008-0.03136	0.01710-0.01837	0.01647-0.01763	0.01515-0.01604	0.01427-0.01501	0.01346-0.01401	
1.0	1	0.01720-0.01850	0.00570-0.00609	0.00518-0.00567	0.00490-0.00538	0.00439-0.00486	0.000422-0.00467	
	2	0.02934-0.03003	0.01684-0.01807	0.01559-0.01656	0.01483-0.01566	0.01347-0.01400	0.01299-0.01344

Figure 5: Moisture dependence (0.2, 0.4, 0.6, 0.8, 1.0 kg kg⁻¹) of reflection loss of paracetamol as the thickness varies from 0 to 1.0 m for temperatures: (a) 20°C, (b) 30°C, (c) 40°C, (d) 50 °C, (e) 60°C, (f) 70°C.

caused by moisture content is the same as that caused by temperature.

In the reflection loss curve related to the moisture content of the paracetamol powder, there is also a matching thickness corresponding to the maximum absorption efficiency. After exceeding this thickness, the fluctuation of the RL curve decreased until the RL gradually approached a constant value after reaching a certain thickness. This is because water is a strong absorbing material. Therefore, the electromagnetic wave absorption of paracetamol powder increases with moisture content, and when the moisture content reaches a certain level, the powder–water mixture consumes almost all of the microwave energy. In this case, the microwave energy reflected back from the latter interface is very rare, and the superposition effect of the wave caused by the impedance mismatch of the front interface reflected wave is not obvious. Therefore, the RL curves gradually become stable. As the moisture content increases, the relative complex permittivity changes, which causes the microwave penetration depth and the wavelength in the powder medium to decrease. This decreasing trend was most pronounced when the moisture content increased from 0.2 kg kg^{-1} to 0.4 kg kg^{-1} . Thus, most changes in the RL curves in Figure 5 can be explained with the above analysis and the $1/4$ wavelength theory. For example, the thickness position corresponding to the absorption peak of the RL curve is at an odd multiple of $1/4$ wavelength under the corresponding condition; as the moisture content increases, the number of absorption peaks increases; the position of the absorption peak shifts toward a smaller thickness direction; and as the thickness increases, the position shift increases.

The above analysis found that the second absorption peaks should be selected as the preferred thickness. In different microwave drying conditions, the best thickness of paracetamol powder for microwave drying should be based on positions of relevant absorption peaks and the thickness ranges within which the RL values are less than -20 dB , as shown in Tables 4 and 5.

3.3 Impact of thickness on absorption efficiency of paracetamol powder

As displayed in Figures 3 and 5, there is a similar rule for the variations of RL curves with thickness. When the thickness exceeds the matching thickness of the maximum absorbing efficiency, and continues to increase, the fluctuation amplitudes of the absorption peaks decrease continuously and the RL gradually tends to a constant value. These phenomena were particularly evident under condi-

tions of relatively high temperature and high moisture content. For example, there are six absorption peaks of the RL curve of paracetamol powder within the thickness range of $0\text{--}0.06 \text{ m}$, at 70°C and with a moisture content of 1.0 kg kg^{-1} . The first absorption peak is located at the thickness of 0.00444 m , with an RL value of -32.86 dB . The RL values of the third, fourth, fifth, and sixth absorption peaks are -13.26 , -9.94 , -8.30 , and -7.73 dB , respectively, for which the thickness range is $0.022\text{--}0.04839 \text{ m}$. After the third absorption peak, the smoothing of the RL curve becomes more obvious. This is because the microwave penetration depth under this condition is small ($D_p = 0.0288 \text{ m}$). When the powder is thicker than the penetration depth of the microwave under the corresponding conditions, the microwave reflected at the latter interface has been attenuated to a small extent, and has little effect on the overall power reflection. At this time, not only is the uniform heating condition not satisfied, but the drying efficiency is also low.

The impedance matching characteristics of the material are also largely influenced by its thickness parameters. The electromagnetic parameters of the material are basically fixed when the temperature, moisture content, and frequency are fixed. In this case, the electromagnetic wave attenuation properties of the material would have little effect on the RL value. The RL value would be mainly subject to whether the impedance matching characteristics of the material are appropriate, based on the equation [26, 27]:

$$d = (2n - 1)\lambda_d/4 \quad (n = 1, 2, 3, \dots) \quad (5)$$

where the thickness (d) of the absorbing material is an odd multiple of the $\lambda_d/4$ thickness of the medium, and the phase difference between the wave reflected by the former interface and the wave reflected by the latter interface is π . Therefore, when the thickness of the drug powder is larger than $\lambda_d/4$, the RL curve exhibits a fluctuation distribution, and, as the thickness increases, the absorption peak appears in sequence.

The above analysis found that the powder thickness should be smaller than the microwave penetration depth (D_p) as much as possible in the microwave drying of paracetamol powder. In addition, under the premise of uniform heating, the absorption efficiency of the powder can be improved by using the right powder thickness (Tables 4 and 5), thereby improving the drying efficiency.

4 Conclusions

The theory of reflection loss was applied to microwave drying, and the moisture characteristics and temperature characteristics of the paracetamol powder reflection loss were calculated and analyzed.

The absorption efficiency of paracetamol powder fluctuates with different temperatures and moisture contents as the powder thickness increases, and the best absorption efficiency occurred within in the thickness range studied. Therefore, the microwave drying efficiency of paracetamol powder can be improved by adjusting the powder thickness.

The powder thickness in microwave drying should be adjusted based on specific conditions. The powder thickness range is subject to specific drying temperatures and drying stages: the initial drying stage with high moisture content, the medium drying stage with moderate moisture content, the final drying stage with low moisture content, and dielectrically assisted drying in the final drying stage.

The findings in this study can provide a reference for the selection of thickness ranges of paracetamol powder in microwave drying, and contribute to better design of microwave drying equipment and optimized process parameters in microwave drying.

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