Research Article

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Research on Electromagnetic Sensitivity Properties of Sodium Chloride during Microwave Heating

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Abstract: The multimode resonant cavity is the most common cavity. The material often shows on selective heating performance during the heating process due to the effect of microwave heating having a closely relationship with the electromagnetism parameters. This paper is based on finite difference time domain method (FDTD) to establish the electromagnetic-thermal model. The electromagnetic sensitivity property parameters of sodium chloride including relative dielectric constant, loss angle tangent and water content of sodium chloride is studied during the heating and drying process. The heating rate and the electric field distribution of sodium chloride, at the different water content, were simulated with the electromagnetic characteristic parameters changing. The results show that with the electromagnetic sensitivity property parameters varying, the electric field strength, heating rate and steady-state temperature of the heating material will all have a variety in the cavity. Some measures are proposed to improve the heating efficiency and ensure the stability of the microwave heating system in the industrial application.

Keywords: Finite difference time domain, Relative dielectric constant, Loss angle tangent, Heating rate, Water content

1 Introduction

Microwave assisted heating technology is a green and efficient heating method with the characteristics of selectivity, instantaneity, integrity, safety, environmental friendliness and efficient energy-saving compared to the traditional heating approaches [1–4]. However, inside a microwave cavity, where microwave heating takes place, localized hot and cold spots occur due to uneven electrical field distributions. Since that would cause severe non-uniform, heating would adversely influence product quality. Several studies [5, 6] about its mechanism have been conducted. But a key issue is that the process of microwave heating and the temperature distribution is difficult to obtain by experimental methods [7]. Microwave heating shows the characteristics of selective heating is due to microwave heating and electromagnetic properties of materials are closely related. The actual heating process of the material with an added reducing agent, catalyst and other auxiliary materials makes the material not be a single heating material, but a more complex mixture. These parameters are often a complex function of temperature, and it will cause sintering, heat out of control and other phenomena [8, 9] if handled improperly. Even for specific heating cavities, different materials exhibit different electromagnetic susceptibility [10, 11], thus causing the same microwave heating chamber to fail to achieve the desired heating effect for all heated materials. Therefore, it is very important to study the electromagnetic parameters of the material during microwave heating with the law of temperature distribution and variation. Li and Xie in University of Electronic Science and technology established the electromagnetic-thermal coupling model of ceramic assisted with microwave heating calculated by FDTD method. The thermal runaway process was simulated by microwave heating. The time - domain process of the steady-state temperature distribution and the change of the ceramic was obtained, and the influence of the material on the thermal runaway under different electromagnetic parameters is discussed [12]. Li of Kunming Univer-

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sity of Science and Technology, who obtained the material properties of the dielectric through experiments and simulation of microwave heating process, summarized the dielectric constant of phosphogypsum [13]. Peng of Michigan University of Technology used the finite difference method to model the microwave heating. The heat transfer characteristics of the dielectric material and the factors influencing the uniformity of the heating were analyzed [14]. The dynamic absorption efficiency of sodium chloride in microwave drying was studied by Shang. The effects of temperature and the water content of the material on the heat absorption efficiency were analyzed [15]. Zhu compared the effects of design parameters and dielectric properties on the temperature distribution by studying the microwave heating of continuous fluids [16]. José M. Catalá-Civera of Spanish designed a dual-mode cylindrical cavity to measure the high-temperature dielectric loss characteristics of a dual-band ceramic material and analyze its properties [17]. Torres discussed the effect of dielectric parameters on microwave heating by studying the relationship between dielectric parameters and the temperature rise of heated materials [18].

The electromagnetism parameters of the materials typically change with temperature at microwave frequencies [19]. As a result, the heating material conversely influences microwave field distribution and heat transfer. It is critical to solve coupled electromagnetic field and thermal field for a three-dimensional transient microwave heating process. Numerical computation methods based on fundamental Maxwell equations and heat transfer equations can assist the design of microwave applicators and select appropriate process parameters to alleviate non-uniform heating. Finite difference time domain method, which is shortly abbreviated as FDTD in the literature, is based on the solving Maxwell equations in a spatio-temporal domain directly according to the finite-differences method. FDTD has become a versatile numerical analysis tool which has been used nearly for the solution of many electromagnetic-thermal problems and since its first declaration in 1966 [18, 20–22].

In this paper, the corresponding electromagnetic thermal model is established by solving the Maxwell equation and the heat transfer equation. FDTD is used to simulate the temperature rising rate of sodium chloride in the resonant cavity. The electromagnetic characteristics and water content of sodium chloride are first discussed for rising temperatures. Secondly, the electric field distribution at different water content were simulated with the electromagnetic characteristic parameters changing. The results show that with the increase of relative dielectric constant, loss angle tangent and water content of sodium chloride,

the electric field strength, heating rate and steady-state temperature of the material in the cavity increase.

2 Fundamentals for electromagnetic-thermal coupling model

For the electromagnetic thermal coupling process, it can be divided into two parts to study, that is, electromagnetic field calculation and heat transfer process. FDTD algorithm uses the Yee grid as the space electromagnetic field discrete unit, transforms the Maxwell equations into the difference equations, so that the electromagnetic field is alternately distributed in time and space.

$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J} \quad (1)$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} + \vec{M} \quad (2)$$

Where E is the electric field strength (V / m^2), D is the electric displacement (C / m^2); H is the magnetic field strength (A / m); B is the magnetic flux density (Wb / m^2), J is the current density (A / m^2); M is the magnetic flux density (V / m^2).

The spatial arrangement of the electric field and the magnetic field in the FDTD discretization is shown in Figure 1. In the Yee cell, the electric field and the magnetic field are staggered half a grid in the spatial position, and the electric field and the magnetic field are also staggered half a grid. And each electric field is surrounded by four magnetic field components, each of which is surrounded by four electric field components. This difference scheme can reflect the two electromagnetic field rotation equation.

Figure 1: Yee cells in FDTD dispersion

In the calculation of FDTD, first with a finite difference to approximate the Maxwell equation in the space and time derivative, followed by the construction of a set of equations. The instantaneous field value of the previous time step is calculated by the previous momentary instantaneous field value, thereby constructing the time advancing algorithm to simulate the process of the electromagnetic field in the time domain. In the Cartesian coordinate system, for the passive space, when μ, ϵ is not a function of time, we can get the Maxwell equation in the three-dimensional FDTD update equation.

The material in the resonant cavity absorbs electromagnetic waves during heating process. At the same time, it converts the absorbed electromagnetic waves energy into heat sources.

$$P = \sigma |E|^2 = 2\pi f \epsilon_0 \epsilon' \tan \delta |E|^2 \quad (3)$$

$$\epsilon_r = \epsilon' - j\epsilon''$$

Where σ is the effective conductivity and $\sigma = \omega \epsilon'' \tan \delta$. ϵ'' is the imaginary part of the complex permittivity of the material. E is the electric field strength in the cavity. ϵ_0 is the dielectric constant of the material in vacuum. ϵ' is the real part of the complex permittivity. f is the microwave frequency. $\tan \delta$ is the value of dielectric loss tangent which refer to the ability of the material to absorb microwave energy [23].

At time t , the temperature change at the interior point (x, y, z) of the material satisfies the heat transfer equation:

$$\rho C_m \frac{\partial T(x, y, z, t)}{\partial t} = k_t \nabla^2 T(x, y, z, t) + P(x, y, z, t) \quad (4)$$

Where ρ is the dielectric density. C_m is the specific heat capacity. k_t is the thermal conductivity. P stands for the heat flux, which is equivalent to the heat source calculated in equation (3). Using FDTD grid form of discrete, for $\Delta x = \Delta y = \Delta z = \Delta$, the temperature field of the difference equation is

$$T^{n+1}(i, j, k) = T^n(i, j, k) + \Delta t D_t \frac{P^n(i, j, k)}{k_t} \quad (5)$$

$$+ \frac{\Delta t D_t}{\Delta^2} \left[\begin{array}{c} T^n(i+1, j, k) + T^n(i-1, j, k) + \\ T^n(i, j+1, k) + T^n(i, j-1, k) + \\ T^n(i, j, k+1) + T^n(i, j, k-1) \\ - 6T^n(i, j, k) \end{array} \right]$$

Where D_t is the heat transfer rate

$$D_t = \frac{k_t}{\rho C_m} \quad (6)$$

Material absorption of microwave energy into heat energy after the heating rate:

$$\frac{dT}{dt} = \frac{2\pi f \epsilon_0 \epsilon' \tan \delta |E|^2}{\rho c_p} \quad (7)$$

The symbols of T, ρ, c_p and t stands for the material temperature, density, heat capacity and heating time respectively.

The study of microwave electromagnetic - thermal model is mainly aimed at solving electromagnetic and thermal coupled equations. The main process of this method is that the microwave acts on the material to be heated and the microwave loss is generated inside. Then the energy of the microwave loss is converted into heat energy. The thermal energy of the conversion is transferred in the object in the form of a heat source in the thermal model, so that the temperature distribution of the object goes up, which will cause the dielectric parameters and the other related parameters of the object varied. Finally, the distribution of the entire electromagnetic field is recalculation, results in the microwave loss is also changed, so repeated until the end of the calculation. The entire calculation process is shown in Figure 2.

3 Numerical results and discussion

The material absorbs electromagnetic waves during heating, converts the absorbed electromagnetic waves into heat energy and the heat energy results in elevated material temperatures. The ability of the material absorbing

Figure 2: Flow chart of FDTD algorithm

Figure 3: Structure model of waveguide loaded resonator

the microwave mainly depends on the relative dielectric constant ϵ'_r of the material, the loss angle δ of the material and the water content of the materials. Therefore, this paper studies the electromagnetic susceptibility of the relative dielectric constant ϵ'_r , the loss angle δ and the water content W of the sodium chloride. The model is shown in the following figure. The model consists of resonator cavity and transmission waveguide which is shown in Figure 3.

The cross section of resonator cavity is 200 mm × 100 mm with the height 100 mm. The BJ-26 waveguide with the length 140mm is adopted for transmission. The uniaxial perfect match layer (UPML) is used here as absorbing boundary. The electromagnetic wave will be reflected from the source surface if no UPML is selected here, as is shown in Figure 4(a). However, the UPML absorbs all the reflected electromagnetic wave as is shown in Figure 4(b). The working frequency here is 2.45 GHz. Equal interval $\Delta x = \Delta y = \Delta z = \Delta = 2$ mm is used, and the time step is $\Delta t = \frac{\Delta}{2c}$, where c is the speed of light in vacuum. Microwave heating process results in the dielectric properties of sodium chloride change. This will in turn affect the absorption efficiency of microwave for the sodium chloride. It is necessary to consider the effect of the change in the dielectric properties of the sodium chloride on the microwave heating effect.

3.1 The influence of dielectric constant on the electric field distribution of sodium chloride

In order to study the effect of different dielectric constants on the distribution of the electromagnetic field during the microwave drying process, the dielectric constant ϵ' , dielectric loss ϵ'' and loss tangent $\tan \delta$ of the water contain-

(a)

(b)

Figure 4: (a) No UPML boundary conditions (b) Add UPML boundary conditions

ing 4% sodium chloride were listed according to Table 1 [24].

At 3000-time step, the electric field distribution of sodium chloride at temperature of 20°C, 60°C and 80°C are shown in Figure 5(a)~(c), respectively. As the temperature of sodium chloride increases, the electric field distribution changed obviously. As can be seen from the figures, when the sodium chloride is at the temperature of 20°C, the electric field distribution is non-uniform. The electric field distribution changes more uniform than that at the temperature 60°C. The distribution of the electric field tends to stabilization and becomes uniform when the sodium chloride with the larger dielectric constant ϵ' , dielectric loss ϵ'' and loss tangent $\tan \delta$ at temperature 80°C. Therefore, it is observed that when the cavity is filled with sodium chloride at different temperatures, the electric field strength distribution is more uniform when the dielectric constant of sodium chloride increase.

Table 1: Dielectric parameters of aqueous 4% sodium chloride at 2.45 GHz [24]

T/°C	20	30	40	50	60	70	80	90	100
ε'	4.55	4.62	4.75	4.81	5.00	5.29	5.48	5.83	6.15
ε''	1.70	1.80	1.97	2.33	2.67	3.14	4.13	5.42	7.65
$\tan \delta$	0.37	0.39	0.42	0.48	0.55	0.59	0.75	0.92	1.24

Figure 5: Electric field distribution of sodium chloride at different temperature

3.2 Electromagnetic sensitivity analysis of dielectric constant for sodium chloride heating rate

At the same time, the heating rate of sodium chloride in different dielectric constant was calculated with the heating time increasing. As shown in Figure 6, the temperature rising rate of sodium chloride increases with the heating time when the dielectric constant ε' are set $\varepsilon'_1 = 4.55$, $\varepsilon'_2 = 5.0$, $\varepsilon'_3 = 5.48$ respectively. When the run time is before 400-time step, the heating rate changes rapidly. However, as the heating time is prolonged, the heating rate tends to be gentle. This is mainly due to the attenuation of the electromagnetic field in the cavity and the change of the thermal physical parameters. And the weakening of the electromagnetic field may be due to the change of the permeability of the material in the cavity, so that most of the microwave energy radiates by the microwave source would be reflected. Thus, reducing the strength of the electromagnetic field inside the cavity causes the final heating rate of sodium chloride will tend to balance and remain unchanged. In general, with the increase of the relative permittivity of the material in the cavity, the intensity of the electric field in the cavity is gradually enhanced, which means the better absorption effect for the electromagnetic wave.

Figure 6: Heating rate of sodium chloride at different dielectric constant

3.3 Electromagnetic sensitivity analysis of dielectric loss on for sodium chloride

The dielectric loss angle can be used to reflect the ability of dissipating the microwave energy into heat energy, which means the "efficiency" of converting the microwave energy. The material is heated and absorbing the microwave mainly because of the dielectric loss. The dielectric loss of the material is mainly related to the imaginary part of the material complex permittivity, so it is important to study

Table 2: Complex permittivity of sodium chloride particles at different water content at 2.45 GHz [25]

W/%	0	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
ϵ'	2.4181	3.1187	3.3806	3.722	3.9943	4.3735	4.5591	4.6201	4.6619	4.9521	5.1951
ϵ''	0.2084	0.3034	0.4506	0.6818	0.9055	1.2132	1.4069	1.6844	1.7673	2.1444	2.5565
$\tan \delta$	0.0862	0.0973	0.1333	0.1832	0.2267	0.2774	0.3086	0.3646	0.3791	0.4326	0.4921

Figure 7: Variation curve of heating rate **Figure 8:** Heating rate of sodium chloride with different water content at 2.45 GHz microwave frequency

the imaginary part of the complex permittivity. Therefore, this paper will also study the impact of ϵ'' on the heating rate, indirectly, to reflect the loss of the absorption of electromagnetic waves.

The sodium chloride with different the imaginary part of complex permittivity is considered here. ϵ_1'' is 2.33 when the temperature is at 50°C. ϵ_2'' is 2.67 when the tempera-

ture is at 50°C. ϵ_3'' is 3.14 when the temperature is at 70°C. The heating rate changes with the heating time are shown in Figure 7. Compared with the three curves in Figure 7, it can be found that the heating rate of the sodium chloride increases fast at first. And the larger the imaginary part of complex permittivity, the faster the heating rate. That means the steady-state temperature is higher when it has larger imaginary part of complex permittivity. However, the temperature rise rate of the sodium chloride rises abruptly at first 100- to 300-time step, which is likely to lead to thermal runaway. Therefore, it is necessary to reduce the microwave power to ensure the stability of the microwave heating system in the industrial application when the temperature increases quickly.

3.4 Electromagnetic sensitivity analysis of water content for sodium chloride heating

As the water content of sodium chloride has an obviously influence on microwave absorbing, therefore this part complex permittivity and loss tangent with the 0-5% water content of sodium chloride is researched, as shown in Table 2.

According to the data provided in Table 2, four kinds of sodium chloride with different water content were selected, and the rise in the temperature rate curve of the sodium chloride was calculated at 2.45 GHz microwave frequency, as shown in Figure 8. Compared with the four curves in the graph, it can be found that the heating rate of the sodium chloride increases with the increase of water content, and the heating rate increase rapidly at the first 300-time step. And the higher the water content rate, the faster the heating rate increases. We can see that when the water content $w = 4.5\%$, it consumes least time to achieve the maximum steady-state temperature. While the water content $w = 0\%$, the heating rate changes slowly, and it used the longest time to achieve the minimum steady-state temperature among the four types of sodium chloride. It is because the lower water content of sodium chloride, the weaker microwave absorbing, which we refer to as a weak absorbing material. It can also be noted that the absorp-

Figure 9: Temperature field distribution with no material in cavity at different time step

Figure 10: Temperature field distribution with material in cavity at different time step

tion of electromagnetic waves will become very low efficiency when at a lower water content for sodium chloride.

It can also be seen that the temperature rise rate of sodium chloride heating is no longer change when a certain value. The running time is 400-times step that four types of sodium chloride will achieve a steady increase temperature. With the increase of water content, the microwave energy has been almost consumed and converts into thermal energy inside of sodium chloride, and Therefore, the heating rate will stabilize.

3.5 Temperature field simulation

In order to study the temperature field distribution change, the resonator cavity in empty and within material are simulated at different time step, which are shown in Figure 9 and Figure 10 respectively. The cross section is selected at height 30Δ , which is equal to 60mm. At first 14-time step, the temperature field has tiny change in both Figure 9(a) and Figure 10(a). It is because that the electromagnetic

field is fed in cavity initially. Then obviously changes can be observed in both Figure 9(b) and Figure 10(b), which means electromagnetic field are fed into the cavity and transformed into thermal field, causing the temperature improved. However, the empty cavity presents a more obviously standing wave distribution because there is no material in cavity. At about 1000-time step later, the temperature field distribution tends to be steady in both Figure 9(c) and Figure 10(c). The temperature field presents more uniformity within material in it because more electromagnetic energy is absorbed and change into thermal energy which finally resulting in the temperature rising.

4 Conclusions

In this paper, the corresponding electromagnetic thermal couple model were established by solving the Maxwell equations and the heat transfer equation based on the FDTD algorithm. The influence of electromagnetic sensi-

tivity factors including dielectric constant change, dielectric loss and water content of sodium chloride were studied for electromagnetic field and heating rate. The results show that the increase of relative dielectric constant, loss angle tangent and water content of sodium chloride will all have influence on electric field strength distribution, heating rate and steady-state temperature. The following results are obtained:

1. With the increase of the relative permittivity of the sodium chloride, the intensity of the electric field distribution is gradually enhanced, which means the better absorption effect for the electromagnetic wave.
2. The larger the imaginary part of complex permittivity, the faster the heating rate. That means the steady-state temperature is higher when it has larger imaginary part of complex permittivity. As a result, the problem of thermal runaway could occur. It is necessary to reduce the microwave power to ensure the stability of the microwave heating system in the industrial application when the temperature increases quickly.
3. The heating rate of the sodium chloride will be faster with the increase of water content. The absorption of electromagnetic waves will become very low efficiency when at a lower water content for sodium chloride.

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