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The Analysis of Parametric Sensitivity Based on Designing and Optimization of a New Microwave Heating System

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Abstract: Microwave-assisted heating technology has become a popular alternative to conventional heating technologies because of its many advantages. However, the matching performance of microwave heating system is of particular concern because it provides an important index of the utilization efficiency of microwave energy. In this work, a new microwave heating system is designed by the theory of optical resonator in first. Then the comprehensive analysis of the mutual coupling of high sensitive geometrical and material parameters were investigated based on this new microwave heating system at 2.45 GHz. It is demonstrated that the thickness of materials dramatically influences microwave energy absorption efficiency and should be carefully considered and perhaps given priority. Moreover, it is shown that matching performance is the best when the titanium concentrates thickness at about 0.075 m.

Keywords: microwave heating, performance matching, optimizing analysis, parametric sensitivity

Introduction

Microwave heating 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]. Microwave heating has recently become an emerging technology, which has been applied to a wide variety of fields, such as metallurgy,

chemical industry, energy, food, medicament, environmental protection and many other fields [5–9]. Microwave-assisted drying technology, as a new-type green heating methods, has become a new leading edge cross-disciplinary science [4, 10–13]. The effective heating object of microwave heating is mainly the small amount of water to be dried. While water has an advantage of high relative permittivity (about 80), much more than the vast majority of the common mineral and compounds, the great majority of microwave energy can be absorbed by the water, which will reduce the overall heating of the material, reduce the energy consumption greatly and effectively avoid the emissions of pollutants and greenhouse gases.

However, a debate indeed exists on the performance matching of microwave drying due to issues related to the non-homogenous field distribution, the efficiency of energy utilization, and lack of adequate optimization analysis [14–16], because of the parametric interdependence and sensitivity for microwave heating system. It is important and difficult to reduce energy reflection of microwave source and improve the energy absorption of material during the optimizing analysis of performance matching.

Moreover, the performance matching is sensitive to some variations in the geometrical and material parameters that are relevant to the uniform of the electromagnetic field [17, 18]. The main factors affecting the performance matching of microwave heating are the cavity size and structure, mutual coupling of microwave transmission system and the cavity, the microscopic characteristics affected by temperature, location and dimensions of the material to be dried and so on [1, 11, 19, 20]. In order to optimize the coupling performance, the interactions of these high sensitive geometrical and material parameters of the coupled microwave heating system should be taken into consideration. This is critical for improving the utilization efficiency of microwave power.

In this paper, a series of geometrical and material parameters are investigated with the aim of improving the matching performance of the new microwave heating

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system and thereby raising the efficiency of microwave heating. The primary geometric parameter considered herein is the structure and the dimension of the cavity. Additionally, the interaction of a variety of geometric parameter variations is taken into account, such as the location of the material coupling of the position of the feeding port. Furthermore, the effect of dielectric properties variation, via temperature variations that affect the temperature-dependent dielectric properties of material, is considered coupling of the thickness of material.

Theoretical basis and model establishment

The theory of cylindrical multimode cavity

On the basis of theory of mode analysis, the uniformity of the field distribution is proportional to the number of resonant modes of the cavity and the number of modes increases with the increase of the cavity volume under the condition of the same input power. While the oversized cavity will affect the efficiency of microwave heating because the energy density of the cavity is reduced, the loss of the inner wall increases, and the heating rate is slowed down. Therefore, the design of the cavity should be taken into account comprehensively.

A cylindrical cavity is one of the common resonant cavities of microwave heating, often used in microwave sintering, microwave heating, wastewater treatment and so on. The two ends of a circular waveguide are closed by a conductor plate to form a cylindrical resonant cavity. The electromagnetic field is the distribution of standing wave along the radial directions and circumference of the cylindrical cavity. Among them, the circumferential direction takes on a *Sine* or *Cosine* distribution and the radius direction assumes the distribution of the *Bessel function* or its derivative. If the radius of the cylindrical cavity is a and cavity length is l , the resonant frequency of TE_{mnp} and TM_{mnp} in the cavity is respectively:

$$TE_{mnp}: f_{mnp} = \frac{ck_{mnp}}{2\pi\sqrt{\mu_r\epsilon_r}} = \frac{c}{2\pi\sqrt{\mu_r\epsilon_r}} \sqrt{\left(\frac{u_{mn}'}{a}\right)^2 + \left(\frac{p\pi}{l}\right)^2} \quad (1)$$

$$TM_{mnp}: f_{mnp} = \frac{ck_{mnp}}{2\pi\sqrt{\mu_r\epsilon_r}} = \frac{c}{2\pi\sqrt{\mu_r\epsilon_r}} \sqrt{\left(\frac{u_{mn}}{a}\right)^2 + \left(\frac{p\pi}{l}\right)^2} \quad (2)$$

where u_{mn} and u_{mn}' are the root values of n th of the m th-order primal *Bessel function* and its derivative,

respectively. And p is an integer multiple of a half wavelength in the direction of the cavity length. When the frequency and the size of the cavity are given, there are many combinations of m , n and p satisfying the formulas of (1) and (2). Because the mode of TE_{mnp} and TM_{mnp} may differ depending on the value of m , n and p , there are many kinds of resonant modes in the cavity. The more modes the cavity generate, the more it is likely to provide mode-complementation. Therefore, it is likely to improve the uniformity of field distribution in cavity, so as to improve the efficiency of microwave heating.

The theory of quasi-optical cavity

By the theory of microwave optics, microwave and light-wave both belong to the electromagnetic waves and comply with the Maxwell's equations. Although microwave wavelength is a few orders of magnitude larger than the wavelength of light-wave, it can be used to analyze and design various microwave devices with more mature optical methods. Reflector introduced in Ref. [21] can be used to focus the microwave energy. A quasi-optical resonator is an open resonator, which is evolved from the optical cavity and its working frequency is in the microwave frequency band [22, 23]. In addition, it is believed that all metal waveguides can be considered as an ideal conductor in the microwave band. If the electromagnetic wave is radiated to the surface of the metal conductor, its penetration depth is zero, which means that the reflectivity is one hundred percent.

By the theory of optical resonator, two spherical mirrors placed coaxially, with the same curvature radius, would form a symmetrical concave cavity. The distance between the two mirrors is cavity length L and the radius of curvature of the two spherical mirrors is R_1 and R_2 , respectively. For a quasi-optical resonator, when the microwave reflects back and forth between the two concave mirrors consisting of two metal conductors, it should guarantee that the microwave do not leave the resonant cavity, so as to constitute a stable resonance during the process. By the matrix representation [24] similar to the rays propagating in the cavity, the stability conditions of the resonator is:

$$0 \leq (1 - L/R_1)(1 - L/R_2) \leq 1 \quad (3)$$

When the geometrical parameters of the resonator meet eq. (3), the stable resonance can be established in the cavity, and the electromagnetic wave in the two mirrors can form a standing wave without escaping from the outside.

The theory of matching performance

It is possible to define matching performance of microwave heating system by the means of reflection coefficient S_{11} , which represents the relationship between incident wave and reflected wave and only one feeding port is considered here. We can judge the matching performance from the reflection coefficient, because the lower reflection coefficient, the higher utilization efficiency. As a result, the reflection coefficient is an important criterion when we design and optimize the cavity.

Microwave heating is selective volumetric heating making full use of dielectric properties of materials in a microwave fields. Complex dielectric permittivity mainly describes the behavior of material in a microwave field for non-magnetic material:

$$\varepsilon = \varepsilon'(T) - j\varepsilon''(T) \quad (4)$$

where the real component ε' is the dielectric constant of the material, which can be used as a criterion for assessing the ability of material to absorb and store the microwave. The imaginary component ε'' is the dielectric loss factor of the material, which describe the ability to make the absorbed microwave energy convert into thermal energy. T is temperature that affects the temperature-dependent complex dielectric permittivity of material. And both components of complex dielectric permittivity vary with the change of temperature and thus significantly affect the microwave heating process.

Microwave is easily be penetrated into almost all materials. When the microwave energy is propagating inside a material, the distance over which the energy of the electromagnetic wave is reduced by $1/e$, is defined as the penetration depth (D) and is given by the following equation:

$$D = \frac{\lambda_0}{2\pi} [2\varepsilon'((1 + \tan^2\delta)^{1/2} - 1)]^{-1/2} \quad (5)$$

where λ_0 is the wavelength of incident wave (122.4 mm at 2.45 GHz), $\tan \delta$ is the dielectric loss tangent of materials:

$$\tan \delta = \frac{\varepsilon''}{\varepsilon'} \quad (6)$$

It is another commonly used term for expressing the dielectric response between the material and the microwave energy.

Results and discussion

The matching performance of microwave heating system is sensitive to some variations in the geometrical and

material parameters that are relevant to the efficiency of microwave heating. It is very important and difficult to reduce energy reflection of microwave source and improve the energy absorption of material during the optimizing analysis of performance matching. The simulation software we used here is ANSYS High Frequency Structure Simulator (HFSS). In this section, a series of geometrical and material parameters are investigated based on the analysis of the reflection coefficient with the aim of improving the matching performance of microwave heating system and thereby raising the efficiency of microwave heating.

The optimum design of the cylindrical multimode cavity

The cavity of microwave heating is a multimode resonant cavity. Because of the restriction of structure of cylindrical cavity, there is some obvious hot, which can result in inhomogeneous heating. Even worse, inhomogeneous heating could produce burned zones in materials, whereas in other zones minimum temperature required for processing is not reached. With the aim of improving the uniformity of microwave heating and the efficiency of microwave heating, the structure of the cylindrical cavity is changed with the upper and lower cavity wall protruded a little based on the principle of quasi-optical resonator to improve the number of modes. The novel quasi-optical microwave multimode cavity designed above is shown in Figure 1. The radius of curvature of the two spherical mirrors is equal to each other as R , and the relationship

Figure 1: The model of the novel quasi-optical microwave multimode cavity.

between the cavity length L and the radius of curvature R meets the following condition:

$$0 \leq \frac{L}{R} \leq 2 \quad (7)$$

It is obvious that it satisfies the condition of a stable resonator, so the novel quasi-optical microwave multimode cavity is a stable resonator and the electromagnetic wave in the two mirrors can form a standing wave without escaping from the outside.

Because of the complexity of the novel quasi-optical microwave multimode cavity compared with cylindrical cavity, it is difficult to obtain the exact analytical solution of the electromagnetic field. Considering that the cavity wall of cylindrical cavity is protruded a little and the additional losses of the inner wall are small, the characteristics of the two cavities can be compared to a certain extent. Therefore, the distribution of the modes for the iso-volume cylindrical cavity compared with novel multimode cavity is discussed. In order to select the optimum cavity dimensions, the relationship between the size of the cavity and the number of modes is analyzed.

Based on the cavity size of the cylindrical microwave chemical reaction device in a lab scale ($l = 0.362$ m, $\alpha = 0.1335$ m), the number of resonant modes in the cylindrical cavity with different dimensions is calculated programmatically via eqs (1) and (2), and the results are shown in Table 1. According to the analysis and comparison, several factors, such as the uniformity of the field, the cavity volume, energy density and the loss on the inner wall of the cavity, are taken into account. The optimal cavity dimension ratio is selected with $L/R = 0.8$ and there are 10 resonant modes in the cavity.

Table 1: The resonant modes of iso-volume cylindrical cavity at different dimensions.

L/R Mode	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
TE_{mnp}	3	5	6	6	7	7	6	6
TM_{mnp}	3	3	3	3	3	3	2	3
Total	6	8	9	9	10	10	8	9

The diagram of the multi-mode cavity after optimization is depicted in Figure 2. It consists of a resonant cavity, a feeding port of microwave source and a load to be heated inside of the cavity. The feeding port of microwave source at 2.45 GHz is a rectangular waveguide with the width of 86.4 mm and the height of 43.2 mm. The heating specimen used in this study is titanium concentrate with the basic dimension $0.09 \times 0.06 \times 0.01$ m³ and the thickness of

Figure 2: The diagram of the multi-mode cavity after optimization with specimen load.

titanium concentrate is the geometrical parameters of material ranging from 0.01 m to 0.1 m.

The mutual coupling of location

In this part, the mutual coupling of location has been studied at 2.45 GHz, as shown in Figures 3 and 4. Figure 3 shows the mutual coupling relations between the position of material along Z axis and the position of microwave source along Z axis. Figure 4 shows the mutual coupling relations between the position of material along X axis and along Y axis. The coupling performance is measured by the values of reflection coefficient at the waveguide feeding port. As shown in Figures 3 and 4, it is possible to conclude

Figure 3: The mutual coupling between the position of material along Z axis and the position of microwave source along Z axis at 2.45 GHz.

Note: $X(m)$: load position along Z axis (m); $Y(m)$: position of feeding port along Z axis (m); Z : Reflection coefficient (Normalization).

Figure 4: The mutual coupling between the position of material along X axis and along Y axis at 2.45 GHz.
Note: X(m): the position of load along Z axis (m); Y(m): the position of load along Y axis (m); Z: Reflection coefficient (Normalization).

that there is at least one coupling position within the microwave heating system at which the reflection coefficient is minimum and therefore the energy efficiency is maximum, although the material to be dried or heated is allowed to be placed to anywhere of the cavity. Indeed, the minimum reflection coefficient at the optimal coupling position is 0.1245 from Figure 3 and 0.019 from Figure 4. It can also be observed that, the mutual coupling of location have a great influence on the values of reflection coefficient. This implies that an important increment of the efficiency can be achieved by adequately adjusting mutual position relationship.

The mutual coupling of dielectric properties and geometrical parameters of material

For non-magnetic material, dielectric properties of material are one of the non-linear characteristic parameters changing with temperature and it has a complex interaction with microwave heating system. The complex dielectric permittivity of the titanium varying with temperature ranging from 20 °C to 100 °C was calculated based on experiment at 2.45 GHz, as shown in Figure 5. Obviously, at room temperature, the dielectric constant of the titanium is 6.2327 and the dielectric loss factor is 0.7853, which belongs to a strong absorbing material. Both components of complex dielectric permittivity of titanium concentrate are growing relatively slowly from 20 °C to 80 °C, but growing rapidly from 80 °C to 100 °C.

Figure 5: Variation of complex dielectric permittivity of titanium concentrate with temperature at 2.45 GHz.

The complex dielectric permittivity of titanium increase with the increase of temperature in general, so the ability to convert microwave energy into thermal energy also increases with the increase of temperature.

The calculated results of reflection coefficient versus the thickness of titanium concentrate with increasing temperature (from 20 °C to 100 °C) at 2.45 GHz are shown in Figure 6. As shown in Figure 6, the distribution of the reflection coefficient at the waveguide feeding port is fluctuating with different thickness and different temperature with the increase of the thickness of titanium

Figure 6: Temperature dependence of reflection coefficient of titanium concentrate as the thickness varies from 0.01 m to 0.1 m: 20 °C, 40 °C, 60 °C, 80 °C, 100 °C.

concentrate. Despite the quantitative mismatch, there is the similar fluctuating behavior. Moreover, a fluctuating pattern of peaks and dips emerges in these graphs and there are three microwave absorption peaks in the reflection coefficient patterns and it was observed that there is some matching thickness for matching temperature at which microwave absorption is optimized.

In addition, the temperature of the material has almost no impact on the efficiency of microwave heating as the temperature varies from 20 °C to 80 °C with the thickness less than 0.03 m. When the thickness of titanium concentrate is more than 0.03 m, the minimum of the reflection coefficient become to change with the changing of temperature. For instance, the thickness of 0.075 m with the temperature at 20 °C exhibits the maximum microwave absorption (reflection coefficient = 0.0939). Besides, the minimum of the reflection coefficient is increasing with the increase of temperature. This may be explained by the fact that with the increase of temperature, the complex dielectric permittivity of titanium concentrate is increasing constantly, therefore the penetrating depth is decreased to some extent and the microwave absorbing properties are weakened.

The mutual coupling of microwave frequencies and geometrical parameters of material

Figure 7 shows the computed behavior of reflection coefficient between 2.4 GHz and 2.5 GHz with some

Figure 7: The mutual coupling between the frequencies and the thickness of titanium concentrate.

optimized thickness given by Figure 6, which represents the mutual coupling of the frequencies of microwave source and geometrical parameters of material, mainly analyzing the thickness of titanium concentrate. Due to the irregular fluctuations and complex interdependent interactions, it would be difficult to analyze the coupling relationship between the frequencies of microwave source and geometrical parameters of material. It is also demonstrated that the reflection coefficient sensitively depends on the thickness of material. Despite the quantitative mismatch, the similar fluctuating behavior is observed in the vicinity of 0.075 m. It is obvious in Figure 7 that the thickness of titanium concentrate at 0.08 m can achieve the maximum of microwave absorption.

Therefore, it can be concluded that the thickness of titanium concentrate at about 0.075 m is superior to others. Moreover, it is possible to optimize the thickness of the material to the matching performance and thereby to improve the efficiency of microwave heating.

Conclusions

The matching performance of microwave heating system is of particular concern because it provides an important index of the utilization efficiency of microwave energy, which is extremely sensitive to some parametric variations that are relevant to the microwave absorption abilities. In this work, a new microwave heating system is designed by the theory of optical resonator in first. Then the interactions of some high sensitive geometrical and material parameters have been thoroughly investigated to optimize the coupling performance of new microwave heating system. It is demonstrated that the thickness of materials dramatically influences microwave energy absorption efficiency. As a result, it should be carefully considered and perhaps given priority. Moreover, the relationship between reflection coefficient and material thickness was investigated with the temperature variation. It is found that the thickness of titanium concentrate at about 0.075 m is superior to others.

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