A New Microwave Heating Method Via the Combination of Rotation and Boundary Movement

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Abstract: The local overheating may occur in microwave heating process, which results in poor heating uniformity. In order to improve the heating performance, in this paper, the boundary movement with periodical movement is added to the traditional rotating turntable model. The continuous algorithm based on moving mesh is adopted to simulate the heating process, and the results of calculation show that the proposed method can not only maintain the uniformity of the traditional rotating turntable method but also increase nearly 30% of the average temperature of the heated object.

1. Introduction
With the rapid development of modern technology, microwaves, as a new highly efficient and clean energy, have been widely used in industrial production, daily life and other fields, such as food engineering, chemical engineering and medical production. The convenience of microwave heating is mainly attributed to the advantages of volume heating and selective heating. It replaces the traditional method of obtaining temperature rise via heat conduction of dielectric material, saving the time for heat conduction and reducing energy consumption.

However, there are still some natural drawbacks that limit the further application of microwave ovens and inhomogeneous heating is the most common one. In order to improve the microwave heating property and to ensure the operation safely and effectively, scholars have put forward many methods to improve the uniformity of microwave heating. Some scholars have improved the uniformity of microwave heating by changing the frequency and phase of the input microwave, optimizing the position of the heated material in the cavity, or setting a rotary plate in the microwave oven [1-5]. Some other scholars improved the uniformity of microwave heating by adding mode stirrer into the cavity, designing the sliding short road surface of moving waveguide [6-8]. In 2018, YE Jing-Hua et al. [9] studied the influence of metal boundary movement on the heating of microwave multimode cavity. It has shown that the heating uniformity of microwave multimode cavity with metal movement is improved by 18% ~ 38% compared with that of fixed size multimode cavity. Huacheng Zhu et al. [10] studied a rotary radiation structure for microwave heating uniformity improvement, and compared with the other two heating methods (heating with turntable and direct static materials heating), it showed that the proposed method had a better heating uniformity or it observed better within different layers of the processing materials. Although the methods mentioned above have a good effect on improving uniformity, it is difficult to obtain a higher temperature rise rate at the same time.

In order to obtain better heating efficiency and uniformity, in this paper, the method of combination of rotation and boundary movement is put forward, since both the rotating turntable and metal boundary...
movement may affect the modes of electric field in the cavity. The numerical results show that the microwave heating system combined rotation and boundary movement can not only improve the uniformity of heating, but also greatly improve the rate of temperature rise at the same time and the average temperature increases by about 30%. In section 2, the theoretical model of combined microwave heating technology based on turntable rotation and boundary movement is analyzed. In section 3, the feasibility of the theoretical model is verified by simulation experiment.

2. THEORETICAL MODEL OF ROTATION AND MOVEMENT METHOD

2.1. Schematic of the microwave heating system

The multimode microwave heating system designed is shown in Fig.1, which consists of a rectangular metallic cavity connected to microwave source via a rectangular waveguide operating in the TE$_{10}$ mode. The dimensions of the cavity and rectangular waveguide are respectively denoted as $l_x \times l_y \times l_z$ and $a \times b \times c$. Besides, the length $l_x$ has a shift range of $\pm 1\text{cm}$, which means the $yz$ plane is moveable and it can move back and forth with a speed of 0.5cm/s within a range of 2 cm. At the center of the bottom and on the rotating turntable, there is a cylindrical object, whose radius, height and volume are respectively $r$, $h$ and $V_d$. Inside the cavity, the permittivity can be shown as

$$\varepsilon(r) = \begin{cases} \varepsilon_\epsilon(r) - \sigma(r), & r \in V_d \\ \varepsilon_\epsilon, & r \not\in V_d \end{cases}$$

(1)

where $\varepsilon_\epsilon(r)$ is relative permittivity of dielectric object, $\varepsilon_\epsilon$ is permittivity of free space, and $\sigma(r)$ is conductivity.

![Fig.1. Schematic of microwave heating.](image)

2.2. Theoretical Basis of the Proposed Heating Method

It has already been well accepted that microwave heating can be much more uniform by using rotating turntable, the theoretical basis of the influence of moving metal boundary can be derived in the following. The electric field inside the cavity is determined by the Maxwell’s equations\cite{11}

$$\nabla \times \mathbf{E}(r) = -j\omega \mu_0 \mathbf{H}(r)$$

$$\nabla \times \mathbf{H}(r) = j\omega \varepsilon_\epsilon \mathbf{E}(r) + \mathbf{J}_e$$

$$\mathbf{D} = \varepsilon \mathbf{E}(r)$$

(2)

where, $\mu_0$ is permeability of free space. $\mathbf{E}(r)$ is the total electric field inside the cavity. Since the total electric field can be represented by the excitation of two different excitation sources, including the impressed field on the external surface $\mathbf{E}^{im}(r)$ and the polarization electric field inside the heated object,
the volume integral equation is applied and after some steps of derivation, the following equation can be obtained\cite{12}

\[
E(r) = E_{\text{inc}}(r) + j\omega\mu_0 \int_{\Omega} \overline{G_e(r,r')} \cdot J \, dr'
\]  

(3)

where, \( \overline{G_e(r,r')} \) is dyadic Green’s function of the empty cavity \cite{13}, \( r \) and \( r' \) represent the source point and field point, respectively. \( J \) is the polarization volume current density which can be expressed as follows \cite{13}

\[
J = \{ \sigma - j\omega\varepsilon_0 \left[ \varepsilon_r(r) - 1 \right] \} E(r)
\]

(4)

Upon submitting (3) and taking the singularity into consideration when the field points coincide with the source points, equation (2) becomes\cite{14}

\[
E_{\text{inc}}(r) = \int_{\Omega} \left[ 1 + \frac{\eta(r)}{3j\omega\mu_0} \right] E(r) - j\omega\mu_0 PV \int_{\Omega} \overline{G_e(r,r')} \eta(r) E(r') \, dr'
\]

(5)

where \( \eta(r) = \sigma(r) - j\omega\varepsilon_0 \left[ \varepsilon_r(r) - 1 \right] \), \( PV \) is the Principal Value of the integral\cite{15}. \( \eta(r) \) can be assumed to be a constant in each sub element and denoted as \( \eta_{V_n}(r) \) by the moment method (MOM). Hence, the equation in each sub element can be given by

\[
E_{\text{inc}}^{V_n}(r) = \left[ 1 + \frac{\eta_{V_n}(r)}{3j\omega\mu_0} \right] E_{\text{im}}^{V_n}(r) - j\omega\mu_0 PV \int_{V_n} \overline{G_e(r,r')} E(r') \, dr'
\]

(6)

where \( V_n \) denotes the volume of sub element, \( E_{\text{im}}^{V_n}(r) \) and \( E_{\text{inc}}^{V_n}(r) \) denote the impressed field and the total field of each sub element, respectively. For the sake of simplicity, we have omitted the subscript \( V_n \) in the following analysis. In this equation, \( E_{\text{inc}}^{V_n}(r) \) is known quantity, and the unknown total electric field \( E(r) \) appears both inside and outside the integral operator. Hence, equation (5) belongs to Fredholm equation of the second kind\cite{16}. Its integral operator form can be expressed as the following equation

\[
(L - \tau I)E(r) = \frac{E_{\text{inc}}^{V_n}(r)}{2\pi^2 \mu_0 \left[ \varepsilon_r(r) - 1 \right]} 
\]

(7)

where the integral operator \( \tau \), \( \sigma \rightarrow 0 \) is the identity operator, and when the \( \sigma \rightarrow 0 \), the coefficient can be represented by\cite{17}

\[
\tau = \frac{1}{4\pi^2 r^2 \mu_0 \left[ \varepsilon_r(r) - 1 \right]} - \frac{1}{12\pi^2 r^4 \mu_0 \varepsilon_0}
\]

(8)

It’s well-known that the characteristic of equation (7) varies with \( \tau \), especially, this equation will be so ill-posed that finally becomes a Fredholm equation of the first kind when \( \tau \ll 1 \). In such a case, equation (7) will become

\[
LE(r) = -\frac{E_{\text{inc}}^{V_n}(r)}{4\pi^2 r^2 \mu_0 \left[ \varepsilon_r(r) - 1 \right]}
\]

(9)

To solve \( E(r) \) is an inverse problem and also a typical ill-posed problem, and equation (9) shows that small change in the geometric parameters of cavity will result in dramatic changes in \( E(r) \) due to the close relationship between the geometry and microwave frequency of the heating system. Hence, better heating property might be obtained by the combination of rotation turntable and boundary movement.

2.3. Multi-physics calculation

The process of microwave heating involves multiple physics, electromagnetic in the cavity and heated samples, as well as mass and heat transport.
2.3.1. Governing equation
For the multi-physics calculation of microwave heating, the electromagnetics and fluid heat transfer are coupled. The basic equations describing the electromagnetic field distribution inside the microwave cavity is the Maxwell equation shown in equation (2). Then, the power dissipation can be determined after the electric field is solved,

\[ P_d = \frac{1}{2} \varepsilon_0 \omega \varepsilon''(\omega) |\mathbf{E}|^2 \]  

and finally, the temperature distribution is given by the Fourier’s law:

\[ \rho_m C_m \frac{\partial T(x, y, z, t)}{\partial t} = k \nabla^2 T(x, y, z, t) + P_d \]  

where \( \rho_m \) is the density of the dielectric, \( C_m \) is the specific heat capacity, \( k \) is the thermal conductivity, \( T \) is the real-time temperature.

2.3.2. Boundary conditions and initial values
The boundary conditions include electromagnetic boundary condition and heat transfer boundary condition. The walls are assumed to be perfect electrical conductors such that at the air-wall interface inside the oven cavity, the tangential component of electric field is as follows:

\[ E_{\text{tangential}} = 0 \]  

In this model, the cylinder object exchanges heat with air by convection, expressed as:

\[ -k_n \frac{\partial T}{\partial n} = h \cdot (T_{\text{air}} - T) \]  

where \( k_n \) is the thermal conductivity perpendicular to the interface, \( \frac{\partial T}{\partial n} \) is the gradient of the temperature perpendicular to the temperature field interface, \( h \) is the convection heat transfer coefficient over a surface and assumed as 10 W/(m²K), \( T_{\text{air}} \) is the temperature of the air inside the cavity and assumed as 293.15 K.

2.3.3. Calculation method
In order to simulate the heating process, the continuous algorithm based on moving mesh is adopted. In the business software COMSOL Multiphysics (5.3 a, COMSOL Inc. In Stockholm, Sweden), there are two main coordinate systems described by the space frame and the material frame. The space frame is usually a fixed Euclidean coordinate system, and its space coordinate table is (x, y). The material frame is a coordinate system that follows the actual changing state of the material, and its coordinates can be expressed as (X, Y). When the moving grid is not used in the model, the spatial frame and the material frame overlap, as shown in Fig.2 (a). When the mesh deformation is defined in the model, the spatial frame and material frame are no longer coincident, as shown in Fig. 2 (b).
At the same time, the grid's coordinates in the material frame remain the same, but its coordinates in
the space frame have changed. The chassis rotates in the XY plane \((\nu r=0.1\text{ hz})\), and its motion equation is
\[
\Delta x = X\cos(2\pi t) - Y\sin(2\pi t) - X
\]
\[
\Delta y = Y\cos(2\pi t) + X\sin(2\pi t) - Y
\]
(14)

The air-wall interface moves back and forth in the XY plane, and its motion function \(w v 1\) is the
triangle wave function of COMSOL Multiphysics. The period of the motion function is set as 0.5s, and
its angular frequency is set as \(\pi/4\). Therefore, the motion equation is as follows:

\[ S = -w v 1(t[1/s]) \]
(15)

3. Result and analysis

The simulation is all conducted in COMSOL Multiphysics software. The model size and the related
parameters of material are shown in Table 1. The model simulation time was set at 10s with a step size
of 0.1s.

Through the controls of turntable rotation and air-wall interface movement, four microwave heating
modes, namely RM (combination of rotation and boundary movement), OR (rotation only),
OM(boundary movement only), and NRM (heating directly), can be realized.

Table 1. The parameters of model size and material.

| Name expression | Name expression |
|-----------------|-----------------|
| \( w o \)       | \( d o \)       |
| \( 267\text{mm} \) | \( 270\text{mm} \) |
| \( h o \)       | \( h g \)       |
| \( 188\text{mm} \) | \( 18\text{mm} \) |
| \( w g \)       | \( d g \)       |
| \( 50\text{mm} \) | \( 78\text{mm} \) |
| \( h p \)       | \( r p \)       |
| \( 35\text{mm} \) | \( 25\text{mm} \) |
| \( b p \)       | \( c p \)       |
| \( 15\text{mm} \) | \( 4180\text{J/(kg·K)} \) |
| \( K \)         | \( \rho \)      |
| \( 0.55\text{W/(m·K)} \) | \( 1000\text{kg/m}^3 \) |
| \( \epsilon \)  | \( \sigma \)    |
| \( \text{er-j*em} \) | \( 0 \) |

Note: \( \epsilon r=5.5+(\epsilon s-5.5)/(1+(2\pi f t o a o)^2);\ e m=2\pi f t o a o * (\epsilon s-5.5)/(1+(2\pi f t o a o)^2);\ t a o=t 0* \exp(w a/k/T); wa=2.96*10^{-20};t 0=6.27*10^{-15};k=1.3806*10^{-23} \)

3.1. The comparison of central section temperature

The temperature of the central section of the material under the four modes is shown in Fig. 3. Through
comparative analysis, it can be found that the heating uniformity of RM and OR modes is significantly
superior to that of OM and NRM modes. By comparing RM with OR alone, it can be found that the
central hot spot of RM is significantly smaller than OR, and the maximum temperature of RM can reach
more than 300.15K.
3.2. The comparison of uniformity

By comparing the uniformity of heating materials under four modes, the average temperature of materials at each moment can be calculated. The mean-square deviation at each moment can be calculated by the coefficient of variation (COV).

\[
\text{COV} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (T_i - T_m)^2}
\]

where \(T_i\) is the temperature of point \(i\), \(T_m\) is the mean temperature, \(T_0\) is the initial temperature.

![Fig. 3. The temperature diagram of Central section.](image)

![Fig. 4. The curve of the COV mean-square error formula.](image)

The COV mean-square error formula is shown in Fig. 4. It can be seen from the curve analysis that the COV of RM and OR are significantly closer to zero than those of OM and NRM. Therefore, it is further verified that the heating uniformity of RM and OR are significantly superior to that of OM and NRM mode. By comparing the COV of RM and OR alone, it can be found that the COV of RM is slightly larger than the COV of OR, but the overall data changes little and has a consistent change trend. Therefore, compared with OR, RM does not improve the uniformity of heating and remains roughly unchanged.
3.3. The comparison of average body temperature rise

![Graph of average body temperature rise](image)

The average body temperature change curve of the material under the four modes is shown in Fig. 5. It can be obtained from the curve analysis that the volume average temperature of OM increased the most. However, according to the above conclusion, the heating uniformity of RM and OR are significantly superior to that of OM and NRM. Therefore, the changes of volume average temperature rise in RM and OR are compared separately. The analysis of results shows that the temperature rise slope of RM is significantly larger than that of OR. According to the data in the Fig. 4, it can be calculated that the temperature increase of RM is 32.07% higher than that of OR in 10 seconds.

To sum up, on the premise of maintaining the uniformity of OR (rotation only), RM (combination of rotation and boundary movement) can substantially improve the temperature rise and effectively improve the heating efficiency and energy utilization rate.

4. Conclusion

Based on the analysis of the electric field characteristics of the microwave heating system, this paper puts forward the microwave heating method combining rotation and boundary movement, and it simulates the microwave heating process of combining rotation and boundary movement with the finite element analysis software COMSOL Multiphysics. Compared with other heating modes, the results show that the microwave heating method combining rotation and boundary movement can improve both the heating efficiency and energy utilization rate more rapidly. In addition, the model will be further verified through experiments, and the control of rotation and boundary movement will be optimized to further improve the microwave heating efficiency.

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References

[1] Bows J R. Variable frequency microwave heating of food [J]. J Microw Power E E, 1999, 34: 227.
[2] Bows J R, Patrick M L, Janes R, et al. Microwave phase control heating [J]. Int J Food Sci Technol, 1999, 34: 295.
[3] Pedreño-Molina J L, Monzó-Cabrera J, Catalá-Civera J M. Sample movement optimization for uniform heating in microwave heating ovens [J]. International Journal of RF and Microwave Computer-Aided Engineering, 2007, 17: 142.
[4] Geedipalli S S R, Rakesh V, Datta A K. Modeling the heating uniformity contributed by a rotating turntable in microwave ovens [J]. J Food Eng, 2007, 82: 359.
[5] Liao y, Lan J, Zhang C, et al. A phase-shifting method for improving the heating uniformity of microwave processing materials [J]. Mater, 2016, 9: 309.
[6] Sebera V, Nasswettrová A, Nikl K. Finite element analysis of mode stirrer impact on electric field uniformity in a microwave applicator [J]. Dry Technol, 2012, 30: 1388.

[7] Plaza-González P, Monzó-Cabrera J, Catalá-Civera J M, et al. Effect of mode-stirrer configurations on dielectric heating performance in multimode microwave applicators [J]. IEEE Trans Microw Theory, 2005, 53: 1699.

[8] Yinhong Liao, Zhiyan Wu, Xiaoping Feng. Characteristics of heating process in microwave applicators with elements in periodic motion [J]. International Journal of RF and Microwave Computer-Aided Engineering, 2018, 21641.

[9] YE Jing-Hua, YU Yu-Tian, Hong Tao, et al. Study on the influence of metal boundary movement on the heating of microwave multimode cavity [J]. Journal of Sichuan University (Natural Science Edition), 2018, 55: 82.

[10] Huacheng Zhu, Jianbo He, Tao Hong et al. A rotary radiation structure for microwave heating uniformity improvement [J]. Applied Thermal Engineering, 2018, 648-658.

[11] Jackson J D. Classical electrodynamics [M]. John Wiley & Sons, Inc 1999.

[12] Alessandri F, Chiodetti M, Giugliarelli A, et al. The electric-field integral-equation method for the analysis and design of a class of rectangular cavity filters loaded by dielectric and metallic cylindrical pucks [J]. IEEE Transactions on Microwave Theory and Techniques, 2004, 52(8): 1790-1797.

[13] Balanis C A. Advanced engineering electromagnetics [M]. John Wiley & Sons, 1999.

[14] Tang, Z., Hong, T., Liao, Y., Chen, F., Ye, J., Zhu, H., & Huang, K. Frequency-selected method to improve microwave heating performance [J]. Applied Thermal Engineering, 131 (2018), 642-648.

[15] Chew W C. Some observations on the spatial and eigenfunction representations of dyadic Green's functions (electromagnetic theory) [J]. IEEE transactions on antennas and propagation, 1989, 37(10): 1322-1327.

[16] Press W H, Teukolsky S A, Vetterling W T, et al. Numerical recipes 3rd edition: The art of scientific computing [M]. Cambridge university press, 2007.

[17] Z. Tang, T. Hong, F. Chen, H. Zhu, and K. Huang, Application of integral equation theory to analyze stability of electric field in multimode microwave heating cavity [J], Eur Phys J Appl Phys 80(2017), 10902.

[18] Chang C W, Okawa D, Garcia H, et al. Breakdown of Fourier’s law in nanotube thermal conductors [J]. Physical review letters, 2008, 101(7): 075903.