Analysis of waveguide with special resonant window which can reduce the energy consumption of waste rubber pyrolysis

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Abstract. Microwave pyrolysis is a new technology for waste rubber treatment. In this paper, the microwave energy transfer characteristic working at a frequency of 2.45 GHz in different types of rectangular waveguides are investigated with HFSS simulation software. The results show that although the quartz sealing plate of the rectangular waveguide can prevent the combustible gas generated by waste rubber pyrolysis from entering the microwave generator, it also causes some microwave reflection at the same time, which will reduce the microwave energy transmission efficiency, shorten the service life of the microwave generator. While the resonant window of the rectangular waveguide, that is, a rectangular window with a certain size in the centre of the copper sealing plate, and with a quartz plate embedded in the window, can avoid such microwave reflection, not only enhance the sealing performance, but also improve the waste rubber pyrolysis efficiency and reduce the pyrolysis energy consumption.

1. Introduction
With the extensive use of rubber products, the amount of waste rubber is also increasing at an alarming rate and the “Black pollution” caused by waste rubber is becoming more and more serious. How to treat waste rubber effectively, especially to realize the recycling of waste rubber, has become an important research subject for environmental protection and resource conservation[1,2]. In recent years, microwave pyrolysis as a new approach for waste rubber treatment has attracted widespread attention in the industry, and is considered to be the most effective and sustainable process for waste rubber recycling due to its eco-friendly process and its advantages over the conventional methods such as its strong penetrability, features of rapidly and uniformly cracking, high energy utilization efficiency and so forth. The commonly used microwave frequencies for microwave pyrolysis equipment is 2.45GHz. In the microwave pyrolysis process, the waste rubber is cracked as high-quality oil, combustible gas and carbon black, thereby realizing high-value recycling of waste rubber[3].

In order to prevent the combustible gas from entering the microwave generator through the waveguide, a quartz sealing plate is set in the waveguide when designing the microwave pyrolysis equipment. Quartz is a material with excellent wave transmission performance. However, it has been confirmed that when the microwave is transmitted in the waveguide, there is some of the microwave energy fail to pass through the quartz sealing plate, but be reflected back to the microwave generator, causing the microwave generator to heat up, it not only shortens the service life of microwave generator, but also increases the energy consumption of pyrolysis[4].

HFSS is a full-wave three-dimensional electromagnetic simulation software, by adopting the finite element method, it can calculate the electromagnetic characteristics of various RF/microwave passive components rapidly and accurately, thereby through gaining the S-parameter, propagation constant, and electromagnetic property to optimize the components performance[5]. In this paper, through
establishing reasonable three-dimensional waveguide models and setting reasonable boundary conditions and excitations, then the HFSS software can accurately accomplish the simulation of the electromagnetic field distribution of the waveguide, and the corresponding S parameter value can be obtained, furthermore, based on this, the influence of quartz sealing plate and resonant window on pyrolysis performance can be analysed.

2. The rectangular waveguide with quartz sealing plate

2.1. Theoretical basis

Scattering parameter, or S parameter for short, is a network parameter based on the relationship between incident wave and reflected wave, and it describes the circuit network in terms of the reflected signal from another device port and the transmitted signal from this port to another port. The scattering matrix equation can be expressed as equation (1).

\[
\begin{pmatrix}
b_1 \\
b_2 \\
\vdots \\
b_n
\end{pmatrix} =
\begin{pmatrix}
S_{11} & S_{12} & \cdots & S_{1n} \\
S_{21} & S_{22} & \cdots & S_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
S_{n1} & S_{n2} & \cdots & S_{nn}
\end{pmatrix}
\begin{pmatrix}
a_1 \\
a_2 \\
\vdots \\
a_n
\end{pmatrix}
\]  

(1)

Here, \(a\) and \(b\) are the matrix representation of the normalized incident waves and normalized reflected waves, respectively, and both contain \(n\) normalized incident waves and \(n\) normalized reflected waves; \(S_{ij}\) is the transfer coefficient from port \(j\) to port \(i\) under the circumstances that all other ports are connected to the load.

In figure 1, a two-port transmission network is taken as an example. Assuming that Port 1 and Port 2 are the signal input port and output port, respectively, according to the aforementioned basis, \(S_{11}\) and \(S_{21}\) served as two more important S parameters is obtained compared to other S parameters, where \(S_{11}\) represents the return loss, that is, how much energy is reflected back to the source port (Port 1); \(S_{21}\) represents the insertion loss, that is, how much energy is transmitted to the destination port (Port 2). Therefore, the S parameter can be used to indicate the reflected and transmitted power, and calculate the efficiency of microwave energy transmission, and thus the microwave pyrolysis effect can be analysed according to the efficiency of microwave transmission. Using the terms \(P, P_1\) and \(P_2\) to represent the microwave incident power, the microwave transmission power from port 1 to port 2 and the microwave reflected power, respectively, and expressing S parameter in logarithmic form, then the internal correspondences of which can be illustrated by equation (2) and equation (3).

\[
S_{11} = 10 \log \left( \frac{P_2}{P_1} \right)
\]

(2)

\[
S_{21} = 10 \log \left( \frac{P_1}{P_2} \right)
\]

(3)

According to equation (2) and equation (3), the calculation equations of energy reflection and transmission efficiency were deduced as follows:

\[
\eta_{11} = \left( \frac{P_2}{P} \right) \times 100\% = \frac{S_{11}}{10} \times 100\%
\]

(4)

\[
\eta_{21} = \left( \frac{P_1}{P} \right) \times 100\% = \frac{S_{21}}{10} \times 100\%
\]

(5)

Where \(\eta_{11}\) is energy reflection efficiency and \(\eta_{21}\) is energy transmission efficiency.

2.2. Simulation analysis

The waveguide model BJ22 is determined by the standard rectangular waveguide selection specification[6]. The three-dimensional dimensions of the hollow and rectangular metal waveguide are 109.22mm, 54.61mm, 200mm in length, width and height, and the microwave frequency is 2.45 GHz. Set the side boundary condition of the rectangular waveguide to Perfect E, and set the excitations of
the two end faces of the rectangular waveguide to Wave Ports. The waveguide model with a quartz sealing plate is shown in figure 2. The sealing plate is made of quartz material with a relative dielectric constant of 3.78 and a thickness of 4mm. Its length and width are parallel with the size of the rectangular waveguide section size. In addition, as a control, an empty waveguide model that has the same parameters but without the sealing plate is also analyzed.

Figure 1. The schematic diagram of a two-port transmission network.

The $S$ parameter values obtained by the simulation of the two waveguide models were listed in table 1. Based on the data in the table, the energy reflection efficiency ($\eta_{11}$) and energy transmission efficiency ($\eta_{21}$) can be calculated by equation (4) and equation (5) mentioned before. Finally, the conclusions can be displayed as follows: For the empty waveguide, the energy reflection efficiency is zero, while the transmission efficiency is 100%. In other words, under ideal conductor boundary conditions, microwave energy can be completely transmitted from port 1 to port 2 through the waveguide if there is no quartz sealing plate. For the waveguide with quartz sealing plate, the energy reflection efficiency is about 10.18%, and the energy transmission efficiency is about 89.82%. According to the conclusions and the comparison of the calculations, it can be seen that the quartz sealing plate will cause some of energy reflection in the process of energy transmission, and as the thickness of the quartz seal increases, the reflection will become more serious. As a consequence, the reflection of microwave energy will reduce the energy transmission efficiency and increase the energy consumption of pyrolysis. In addition, if the reflected microwave energy is absorbed by the microwave generator, it’s service life will be shortened in some way.

Table 1. The $S$ parameters of empty waveguide and waveguide with a quartz sealing plate.

| Model                             | Frequency (GHz) | $S_{11}(\text{dB})$ | $S_{21}(\text{dB})$ |
|-----------------------------------|----------------|--------------------|--------------------|
| Empty waveguide                  | 2.45           | -70.569268         | 0                  |
| Waveguide with a quartz sealing plate | 2.45           | -9.922160          | -0.466770          |

3. The rectangular waveguide with a resonant window

3.1. Working principle of the resonant window

Combining the capacitive diaphragm and the inductive diaphragm together will form a rectangular window-shaped diaphragm, and its equivalent circuit is a parallel-resonance circuit called resonant window[7].

The schematic diagram of the resonant window and its equivalent circuit are shown in figure 3.

As is demonstrated in figure 3(a), the resonant window can be regarded as the small waveguide with length $a'$, width $b'$ and height $t'$, while the waveguide with length $a$, width $b$, and height $t$ is considered as the main waveguide. If the characteristic impedance of the small waveguide is equal to the characteristic impedance of the main waveguide, it is equivalent to the state where the inductance and the capacitance of the equivalent circuit are in a state of parallel resonance, and the relation can be illustrated by equation (6).
\[
\frac{b}{a} \cdot \eta_1 \left( 1 - \left( \frac{\lambda_1}{2a} \right)^2 \right)^{\frac{1}{2}} = \frac{b'}{a'} \cdot \eta_2 \left( 1 - \left( \frac{\lambda_2}{2a'} \right)^2 \right)^{\frac{1}{2}}
\]

In the expression above,
\[
\eta_1 = \left( \frac{\mu_1}{\varepsilon_1} \right)^{\frac{1}{2}}, \quad \lambda_1 = \lambda_0 \cdot (\varepsilon_1)^{\frac{1}{2}}; \quad \eta_2 = \left( \frac{\mu_2}{\varepsilon_2} \right)^{\frac{1}{2}}, \quad \lambda_2 = \lambda_0 \cdot (\varepsilon_2)^{\frac{1}{2}}.
\]

Here, \( \mu_1, \varepsilon_1 \) and \( \varepsilon_{r1} \) are the permeability, dielectric coefficient and relative dielectric constant of the packing medium in the main waveguide respectively. \( \mu_2, \varepsilon_2 \) and \( \varepsilon_{r2} \) are the permeability, dielectric coefficient and relative dielectric constant of the packing medium in the small waveguide respectively.

The characteristics of the rectangular waveguide with a resonant window are as follows: (1) when the operating frequency is exactly equal to its resonant frequency, the microwave can pass through the resonant window without reflection; (2) when the operating frequency is not equal to its resonant frequency, microwave radiation reflection occurs due to the inductive or capacitive nature of the resonant window. Therefore, if the rectangular waveguide has a resonant window with appropriate size and its resonant frequency is 2.45GHz, theoretically, the energy transmission efficiency of the waveguide can reach 100% and with no reflection occurs.

3.2. Simulation analysis
The form of the sealing plate is changed from the quartz plate shown in figure 2 to the resonant window shown in figure 4. And the sealing plate is composed of a copper sealing plate and a quartz plate, both have a thickness of 4 mm. Specifically, the length and width of the copper sealing plate are the same as those of the rectangular waveguide, and in the center of the copper sealing plate opened a rectangular window, the quartz plate is embedded exactly in the rectangular window, in fact, it is equivalent to setting a quartz window in the center of the copper sealing plate figure 4 shows the rectangular waveguide model with a resonant window (quartz window).

![Figure 3](image1.png)  ![Figure 4](image2.png)

Figure 3. The schematic diagram of the resonant window and its equivalent circuit.

Figure 4. The rectangular waveguide model with a resonant window.

To obtain the appropriate size of the resonant window, the simulations targeting at different rectangular quartz windows with different lengths and widths were performed. The simulation results indicate that when the length and width of the rectangular quartz window are 55mm and 35mm respectively, the transmission efficiency of the waveguide is the highest. And in this case, the S-parameter curve and the electric field distribution of the waveguide were obtained and they have been provided in figure 5 and figure 6.

It can be seen from figure 5 that the rectangular waveguide with resonant window has higher energy transmission efficiency while the microwave frequency is between 2.4GHz and 2.5GHz. It should be noted that when the microwave working frequency is 2.45GHz, the return loss reached its peak close to zero, that is, the energy transmission efficiency is about 100%, almost the same as the transmission efficiency of the empty waveguide. So, it is reasonable to believe that the arrangement of the resonant window does significantly reduce the generation of reflection and improve the transmission efficiency of the microwave energy provided by the microwave generator working at 2.45GHz frequency. From figure 6, it can be seen that the waveguide electric field distribution is uniform, indicating that the
microwave energy distribution is uniform. Hereby it is easy to draw a conclusion that the resonant window set in the rectangular waveguide solves the microwave energy reflection problem well, improves the transmission efficiency, and reduces the energy consumption. The results of the subsequent experiment are in agree with the results of the analysis conclusions.

Figure 5. The S parameter curve of the resonant window.

Figure 6. The electric field distribution of rectangular waveguide with a resonant window.

4. Conclusions
Aiming at the microwave energy reflection problem caused by the quartz sealing plate set in the waveguide of the microwave pyrolysis equipment, simulation about the microwave transmission behavior in different types of rectangular waveguides is performed through HFSS software in the paper. According to the performance of the simulation, the following conclusions were drawn, and it’s been verified to be correct by experiments:

(1) Although the quartz sealing plate of the rectangular waveguide can prevent the combustible gas from entering the microwave generator, it will also cause microwave energy reflection, accounting for 10.18% of the total microwave energy, which will result in a decrease in microwave energy transmission efficiency, shorten the service life of the microwave generator.

(2) The microwave energy transmission efficiency of the waveguide can be improved while a resonant window is set inside the waveguide. And when the length and width of the resonant window are 55mm and 35mm, respectively, actually, that means the length and width of the embedded quartz window are 55mm and 35mm, respectively, the waveguide can achieve a microwave energy transmission efficiency of about 100%. In consequence, there is reason to believe that the resonant window can not only enhances the sealing performance, but also improves the waste rubber pyrolysis efficiency and reduces the pyrolysis energy consumption.

5. References
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