Development of a highly efficient microwave heating device using an elliptical chamber
- Verification of the effectiveness of automatic impedance matching device -

Hagino FUJITA†

†Department of Electrical Energy Systems Engineering, Kanazawa Institute of Technology 7-1 Ohgigaoka, Nonoichi, Ishikawa 921-8501 Japan

E-mail: †hagino_fujita@neptune.kanazawa-it.ac.jp

Abstract When a monopole antenna is placed at a focal point of an elliptical chamber and microwaves are radiated into the cavity, an object located at the other focal point can be efficiently heated. However, depending on the geometry and electrical properties of the object, the electromagnetic field inside the chamber is inevitably distorted, and reflected waves are generated. In this work, we demonstrate a method for eliminating such reflections in an elliptical microwave cavity by employing an automatic impedance matching device, and we verify its effectiveness.

Keyword Microwave, Elliptic Chamber, Semiconductor Oscillator.

1. Introduction

In general, in radio frequency wave propagation, as shown in Fig.1, when electromagnetic waves emitted from a transmitter (Tx) are received by a receiver (Rx), the phase of the electromagnetic waves, which reaches Rx from Tx via a rotating ellipsoid with the position of Tx and Rx being the focal points becomes equal. The ellipsoid is called the Fresnel zone. Electromagnetic waves propagate along the shortest path between Tx and Rx, and waves that propagate along paths that pass through the ellipsoid, such as those shown in the figure, interfere constructively with the waves propagating along the shortest path when the difference in the path length is a multiple of half wavelength. Ultimately, these waves converge at the Rx location and are received. Electromagnetic waves do not propagate only along the shortest distance but also propagate within the Fresnel zone and they are superimposed at the receiving location, i.e.,

$$d_1 + d_2 = d_0 + \frac{\lambda}{2} \quad (1)$$

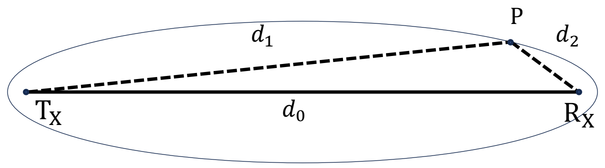


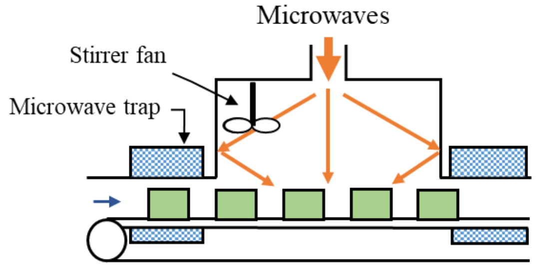
Fig.1 Transmission/Reception of radio frequency waves and the Fresnel zone.

Here, λ is the wavelength of the electromagnetic wave. Equation (1) shows the condition for the first Fresnel zone, where the path length difference is λ/2. If there is an obstruction within the first Fresnel zone, the propagation loss of the electromagnetic wave increases.

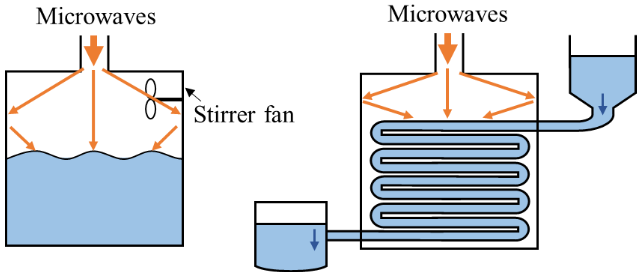
In this paper, we redesigned this Fresnel zone as a heating chamber and present a new microwave heating device [1].

2. Development of a microwave chamber eliminating reflection

2.1. Conventional microwave heating devices



(a) Example of Continuous Conveyor Heating System.



(b) Examples of liquid heating systems.

Fig.2 Example of industrial microwave heating systems.

Microwave heating devices do not require heat transfer by conduction in or through an equipment and are widely used as a non-contact heating method. They are employed in various processes from raw material stages to final products including sterilization, drying, expansion, and baking. In processes requiring continuous heating, such as those illustrated in Fig.2(a), where the heated material is transported via a conveyor while being heated, large-scale shielding devices are necessary to prevent microwave leakage [2].Additionally, methods such as those illustrated in Fig.2(b) have been proposed for heating liquids, but the effectiveness of microwaves was limited. In response to a strong demand from manufacturers stating that “if heating time can be reduced by even one second, heating costs are not an issue,”, large-scale devices equipped with not only microwaves but also steam or hot air convection devices as standard features are currently being sold at prices ranging from several million dollars to several billion dollars.

2.2. Testing equipment for elliptical heating chamber

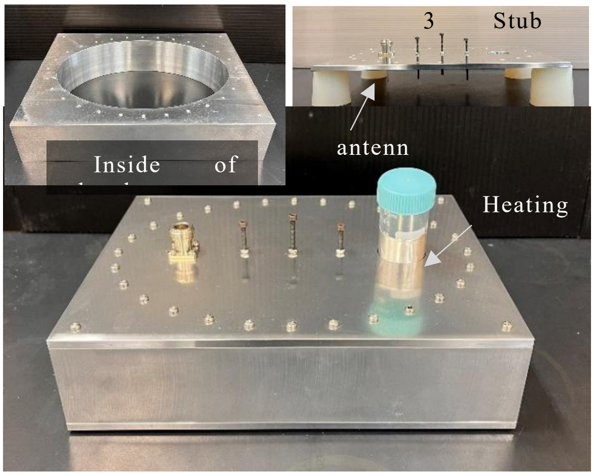


Fig.3 Microwave heating equipment.

Fig.3 shows a prototype of a microwave heating test device. A semiconductor microwave generator was used to superimpose microwaves inside the chamber. This microwave generator unit is manufactured by M-RF Co., LTD., with an output of 250 W. The elliptical chamber consists of three parts: the main body, the upper cover, and the lower cover. The main body is made of 50 mm thick aluminum plates formed into an elliptical shape. The upper and lower covers are made of 5 mm thick aluminum plates fixed to the main body with screws along the elliptical shape. The upper cover features a 30 mm diameter opening for inserting an antenna at one of the ellipse focal points and an opening at the center of the other focal point for inserting the heating target. The heating target is heated as it passes through the chamber, enabling a continuous heating process. Additionally, an impedance matching mechanism is designed to adjust the electromagnetic field within the chamber. This adjustment mechanism consists of three tuners arranged at 1/4 wavelength intervals along the straight line passing the two focal points as shown in Fig.1.

2.3. Electromagnetic field matching within the chamber

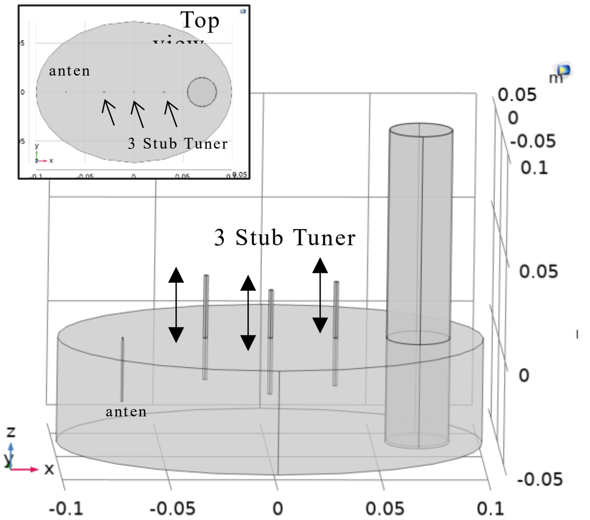


Fig.4 Simulation model for 3 stub tuner positions.

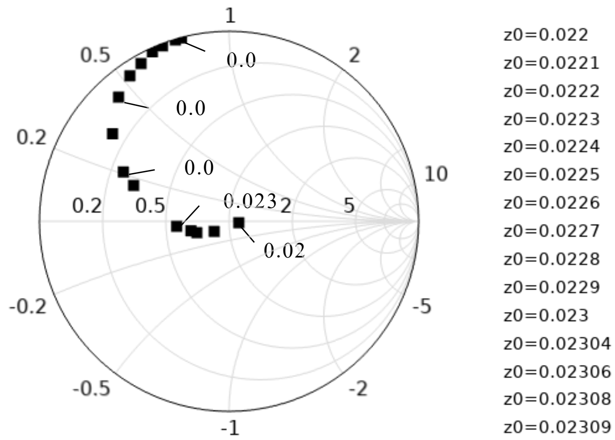


Fig.5 S11 Smith chart for 3 stub tuner positions.

The effects of the adjustment mechanism were simulated in an elliptical chamber. Fig. 4 shows the calculated model of the device. The chamber height was set to 50 mm, and the diameter of the heated object was set to 30 mm. Fig.5 shows a part of the simulation results when the insertion depth of the tuner was varied in the range of 0 to 50 mm, with each step being 0.01 mm. The figure plots one of the S parameters, S11, on the Smith chart. When the depth of the stub closest to the heated object is 0.03 mm and the depth of the central stub is 0.027 mm, the reflection approaches zero as shown in the figure by varying the depth Z0 of the stub closest to the antenna from 0.022 mm to 0.02309 mm. This indicates that there is a stub position where the impedance can be matched, as confirmed by the numerical calculations.

2.4. ELECTRICAL PROPERTIES OF WATER IN MICROWAVE HEATING

Fig.6 shows the relationship between the water temperature and the permittivity[3]. The permittivity is a property unique to each material, and similar to the conductivity, the higher the value, the easier it is to heat. This figure shows that as the water temperature changes from 0°C to 100°C, the permittivity changes from 88 to 56. Fig.7 shows the results of calculating the reflectance when the permittivity is changed using the numerical model in Figure 4. The permittivity at the minimum reflectance in the figure is 79, and from Figure 4, the water temperature at this point is 20 to 25°C. Water is most easily heated at the room temperature (20 to 25°C), but even a temperature change of ±5°C makes heating extremely difficult.

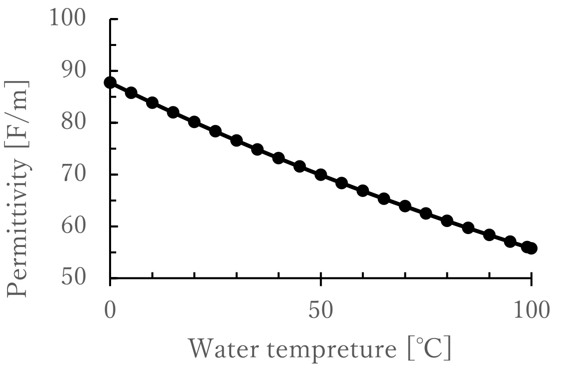


Fig.6 Relationship between water temperature and permittivity.

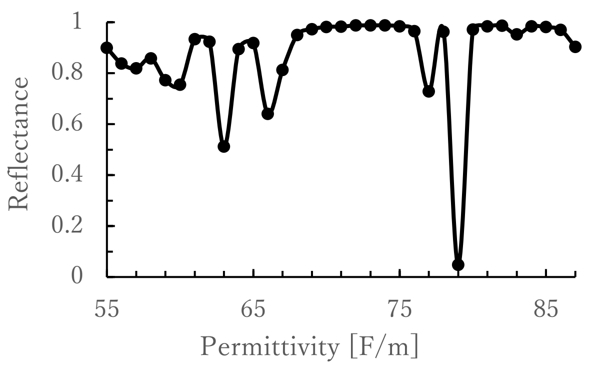
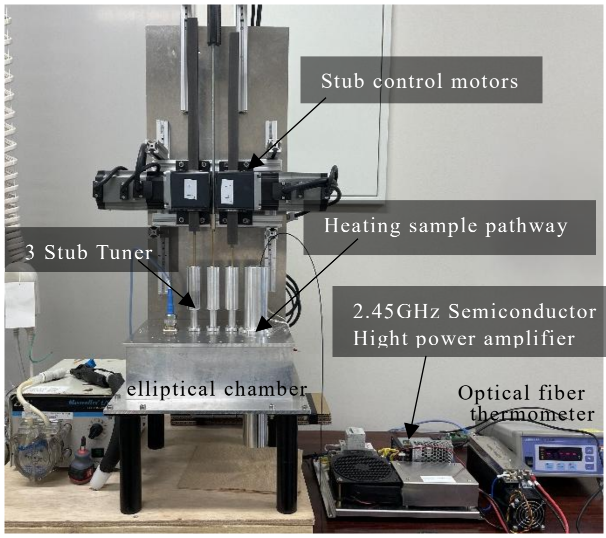


Fig.7 Relationship between permittivity and reflectance of water in microwave heating.

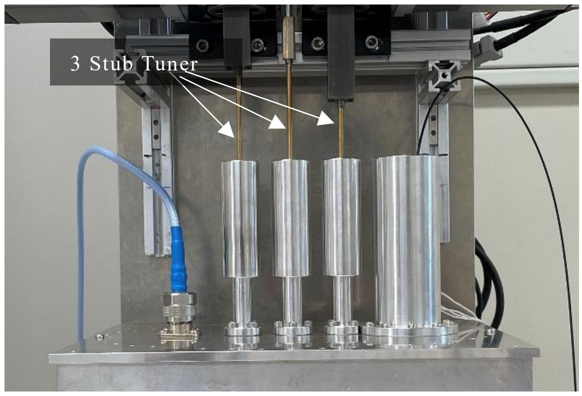
Most industrial microwave devices are used for heating applications involving water. To reach the target temperature quickly, microwave devices alone have poor heating conditions, so devices as in Fig.2 need to use the combination of hot air and steam.

3. PERFORMANCE EVALUATION OF THE DEVICE

3.1. DEVICE WITH AUTOMATIC IMPEDANCE MATCHING



(a) Equipment configuration



(b) Enlarged view of chamber

Fig.8 Microwave heating chamber with auto adjustment mechanism.

In order to continuously match the impedance of the chamber during the heating process, we installed a motor for each of the three stub tuners as shown in Figure 3 and modified the device to enable automatic control. Fig.8 shows the device configuration, and Fig.9 shows the control flowchart. The chimney-like structure installed on the chamber lid is a tunnel to prevent electromagnetic field leakage from the heated object passage and the holes through which the stub tuners pass.

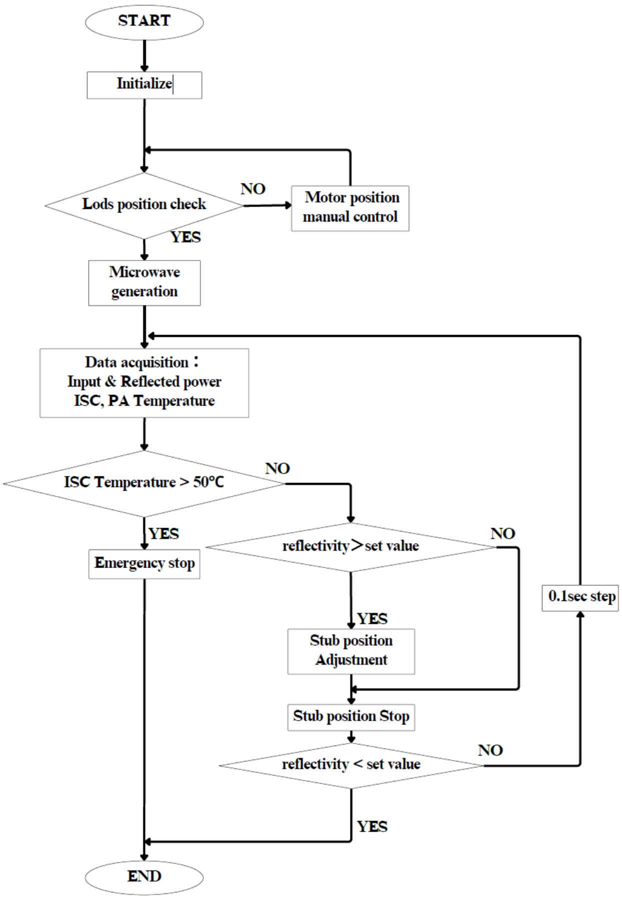


Fig.9 Flowchart of automatic adjustment mechanism.

3.2. Results of water heating

This device is a continuous processing of heated objects. However, to clearly demonstrate the adjustment effect of the stub tuner during the temperature rise of the heated object, batch heating was performed. 45 g of water was placed in a plastic test tube with 30 mm diameter and heated at an output of 100 W. Temperature measurements were performed using FL2000 optical fiber temperature sensor manufactured by Anritsu Co., Ltd. Fig.10 shows the measurement results. Without the stub, as the water temperature increases, the reflected wave grows larger, and the heating rate decreases. On the other hand, when the automatic stub adjustment was performed, the heating rate was faster than without the stub adjustment until around 50 seconds, but from 50 seconds to 70 seconds, the reflectance increased to approximately 50%. At this point, the increase in water temperature was also suppressed. At 75 seconds, when the automatic stub adjustment resumed, the water temperature began to rise again. The final heating efficiency (the ratio of water temperature increases to the input power) was 61.3% without the adjustment and 79.3% with the automatic adjustment.

The increase in reflected waves observed around 50 seconds was attributed to a rapid rise in

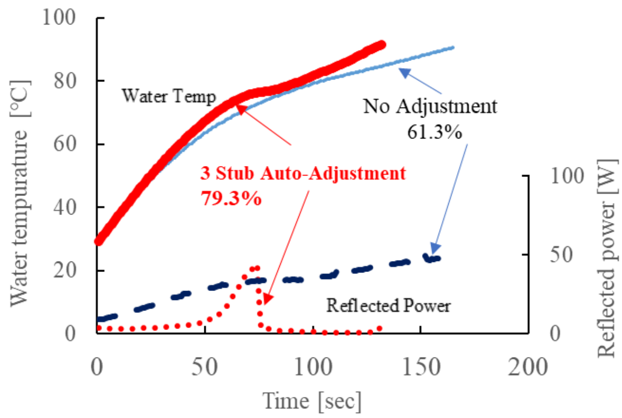


Fig.10 Temperature rise in elliptical chamber with and without automatic adjustment (100 W).

temperature, which exceeded the response capability of the automatic adjustment system. Going forward, we will improve the algorithm to enable continuous adjustment of the stub position to suppress reflected waves.

4. Conclusion

We have demonstrated a method for eliminating reflected waves in the device using the developed automatic impedance matching device and verified its effectiveness. In the future, we expect that the microwave absorption efficiency can be improved to nearly 100% through algorithm optimization.

Furthermore, while the batch-type microwave heating devices are currently the mainstream, this device is a novel design that enables an inline heating by arranging piping to pass through an elliptical focal point. In conventional methods, converting to an inline device required large-scale shielding devices to reduce microwave leakage, but this device has the advantage of being compact since heating is completed within the chamber.

This device can be used in processes involving vacuum and pressure, and is expected to be applied to a wide range of heating plants, such as food processing, promoting reactions in heating materials, and melting.

References

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