Walailak J Sci & Tech 2006; 3(2): 237-250.

Development of a Microwave System for Highly-Efficient Drying of Fish

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ABSTRACT

Dried fish is an important product of Nakhon Si Thammarat province, located in southern Thailand. Fish are conventionally dried using heat from the sun or heat from burning wood as energy sources. These drying methods have problems such as low efficiency and environmental problems. Exploiting the strong electric dipole of the water molecules in the fish, which allows the fish to absorb microwave energy effectively, we have developed a novel microwave heating system for the efficient drying of fish. The system utilizes a high-voltage power supply so that the magnetron can generate a microwave field continuously, and its output power can be adjusted from 0 - 200 W making it very different to commercial microwave oven. The waveguide is designed for effective transmission of microwave fields into the multi-mode heating cavity. The experimental results reveal that heat produced by the microwave system causes evaporation of moisture from the fish making it possible to produce high quality dried fish. The drying process also shows a dependence of fish surface temperature and moisture content on the radiation time and microwave power.

Keywords: Drying technology, electromagnetic waves, microwaves, magnetron, high-voltage, dielectric heating, fish

INTRODUCTION

Nakhon Si Thammarat, a province on the east coast of southern Thailand, produces a lot of dried fish for local consumption and export. The conventional drying process utilizes heat from the sun in the dry season or heat from burning wood during the rainy season as energy sources. Such natural energy sources unfortunately require a long period for drying the fish, and may lead to contamination from dust and pathogens. It follows, that it is very difficult to control the quality of the dried fish products.

Microwave technology developed for RADAR application in the 2nd World War [1], has long been known as an effective energy source for the drying of agricultural products [2]. Microwaves are electromagnetic waves with a frequency ranging from 300 MHz to 300 GHz. Typically, microwaves at 2.45 GHz are used for processing food products because these materials contain a lot of water molecules which can absorb energy from microwave very effectively [3]. However, since the water molecules in food materials are bound by other larger molecules such as proteins, lipids and fibers, the mechanism of microwave energy absorption or microwave heating of fish and other foods, known as dielectric heating, is very complicated. To obtain dried fish with a good taste and attractive color microwave drying conditions, in particular microwave power and circulation of air and moisture in the cavity, have to be controlled carefully.

The aim of this study was to make a prototype microwave drying oven with better control and finer tuning at low levels of microwave power than a conventional microwave oven. Such a system would allow the preparation of dried fish instead of cooked fish. In this paper, we begin by discussing the theoretical background of high frequency microwave propagation before moving onto dielectric heating. The various components of the microwave drying oven are then presented including the high-voltage power supply for the magnetron to generate continuous microwave radiation and controllable output power, and an effective microwave transmission and heating system, composed of a waveguide and multi-mode cavity. We conclude with a presentation of our preliminary results and ideas for future work.

Theory of Microwave Propagation and Dielectric Heating

Microwaves are electromagnetic waves whose propagation characteristics can be described by Maxwell's equations [4].

$$\vec{\nabla} \times \vec{E} = \frac{-\partial \vec{B}}{\partial t} \tag{1}$$

$$\vec{\nabla} \times \frac{\vec{B}}{\mu} = \vec{J} + \frac{\partial (\varepsilon \vec{E})}{\partial t} \tag{2}$$

$$\vec{\nabla} \bullet (\varepsilon \vec{E}) = \rho_f \tag{3}$$

$$\vec{\nabla} \bullet \vec{B} = 0 \tag{4}$$

where $\vec{E}$ and $\vec{B}$ are the electric and magnetic fields, respectively, $\vec{J}$ is the conduction current, ρ_f is the free charge, μ is the magnetic permeability and ε is the electric permittivity of the medium. The interaction of the microwave field with the surrounding medium will depend on its dielectric properties. In a vacuum, $\varepsilon = \varepsilon_0 \approx 8.85 \times 10^{-12}$ F/m is a constant, and the microwaves will propagate with a velocity of $c \approx 3 \times 10^8$ m/s and no interaction and energy absorption will occur. However, when microwaves propagate into dielectric materials, the dipole will interact with the electric field component of the microwave, and thus wave propagation and its interaction with the materials can become very complicated.

To understand how the dielectric material absorbs microwave energy, the permittivity ε is written as;

$$\varepsilon = \varepsilon' + \mathrm{i}\varepsilon''. \tag{5}$$

In this equation, the real part ε' and the imaginary part ε'' of the dielectric permittivity ε will represent whether the dielectric material stores or absorbs the microwave field energy. There is no energy absorption in a vacuum, because ε'' is zero. ε' and ε'' are non-linear functions of the microwave frequency f. **Figure 1** shows the dependence of ε' and ε'' on the microwave frequency in liquid water at 25 °C. The variation in ε'' indicates that strong energy absorption occurs at $f \approx 20$ GHz.

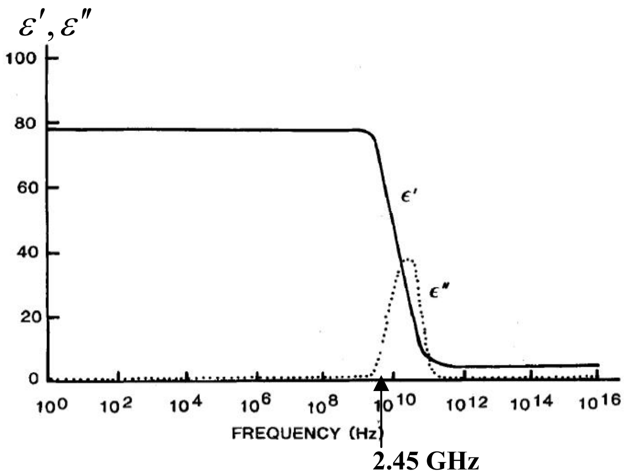


Figure 1 Dependence of ε' and ε'' on microwave frequency in liquid water at 25 °C [5].

The absorbed energy is dissipated as heat inside dielectric materials. The mechanism for the absorption is modeled in **Figure 2**.

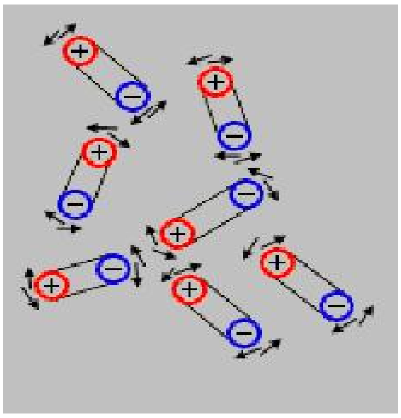


Figure 2 Model of rotation of dipoles in dielectric materials caused by alternating electric field component of the microwave [5].

Collisions between polar molecules occur during rotation under the influence of the alternating electric field component of the microwaves, generating friction and heat. The efficiency of energy absorption will depend on the microwave frequency. For liquid water at 25 °C, the resonance of the energy absorption occurs at $f \approx 20$ GHz . The energy absorption, $P_{\text{abs.}}$ is expressed in Eq. (6).

$$P_{\text{abs.}} = 2\pi f \varepsilon' \varepsilon'' E^2, \tag{6}$$

where E is the amplitude of the microwave electric field component.

In order to use microwave heating for drying fish, a microwave frequency of 2.45 GHz, the same as in a conventional microwave oven, is used. At this frequency, the microwave field can penetrate into the fish about 8 mm. This is determined by an important parameter in microwave heating known as the power penetration depth. It is calculated by Eq. (7) [2].

$$d_p = \frac{c}{2\sqrt{2}\pi f \left\{ \varepsilon' \left[\sqrt{1 + (\frac{\varepsilon''}{\varepsilon'})^2} - 1 \right] \right\}^{1/2}} \tag{7}$$

where c is the speed of light in vacuum, 2.998×10^8 m/s, f is the frequency in Hz and ε' is 49.8, ε'' is 17.2 when measured a raw fish at 71% water, 20 °C and 2.4 GHz [6].

MATERIALS AND METHODS

The picture and schematic diagram of the experimental setup are shown in **Figures 3a** and **3b**, respectively. The system includes a high-voltage DC power supply, magnetron, waveguide and multimode cavity.

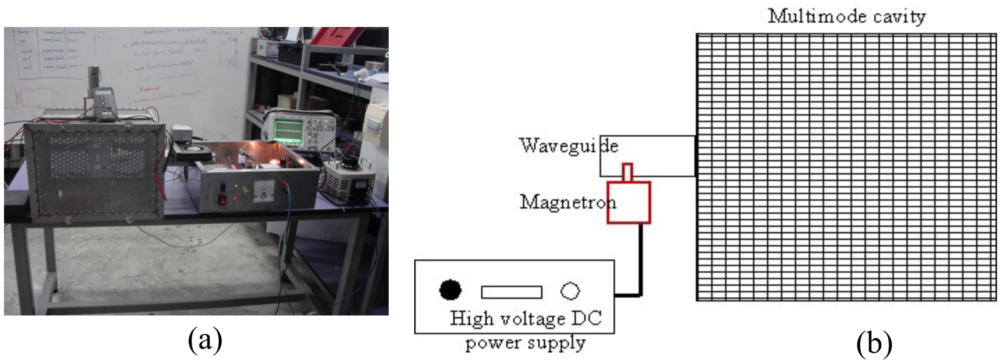


Figure 3 (a) Picture of experimental setup and (b) schematic diagram of experimental setup.

Magnetron

The magnetron is used as a microwave radiation source. To generate continuous and adjustable microwave power between 0 and 200 W, the magnetron was biased by appropriate currents and voltages from the power supply. The details of each component in the magnetron are described below:

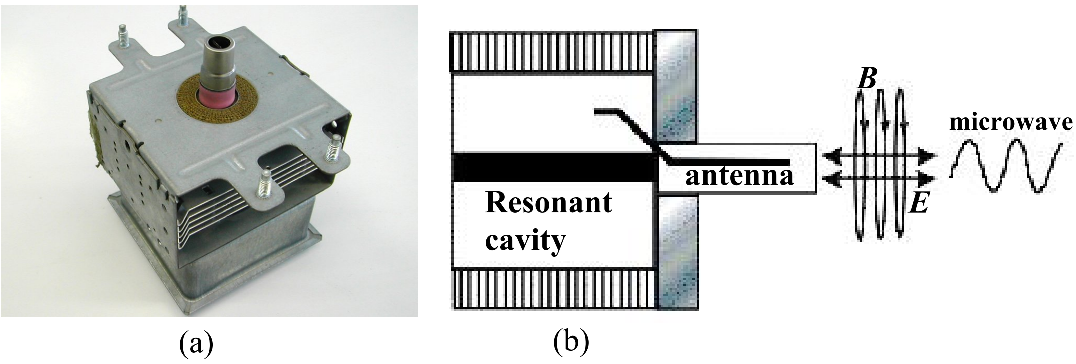


Figure 4 (a) Picture of a commercial magnetron and (b) schematic diagram of a magnetron.

A commercial magnetron producing microwaves with a frequency of 2.45 GHz, found in a domestic microwave oven, is shown in **Figure 4a**. **Figure 4b** shows the magnetron resonant cavity where the microwave field is generated by motion of an electron cloud under electric and magnetic fields. The electrons are emitted from a hot filament, supplied by a 3 V and 11 A power supply. The electric field is produced between the cathode and anode by an external high-voltage power supply, and magnetic field is produced by two permanent magnets. The threshold voltage for radiation of microwave power is about 4,000 V. As the voltage is increased from 4,000 to 6,000 V, the microwave power increases from 0 to 200 W. The microwave field in the resonant cavity is coupled to the antenna allowing propagation of microwave radiation.

High-voltage power supply

The circuit and picture of the high-voltage power supply which produces continuous and adjustable voltage is shown in **Figure 5**.

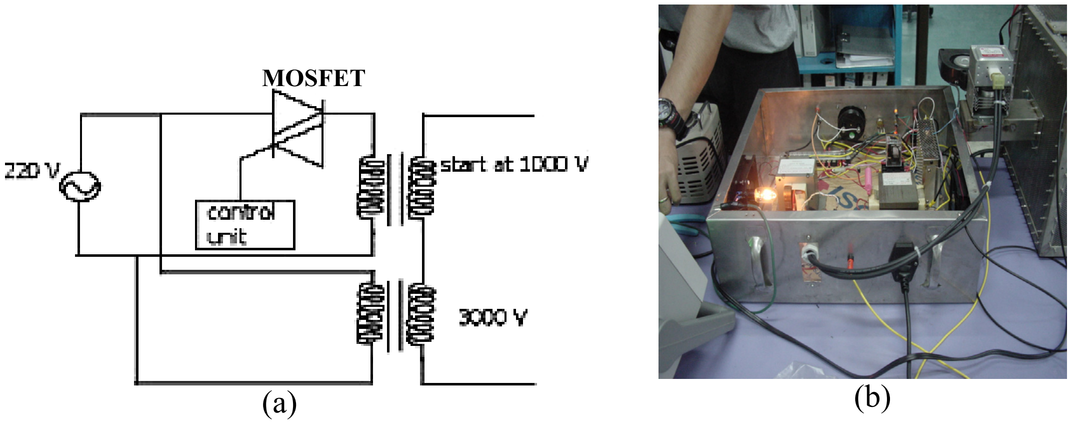


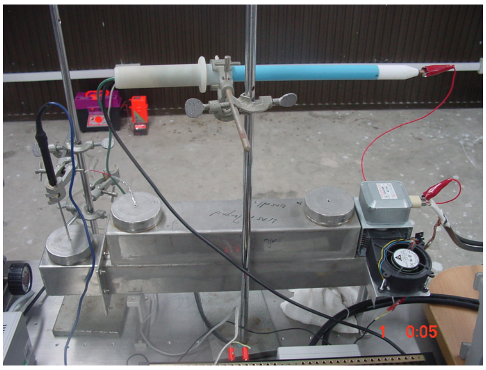
Figure 5 (a) Schematic circuit of High-Voltage Power Supply and (b) picture of HV power supply.

The voltage can be varied from 4,000 V to 6,000 V by controlling two high-voltage transformers. A switching technique using a control unit and high-power MOSFETs is utilized to adjust the input voltage properly for the two transformers. The output of the lower transformer is fixed at 3,000 V, whereas the upper transformer produces an output voltage between 1,000 and 3,000 V.

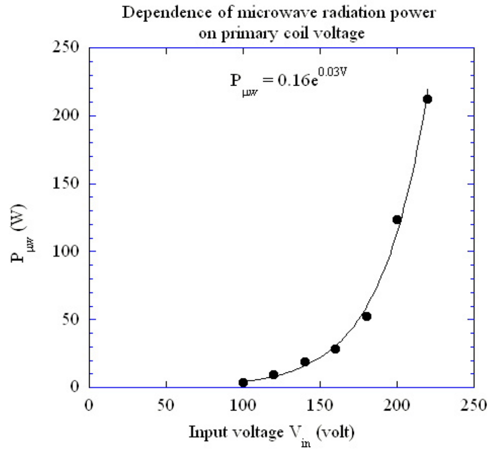
The setup for microwave power calibration is shown in **Figure 6a**. The microwave power, $P_{\mu w}$ is calculated from the heat generated in the water, as it absorbs microwave power. $P_{\mu w}$ is calculated using Eq. (7).

$$P_{\mu w} = \frac{4.19 V \Delta T}{t}, \tag{7}$$

where t is time, V is the water volume, ΔT is the temperature difference of the water after absorbing microwave power for t seconds.



(a)



(b)

Figure 6 (a) Experimental setup for microwave power calibration, (b) dependence of microwave power $P_{\mu w}$ on input voltage V_{in}.

Figure 6b shows that $P_{\mu w}$ increases exponentially with input voltage, V_{in}. The threshold input voltage for radiation of microwave power is about 100 V.

Waveguide

For effective transmission of microwave power to the fish, the waveguide and multimode cavity were designed carefully. The rectangular waveguide, made of aluminum, is designed for a TE_{01} mode where TE is the transverse electric field mode. The dimension of the waveguide's cross-section and the $\vec{E}$ and $\vec{B}$ pattern of the TE_{01} mode in the waveguide are shown in **Figure 7**. The values of a and b are calculated from Eq. (8).

$$f_{mn}^{c} = \frac{c}{2\pi}\sqrt{\left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2}, \quad (8)$$

where $c \approx 3\times10^8$ m/s, m = 0, n = 1 and f^{c}_{mn} is the cut-off frequency for the TE_{mn} modes. For microwave propagation at $f = 2.45$ GHz in the waveguide, f^{c}_{01} is chosen to be 1.88 GHz. Therefore, a = 8 cm and b = 4 cm are obtained.

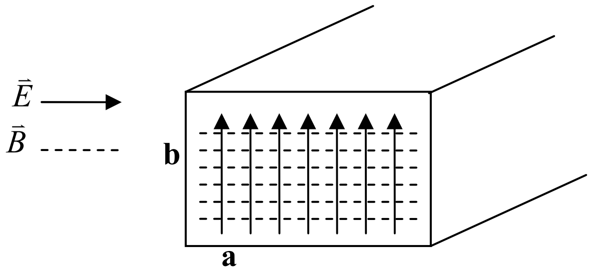
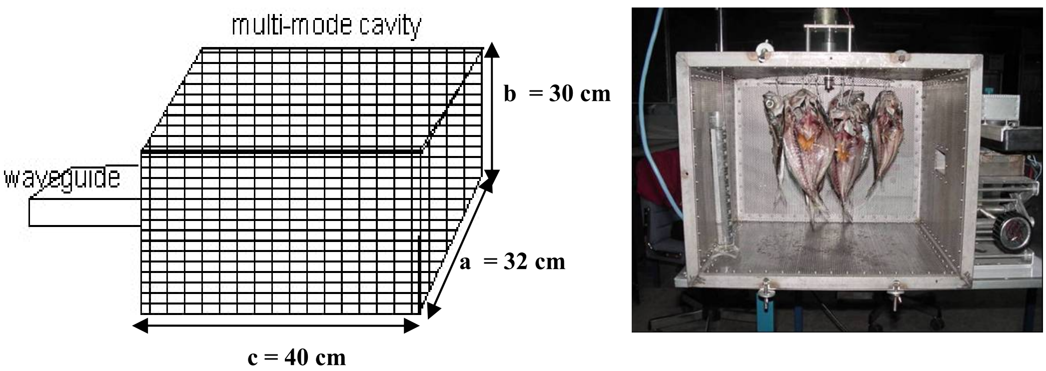


Figure 7 Cross-section of the rectangular waveguide. Dashed and solid lines represent electric and magnetic microwave fields respectively.

Multi-mode cavity

The multi-mode cavity that is excited at $f = 2.45$ GHz is shown in **Figure 8**.



(a) (b)

Figure 8 (a) Schematic diagram and (b) picture of multi-mode cavity for microwave excitation at 2.45 GHz.

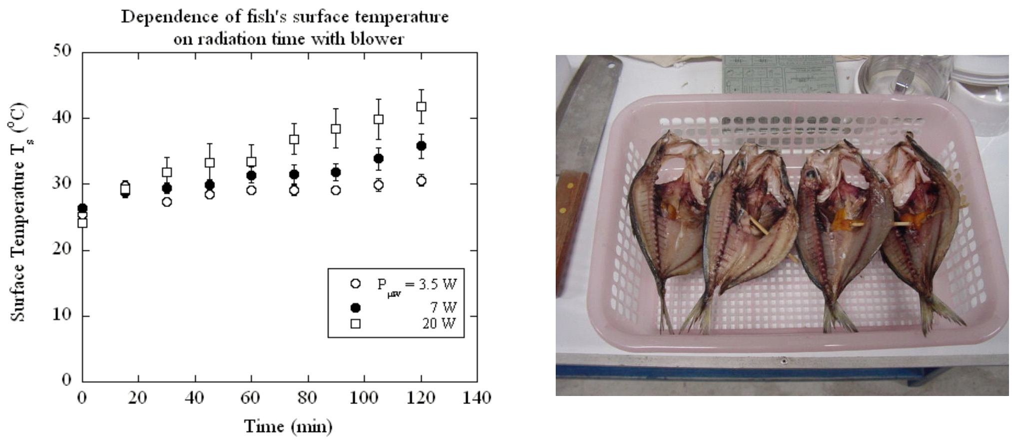
The wall of the cavity is made of stainless steel mesh measuring 2×2 mm^2 which is much smaller than the wavelength of microwave. Since the impedance of the fish will vary widely during drying, it is very difficult to acquire impedance matching by a single-mode excitation. The values of l = 32 cm, b = 30 cm and h = 40 cm are calculated from the equation of cut-off frequency, $f_{\mathrm{mnp}}^{\mathrm{c}}$.

$$f_{\mathrm{mnp}}^{\mathrm{c}} = \frac{c}{2}\sqrt{\left(\frac{m}{l}\right)^2 + \left(\frac{n}{b}\right)^2 + \left(\frac{p}{h}\right)^2} \tag{9}$$

where m, n, p are integers, and $f_{\mathrm{mnp}}^{\mathrm{c}} = 1.88$ GHz. The microwave field pattern inside the cavity is the superposition of all possible modes. The characteristics of each mode are determined from a combination of m, n and p.

RESULTS AND DISCUSSION

To study the drying of fishes by microwave energy, the surface temperature T_{s} and percentage of moisture content of fishes were measured as functions of radiation time and microwave power $P_{\mu\mathrm{w}}$. The fish were hung vertically inside the cavity as shown in **Figure 8b**. When the microwave power was on, the fish were rotated slowly at 10 rpm. A FLUKE 63 Infrared thermometer was used to measure surface temperature every 15 min. **Figure 9a** shows the dependence of T_{s} on radiation time for $P_{\mu\mathrm{w}} = 3.7, 7$ and 20 W. For each value of $P_{\mu\mathrm{w}}$, T_{s} increases slowly. The dried fish shown in **Figure 9b**, heated at $P_{\mu\mathrm{w}} = 7$ W, have the best appearance when compared with commercial dried fish.



(a) (b)

Figure 9 (a) Dependence of the surface temperature T_s of fish upon radiation time and (b) dried fish after heating at $P_{\mu w} = 7$ W.

Figure 10 shows the dependence of T_s on radiation time when the blower is on or off. From this, we conclude that using the blower increases T_s and the rate of evaporation of moisture from the fish's surface.

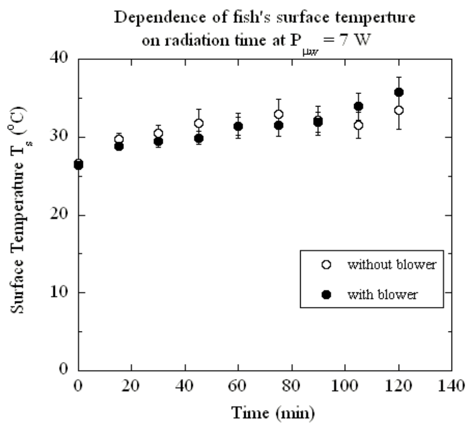


Figure 10 Dependence of T_s on radiation time at $P_{\mu w} = 7$ W when the blower is on or off.

Figure 11 shows the dependence of percentage of moisture content on $P_{\mu w}$ after radiating for 6 h. The moisture content decreases as $P_{\mu w}$ is increased. The best quality dried fish has a moisture content of about 50 %. Therefore, a microwave power of 9 W for 6 h should give good quality dried fish.

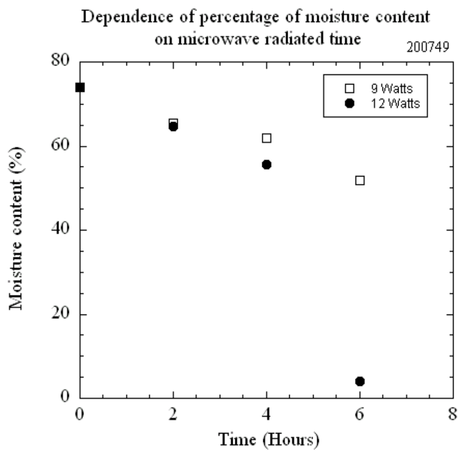


Figure 11 Dependence of percentage of moisture content on microwave power after radiating for 6 h.

CONCLUSIONS

In conclusion, we have developed a new system of drying fish utilizing an innovative microwave oven. The system incorporates finely adjustable microwave power for the highest quality dried fish. Experimental results show that dried fish with a surface temperature and moisture content of about 30 °C and 50 %, respectively can be produced. The use of a blower greatly increases the rate of evaporation of moisture from the fish. These preliminary results suggest that fish can be dried more effectively and in a much shorter time than with conventional technology. Further studies into the optimization of the dried fish's colour, taste and smell are underway.

ACKNOWLEDGEMENTS

We would like to thank The Research Technological Transfer to Community Commission on Higher Education, Upper Southern Region, Thailand and Institute of Research and Development, Walailak University for their financial support.

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บทคัดย่อ

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การพัฒนาระบบไมโครเวฟเพื่อการอบปลาแห้งประสิทธิภาพสูง

ปลาแห้งเป็นผลิตภัณฑ์ทางการเกษตรที่สำคัญของจังหวัดนครศรีธรรมราช ซึ่งกระบวนการดั้งเดิมในการผลิตปลาแห้ง คือการให้ความร้อนโดยใช้แสงแดด หรือเตาเผาที่มีไม้ฟืนเป็นเชื้อเพลิง วิธีการดังกล่าวมีปัญหาที่สำคัญคือมีประสิทธิภาพของการถ่ายเทความร้อนต่ำ มีการปนเปื้อนจากฝุ่นและเชื้อโรค ดังนั้นในงานวิจัยชิ้นนี้จึงได้พัฒนาระบบการให้ความร้อนแบบใหม่ด้วยคลื่นไมโครเวฟ โดยคลื่นไมโครเวฟจะเคลื่อนที่เข้าไปในปลาแล้วเปลี่ยนเป็นความร้อน เนื่องจากสนามไฟฟ้าของคลื่นไมโครเวฟจะทำให้โมเลกุลของน้ำซึ่งเป็นโมเลกุลชนิดมีขั้ว เกิดการหมุนตามความถี่ของไมโครเวฟแล้วชนกันเกิดเป็นความร้อน ฉะนั้นโมเลกุลน้ำจะมีพลังงานสูงขึ้น กลายเป็นไอแล้วเคลื่อนที่ออกจากปลา ทำให้ได้ปลาแห้งที่มีคุณภาพสูง ในการพัฒนาระบบการให้ความร้อนด้วยคลื่นไมโครเวฟ ได้สร้างแหล่งจ่ายกำลังไฟฟ้าความต่างศักย์สูงสำหรับแมกนีตรอน ซึ่งแมกนีตรอนจะจ่ายคลื่นไมโครเวฟที่สามารถปรับกำลังได้ 0 - 200 วัตต์ และได้พัฒนาท่อนำคลื่น และเตาอบ คลื่นไมโครเวฟจะถูกส่งจากแมกนีตรอนผ่านท่อนำคลื่นไปยังเตาอบ โดยภายในเตาอบจะสามารถกระตุ้นให้เกิดคลื่นไมโครเวฟในโหมดต่างๆได้ ในการทดลองอบปลานั้นได้ศึกษาว่ากำลังของคลื่นไมโครเวฟและเวลามีผลต่ออุณหภูมิและความชื้นของปลาอย่างไร

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