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Effects of Assistance of High Frequency Dielectric and Infrared Heating on Vacuum Freeze Drying Characteristics of Food Model

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Abstract

By combining vacuum freeze drying combined with high-frequency dielectric and/or infrared heating, the drying time for frozen gels containing 1% agar with sucrose or sodium chloride was successfully shorten, and the drying time was influenced by the heating methods and by the additive component to the sample. Additionally, it was experimentally confirmed that the power consumption for freeze drying combined with electromagnetic wave heating could be reduced because of the shortened drying time. Consequently, this study could be a very important step for designing a vacuum freeze drying process optimally combining electromagnetic wave heating for each sample component.

Keywords: *freeze drying, electromagnetic wave heating, food model, sucrose, sodium chloride*

1. Introduction

Vacuum freeze drying (FD) is less physical and with less chemical changes in the sample qualities; in recent years the application fields have been expanded. Vacuum FD is commonly and widely utilized for high quality preservative foods [1]. However, the drying time for conventional FD is very long (for example; several tens of hours). Therefore, freeze drying is actively studied for the purpose of shortening the drying time. Wang et al. performed FD of sliced potatoes by combining microwave heating, and established the drying time could be shortened by 37% [2, 3]. Microwave, combined FD is not enough uniform heating under the high vacuum. Additionally, Pan et al. tried to shorten the FD process of sliced bananas in consideration of the influence of infrared irradiation [4]. Furthermore, Schössler et al. studied an ultrasound assisted freeze drying of red bell pepper pieces cut into 1-cm squares, but noted only a minimal effect [5].

We then focused our attention on high-frequency dielectric (HF) heating to directly heat frozen foods for the purpose of the reduction of the time of the vacuum FD. The combined vacuum FD and HF heating has the potential of a multi-stage operation without a heating medium, and a large number of samples could be vacuum freeze-dried at one time. As the results, drying time could be shortened by using HF heating [6]. However, on the first half of the drying, the combination effect was very slight. This study aims to further shortening the drying time by combining vacuum FD combined with HF and/or infrared (IR) heating since infrared rays could be significantly absorbed by all phases of water. As the food model, a cylindrical frozen agar gel was selected because of easy formability and adjustments to its components. We then study the effects of the assistance of HF and/or IR heating on the FD characteristics and the influences of the additive of sucrose or sodium chloride (NaCl) to the food model on them.

2. Materials and Methods

2.1. Materials

Frozen agar gels containing 1 wt% agar were used as the food model samples. We also made the frozen agars including sucrose of 20 wt% or NaCl of 7.5 wt% as the drying samples. The outline of the sample preparation procedure is shown in Figure 1. The agar, sucrose and NaCl were of special grade and obtained from Wako Pure Chemical Industries (Osaka, Japan). The initial water content of the agar was preciously controlled by suppressing the moisture evaporation. The formed sample was stored in a freezer which was set to 253 K.

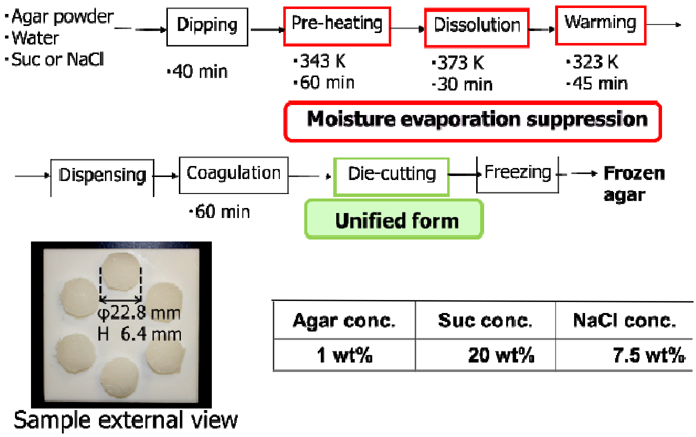
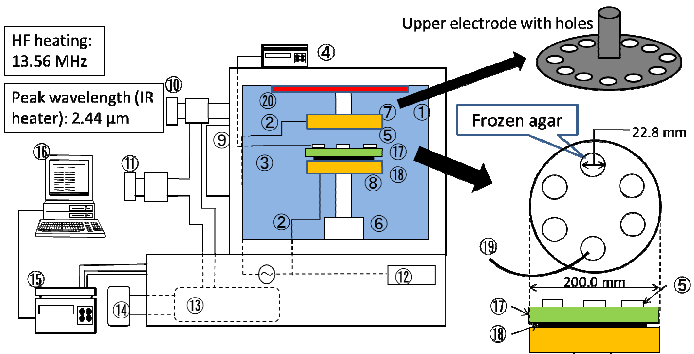


Fig. 1 Outline of sample preparation procedure.

2.2. Experimental apparatus

Drying experiments were performed in a Lab-scale vacuum chamber (Espec Co., Ltd., Osaka, Japan) equipped with the high frequency dielectric and infrared radiative heating



① Vacuum chamber ② HF introduction part ③ Optical fiber temperature and humidity sensors ④ Thermometer ⑤ Drying sample ⑥ Thermal and electrical insulator ⑦ Upper electrode ⑧ Lower electrode ⑨ Matching box ⑩ Vacuum exhaust valve ⑪ Piping leak valve ⑫ HF power source (13.56 MHz) ⑬ Oil-sealed rotary vacuum pump ⑭ Oil-water separator ⑮ Data logger (pressure, HF power recorder) ⑯ P C ⑰ Teflon® plate ⑱ Teflon® O-ring ⑲ Optical fiber type temperature sensor ⑳ Infrared heaters

Fig. 2 Schematic diagram of high frequency dielectric heating with freeze-dryer.

systems. A scheme of the drying equipment is presented in Figure 2. The output power of the high frequency dielectric heating is automatically adjusted to a set point by the matching box ⑨ during freeze-drying. The upper electrode ⑦ has the holes on the circumference for transmitting the infrared rays from the infrared heaters ⑳ equipped on the top plate inside the vacuum chamber ①. The infrared radiative power is controlled by adjusting the energization time to the infrared heaters. A vacuum pump was used for maintaining the vacuum in the chamber. The data of the pressure, high frequency traveling wave power and high frequency reflection wave power are recorded using the data logger ⑮.

2.3. Drying experiments

Six frozen agar samples are put on the Teflon® plate (82× 82× 10.5 mm) and are kept in a freezer set at 253 K overnight. The samples and the plate were put on the lower electrode. To avoid the heat transfer from the lower electrode to the sample, a Teflon® O-ring (φ3, 60 mm inside diameter) ⑱ was put on the lower electrode ⑧, and the samples ⑤ on the plate ⑰ were put on the O-ring. The distance from the sample to the upper electrode (GND) was set at 15 mm based on the preparatory experiment results.

In case of the assistance of HF heating, after the pressure in the vacuum chamber reached around 100 Pa, HF power was supplied to the frozen samples and the drying experiment was started. During drying, the sample temperature and the pressure in the chamber were continuously monitored. At the specified drying time, one agar was sampled from the chamber after the inner pressure was returned to atmospheric pressure. Drying of the remaining agar samples were then started again. To determine the moisture content of the sample, the sample after vacuum freeze drying was dried in an oven set at 378 K for 24-72 hours. The dry weight of the sample was gravimetrically measured.

3. Results and Discussion

3.1. Drying characteristics

The influences of the HF power on the combined vacuum freeze drying characteristics of the frozen agar gel were experimentally studied, and Figure 3 shows the influences on the time courses of the normalized water content (ω/ω_0) relative to the initial one (ω_0) for the frozen agar gel (no additive) and of the sample temperatures. As shown in Figure 3, the drying rate was accolated by combining electromagnetic wave heating. The drying time was shortest when HF and IR heating were simultaneously used (HF+IR). However, the sample temperature rose and the part became burned. We then performed the other combination of HF and IR heating with FD (HF+IR→HF). Drying with HF+IR was carried out in the initial stage, and infrared irradiation was cut off when the sample temperature began to rise. As the result, the temperature rise of the sample was suppressed, and it was possible to shorten the drying time almost the same as HF+IR drying.

Drying of frozen agar supplemented with sucrose or NaCl was performed by combining electromagnetic wave heating, and Figure 4 shows the relationship between the drying time t_d and the final temperature of the samples. We then performed the preliminary approach to quantitatively confirm the differences of the drying characteristics of each sample. For the additive free sample under the FD process without the assistance of HF and/or IR heating, the time course of the normalized water content was fitted using the following simple

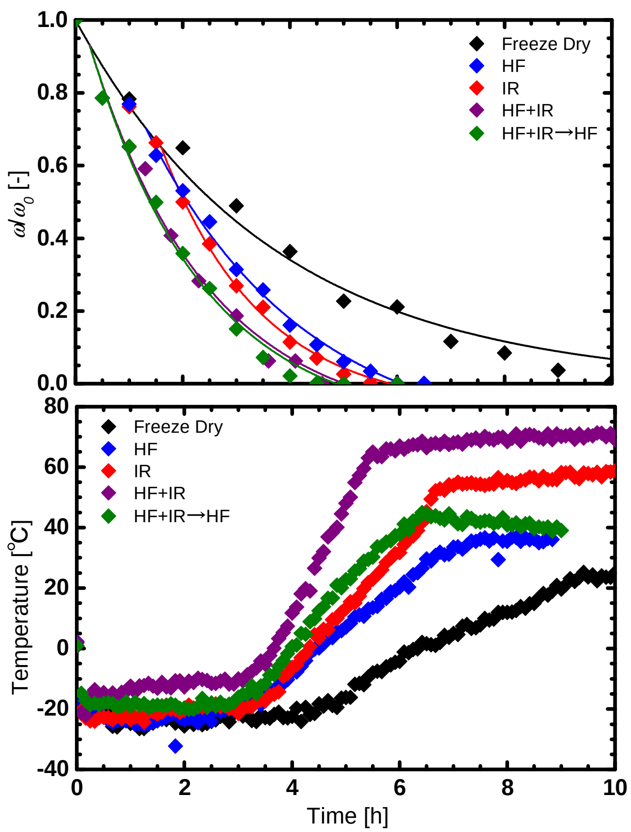


Fig. 3 Time courses of normalized water contents and temperatures of frozen agar gel (no additive).

exponential equation.

$$\omega/\omega_0 = \exp(-kt) \qquad (1)$$

Here, t and k are the drying time and the drying rate constant, respectively.

For the other samples, the curve fitting for the time courses of the normalized water content was carried out using the following equation which modified Eq. (1) from the middle of the drying process [6].

$$\omega/\omega_0 = \left\{\left(\omega/\omega_0\right)_s - 1\right\} + \exp\{-k_1(t - t_s)\} \qquad (2)$$

Here, t_s and $(\omega/\omega_0)_s$ are the start point of the exponential curves for parallel translation of Eq. (1). An intersection of both curves expressed by Eq. (1) and (2) means the critical point of the drying characteristic. k_1 is the drying rate constant for the latter exponential curve. We could then calculate the drying time t_d based on Eq.(2).

As indicated in Figure 4, for the samples added sucrose as an organic substance, the effect of shortening the drying time was more pronounced for IR heating assistance than for HF heating assistance. In addition, for the samples added NaCl as an electrolyte substance, no significant difference was observed in the time reduction effect by HF and IR heating assistance, but the dry sample temperature was lower for HF heating assistance than in for IR heating assistance.

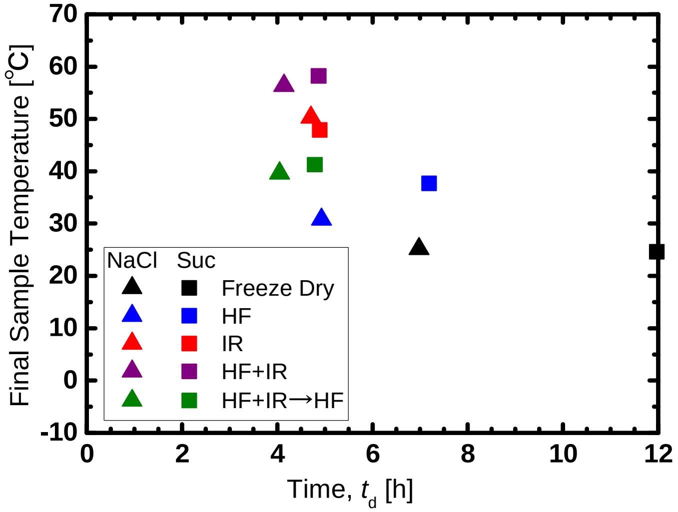


Fig. 4 Relationship between dried sample temperature and drying time.

3.2. Electric power consumption during drying process

We also measured the electric power consumption during each drying process. Figure 5 illustrates the relationship between the electric power consumption and the drying time. It was confirmed that the power consumption could be reduced by shortening the drying time with the assistance of electromagnetic wave heating. In addition, based on the near-infrared spectroscopic imaging results of the dried samples (data not shown), it was experimentally confirmed that the component changes of the dried samples except for those dried under the HF+IR drying conditions could be negligible. Consequently, from the experimental results indicated in Figure 3, 4 and 5, the effectiveness of the assistance of electromagnetic heating to vacuum FD of the food model was experimentally found.

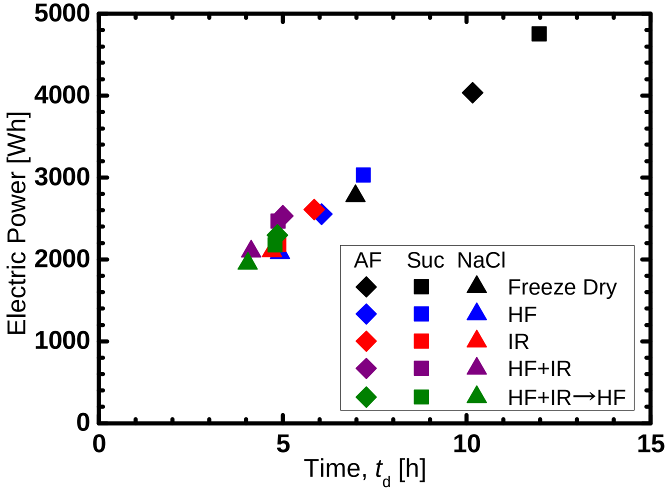


Fig. 5 Relationship between electric power consumption and drying time.

4. Conclusions

By controlling the combined use conditions of HF and/or IR heating for each sample component, drying time could be shortened. Additionally, a vacuum freeze drying process could be optimally designed by combining electromagnetic wave heating with the reduction of electric power consumption and without the quality change of the dried sample.

5. Nomenclature

k	drying rate constant	h^{-1}
t	drying time	h

Greek letters

ω	water content	kg-water kg^{-1}-dry material

Subscripts

0	initial state
1	state after critical point
s	start point defined by Eq. (2)

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