Variable far infrared radiation (VFIR) technique for cubic carrot drying

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Abstract

Far Infrared Radiation (FIR) technology has rarely been used for agricultural products. In this paper, FIR technique was applied to dry a carrot and its drying performance was experimentally investigated by observing structural deformation and color change of the dried product. A Computed Tomographic (CT) scanner was employed for the observation of internal structure of product. Variable FIR drying was tested to dry carrot in the initial moisture content of 1125 %d.b. The power of variable FIR was controlled with moisture content of test carrot as follows; 600 W for 2 hours, followed by 400 W for 2 hours and maintained at 200 W FIR until the end of process. The quality of dried carrot was examined from CT image analysis and the dried carrot structure by variable FIR drying was similar to the hot air drying process. The color of the dried carrot was maintained like fresh carrot. We concluded that variable FIR drying had some advantages for energy saving, shorter drying time and quality of product in comparison with hot air drying.

Keywords: *CT image, drying characteristics, FIR drying, shrink*

1. Introduction

Far Infrared Radiation (FIR) is to be beginning widespread for drying technology. The development of FIR use for drying process was developed in combination with several systems such as the application of FIR for freeze-drying sweet potato [1], FIR application combined with low-pressure superheated steam on banana slices [2],[3] or FIR application under vacuum conditions to dry welsh onion [4]. Effects of FIR in drying process are the radiative heat flux from FIR completely attenuated to a certain depth and the influence of radiation heating. The evaporation of water starts at the depth of attenuation and moisture from the interior is transferred to outside very rapidly and so the drying rate is high [5]. Therefore, the performance of a drying system can be improved by using FIR. However, the combination of system has some disadvantages, such as installation, operating processes, and so on.

Our previous study of drying cubic carrot (3 cm x 3 cm x 3 cm) by using the FIR process showed that a long drying time with high power of FIR heater made product damaged. The damage of carrot structure was less by means of lower power heater. It is more difficult to decrease moisture content with low power heater when the carrot moisture content is low. Comparing energy consumption of lower power FIR drying to that of hot air convection drying, it was found that lower power FIR drying consumed more energy [6].

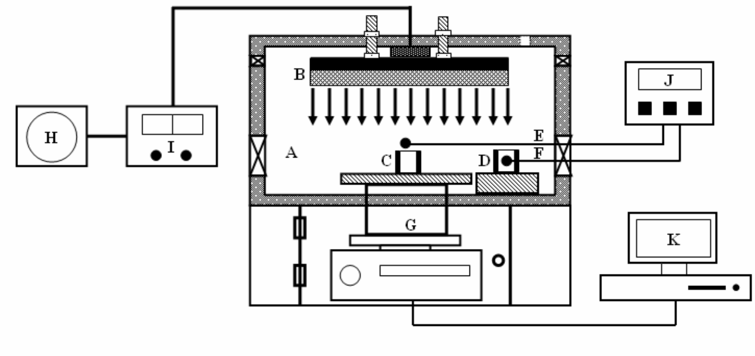
Variable control of FIR heater power is one option to solve the above mentioned problems of drying by using a FIR heater alone. Problems of FIR drying such as damaging product structure, increasing energy consumption, and shortening the time requirement are expected to be solved by variable power FIR drying.

The aim of this study is to investigate drying characteristics of cubic carrot by controlling FIR heater power in comparison to hot air convection drying. The effects of the power level of the FIR heater on the drying rate, water distribution and the deformation of the test material were studied using CT imaging technology.

2. Materials and Methods

2.1 Experimental instruments

Several physical and thermal properties of carrot were measured to compare the drying performance between hot air drying and FIR drying. A drying chamber size with internal dimensions 450 x 600 x 450 mm was covered with 50 mm adiabatic fiberglass as shown in Figure 1. An electric FIR heater, maximum power of 1500W is installed at the top cover side in the drying chamber and the distance between FIR heater and carrot is 300 mm. In the hot air drying process, a normal electric heater was used to keep air temperature constant and air flow in chamber was forced by a fan. The power of FIR heater was controlled with a voltage controller (VQ-71510B, Matsushita) and the input power was measured with a voltmeter and ammeter. The test sample was placed on a tray parallel to FIR heater. The mass of test sample was measured with an electronic balance (HF-2000, A&D), and the data was recorded at 1-minute intervals. A type T thermocouple was inserted into the middle of test sample to measure the sample's temperature and was recorded by a data logger (2100A, Etodenki) at 5-minute intervals.



A: Drying chamber	B: FIR heater	C: Drying material 1
D: Drying material 2	E: Thermocouple 1	F: Thermocouple 2
G: Electronic Balance	H: Power controller	I: AC Watt meter
J: Data recorder	K: Computer	

Fig. 1 FIR drying experiment system.

2.2 CT image analysis

The physical properties of cubic carrot were measured with an X-ray CT scanner (TOSCANER-20000, Toshiba) which was designed for agricultural and industrial applications. Images were taken at an X-ray energy level of 150 keV and electron current of 3 mA. The quantity for measuring X-ray absorption with CT systems is standardized by CT number defined as the following equation;

$$H = \frac{\mu(x,y) - \mu_w}{\mu_w} K \quad (1)$$

where the H is CT number, μ (x,y) which represents the linear attenuation coefficient of the test material, μ_w represents the linear attenuation coefficient of water, and the constant factor K=1,000 [8] CT numbers use a normalization of zero for water and -1000 for air. Dense materials such as aluminum alloy have a CT number of 2000 [7]. CT number of the X-ray CT scanner ranges from -1000 to +4000. CT number was represented by brightness in a reconstructed image.

The shape of the test material was smaller than its original size during the drying process. In this experiment, the border of the test material cross section was determined by CT number. CT number of the border pixel of the test material was extremely higher than that of air fraction. Threshold value of CT number at the border pixel is defined as follows;

$$X_c = \frac{X_o + X_i}{2} \tag{2}$$

where X_c is threshold value of CT number, X_o is CT number of the test sample at the start (the air = -1000), X_i is CT number of the test material at time *i* (i.e. the initial test material = 100). Cross-section area ratio of shrinkage is defined as follows;

$$S_i = \frac{A_i}{A_o} \times 100 \tag{3}$$

where S_i is cross-section area ratio (%), A_o is the initial cross-section area of the test material (number of pixels), A_i is the cross-section area of the test material (number of pixels) at time *i*.

2.3 FIR heater

Three FIR heater made of ceramic elements 10.2 mm in diameter and 420 mm in length were used in the experiment. The maximum power is 500W for each element. The surface of FIR heater was colored black for maximum emissivity. The efficiency of a FIR heater is defined by the following equations (4) and (5).

$$Q = \sigma \varepsilon T_h^{\,4} A_h \tag{4}$$

$$\eta = \frac{Q}{P} \times 100 \tag{5}$$

where Q is the transferred heat, A_h is surface area of the heater (m^2), σ is a proportionality constant known as Stefan–Boltzmann constant equal to 5.67 x 10^{-8} $Wm^{-2}K^{-4}$, εis the emissivity of the heater, T_h is absolute temperature of the heater (K), P is the electric power input of the heater (W), and ηis the heater efficiency (%).

2.4 Sample preparation

Fresh carrot samples were soaked in water for 24 hours, then packed in plastic bags and stored in a refrigerator at 4°C to reach the desired initial moisture and temperature. The carrots were then cut into uniform dice slabs of 30 x 30 x 30 mm.

2.5 Drying conditions

In the hot air convection experiment, air temperature was controlled at 50°C $\pm 1^{\circ}$C and air velocity was maintained at 0.6 m/s. In the FIR drying experiment, heater power was set at three levels of Watt-power input: 200, 400 and 600W. Temperature of the sample was measured every 5 minutes. Variable FIR condition was set up to save drying energy and to decrease drying time. Moisture content was used as indicator to keep the color of test material. The steps of the drying process in variable FIR drying are shown in Fig 2. In the drying process, the color variation of the carrots is effected by the heating values at different moisture conditions. From the experiments of drying the carrots at the different power supplies of 600 W, 400 W, and 200 W, it was found that the color of dried carrots was changed at 600 W with 800 %db and 400 W with 200%db as shown in Fig 3. There is no color change at power of 200 W. Therefore, power supplies to FIR heater was adjusted according to the color variation.

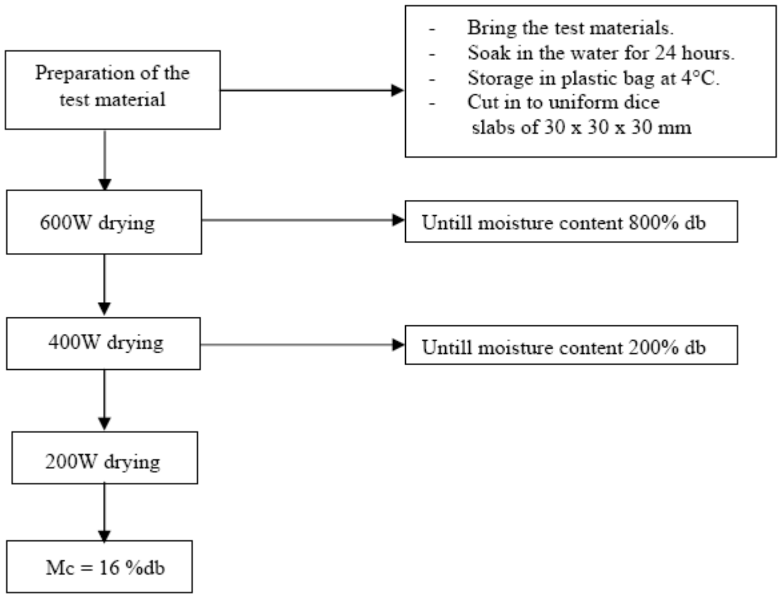


Fig. 2 Procedure of variable FIR drying for carrot.

The moisture content and drying rate were calculated based on the final mass of the sample in this paper. The moisture content is defined by the following equation;

$$Mc = \frac{Wi - Ws}{Ws} \times 100 \tag{6}$$

where *Mc* is the moisture content (% d.b.), *Wi* is the mass at time *i* (g) and *Ws* is the mass of completely dried material (g).

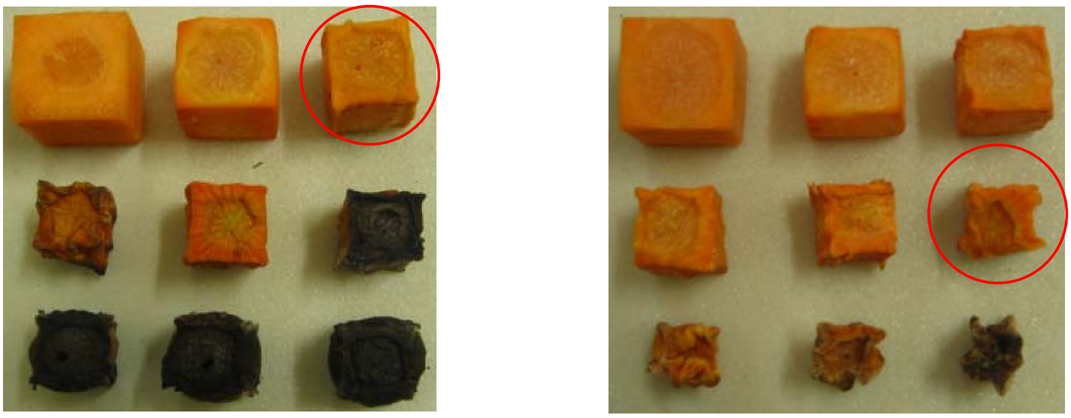
3. Results and discussion

3.1. Drying characteristic of FIR and variable FIR

One of important parameters observed in drying process was color. The best product quality after drying can be shown by the change of color and it was nearly negligible. Carrots dried by hot air and FIR 200W power have good quality in color but it takes long time to dry (Table 1). During the drying process at high FIR power, the color of the carrot became darker with time. The other effect of FIR drying can be observed on the change of internal structure of carrot in the case of 600 and 400 W power (Fig. 2). The advantage of high power FIR drying is shorter drying time in comparison with the lower power FIR drying and the hot air drying (Table 1). In addition, it was found that the specific energy consumptions under hot air and VFIR conditions are 9.05 kWh/kg H_2O_{evap} and 7.00 kWh/kg H_2O_{evap}, respectively. Therefore, the VFIR condition can save more energy consumption. From the experiment, the color of carrot changed dramatically at around 800 %d.b. and 200 %d.b. by FIR drying 600W and 400W, respectively (Fig. 3). We conclude that color can show the limits of moisture content for drying carrot with FIR power intensity.

Table 1 Drying time and energy consumption in the drying process.

Condition	Moisture content, %db		Drying time, hr	Energy consumption, kWh	Color change (moisture content, %db)
	initial	final			
Hot air 50 ^{O}C	1150	32.3	126.0	4.95	-
FIR 200 W	1125	30	32.5	6.50	-
FIR 400 W	1125	10	11.7	4.68	200
FIR 600 W	1125	10	6.3	3.78	800
VFIR	1125	16	13.0	3.80	-



a) 600 W FIR drying b) 400 W FIR drying

Fig. 3 Effect of high Watt power in color change.

The drying characteristic of the test carrot by FIR drying (FIR heater power at 200, 400 and 600W) and variable FIR drying was observed as the relationship between moisture content and drying rate as shown in Fig. 4. Initially, the behaviors of the drying rate at 200, 400 and 600W were similar. After, the drying rate increased rapidly to a maximum, then decreased gradually. The initial drying rate at 200, 400 and 600W was 36, 116 and 167 %d.b./hr, respectively, and the maximum drying rate was 97.3, 209 and 331 %d.b./hr, respectively. The change of drying rate was rapidly increased due to high moisture content on the surface of the sample and was also affected by the power of FIR heater during the initial stage of the drying process. The sample temperature was increased by radiation from the FIR heater and all of the radiation was converted to heat inside the sample body [5]. The maximum temperatures at 200, 400 and 600W were 80, 121 and 158 ºC, respectively, as shown in Fig. 5.

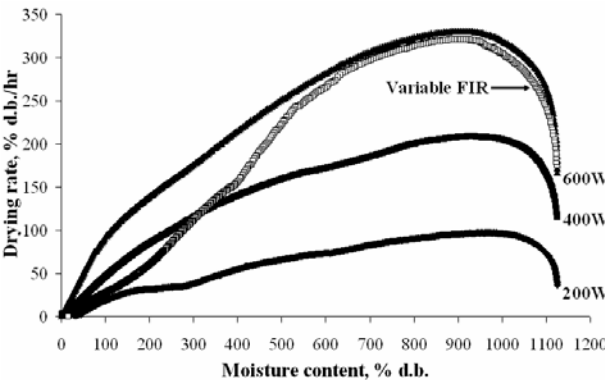


Fig. 4 Comparison between drying characteristic curve of 200, 400 and 600W FIR drying with variable FIR drying as a function of moisture content.

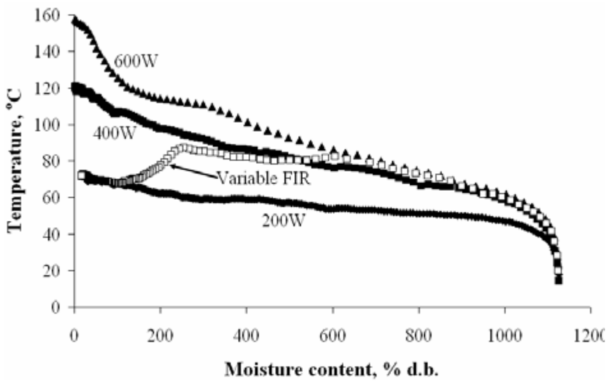


Fig. 5 Relationship between of temperature and moisture content on drying characteristic curve of 200, 400, 600W FIR and variable FIR drying.

Drying time of variable FIR was about 13 hours with initial and final moisture content 1125 %d.b. and 16 %d.b., respectively. Energy consumption of variable FIR was about 3.8 kWh. The comparison between variable FIR and hot air drying in energy consumption and drying time showed the fact that variable FIR had less energy consumption and shorter drying time than those of hot air drying. The result of color change showed that the color of the dried carrot by variable FIR was the nearly same color as fresh carrot (Figure 6). Internal temperature of carrot by variable FIR in drying process was less than 100 ^{O}C as show in Figure 5.

Fig. 6 Color change of the dried carrot with variable FIR drying.

The change of drying rate by variable FIR drying was the same trend as that by 600W FIR drying in the first 2 hours. After that, the drying rate was gradually reduced to the level of 400W FIR drying at 600-700% d.b. Then, the drying rate was decreased to the level of 200W FIR drying in 4 hours, at about 250% d.b., and the moisture content was 16.6% d.b. in 13 hours.

Considering the relationship between moisture content and temperature, inner temperature of carrot by variable FIR drying was similar to the temperature change by 600 W FIR drying at the first stage. After 2 hours, temperature of variable FIR drying was decreased to that of 400W FIR drying at 600-700 %d.b. of moisture content. In 4 hours, FIR power was reduced to 200W at 250 %d.b. of moisture content. Inner temperature of carrot by variable FIR drying was, then, decreased continuously to similar temperature by 200W FIR drying at 100 %d.b. of moisture content

3.2. CT image analysis

The changes of CT image of the test materials in each experiment are shown in Figure 7. The structure of test carrot by variable FIR drying was shrunk in similar trend by hot air drying and 200W FIR drying.

In hot air drying and 200W FIR drying, CT image indicated that the test carrot was shrunk continuously and isotropically. Shrinkage started from the edge to the center of the test material. As for the case of 400W and 600W FIR, test carrot was shrunk very fast. However, damage of the internal structure was observed in the sample from 8 hours and 5 hours by 400W and 600W FIR drying.

CT image of variable FIR showed that continuous shrinkage of test carrot was progressed and internal structure was not damaged. The effect on carrot quality by variable FIR drying was nearly same as hot air drying and 200 W FIR drying. However, the time requirement was less than their times.

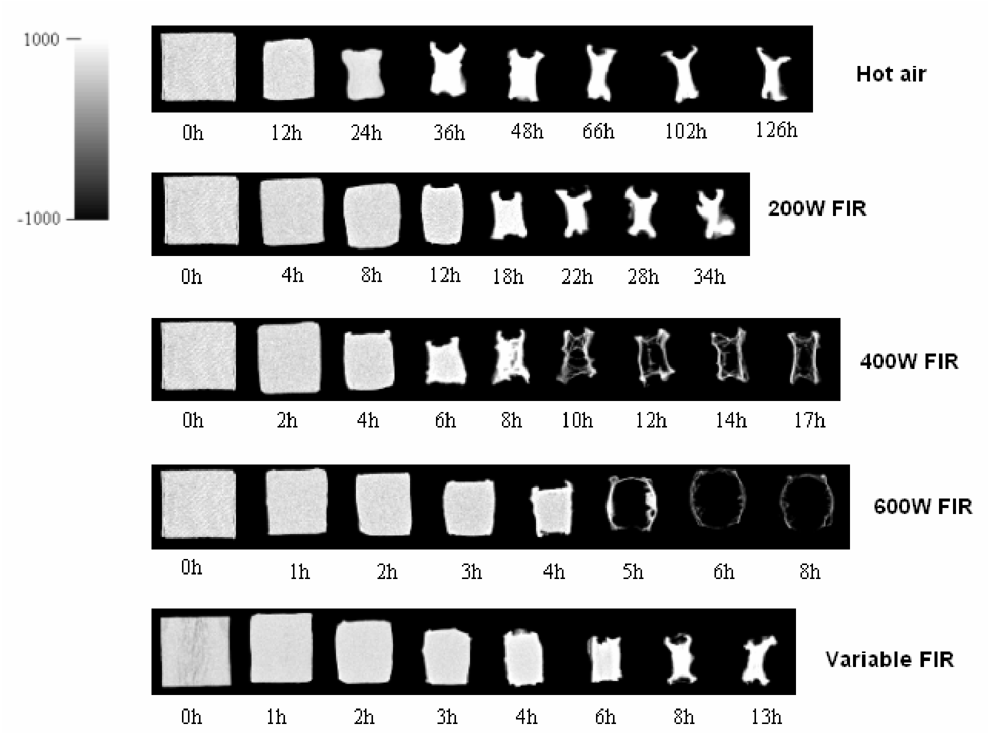


Fig. 7 Changes of CT image of test carrot.

The change of CT number was as shown in Figure 8. CT number by variable FIR drying started from 74.5, which indicated that test carrot had high moisture content. In the way of experiment CT number increased gradually and it ended with 342 at 13 hours drying, which indicated that carrot had low moisture content and became solid stage.

The change of CT number by variable FIR drying was similar with hot air drying and 200 W FIR drying. Minus value of CT number indicated that the internal structure of test carrot was damaged and its structure became porous.

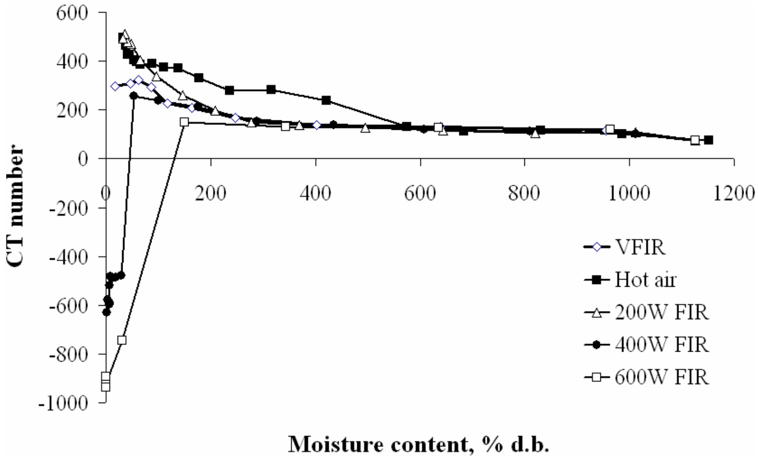


Fig. 8 Change of CT number by hot air drying, 200, 400 and 600W FIR drying in comparison with that by variable FIR drying (VFIR).

4. Conclusion

Variable FIR drying controlled with moisture content of test material is suitable for drying vegetables. The advantages of this technology are energy saving, shorter drying time and higher product quality. Variable FIR power was controlled at 600 W for initial 2 hours and adjusted with 400 W for following 2 hours and then maintained at 200 W until the end of process. The quality of product by variable drying was same grade as that by hot air drying and 200W FIR drying. The technique will be applied to other agricultural products after the suitable power depending on the material is determined with the further experiment.

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